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Crop yields and global food security

**Will yield increase
continue to feed the world?**

**Tony Fischer, Derek Byerlee
and Greg Edmeades**



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Short (75 cm) high-yielding (11 t/ha) modern winter wheat variety towards the end of grain filling in Henan Province, China. (Photo: Professor Tiancun Zheng, Zhoukou Agricultural Research Institute)

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Foreword

World food security is a serious and pressing contemporary issue. This book examines the extent to which future crop yield increase can continue to feed the world. It highlights for scientists and policymakers the role of technological innovation as a key driver of past and future yield gains. It considers the broader consequences and challenges for these gains through intensified crop production.

Improving global food security and alleviating poverty through agricultural innovation is central to the mission of the Australian Centre for International Agricultural Research (ACIAR). As part of the Australian Government's overseas aid program, ACIAR supports collaborative agricultural research in developing countries of Asia, the Pacific region and Africa. Since 1982 ACIAR has funded research into crop production and has often contributed to the technological progress referred to in this book. Examples include the strengthened wheat rust resistance breeding across South Asia, the dramatic increase in rice production in Cambodia, the spread of direct seeding and conservation agriculture in several Asian countries, and improved efficiency of nitrogen fertiliser management for wheat–maize systems in China. Moreover, the CGIAR centres, supported by ACIAR, have played a major role in lifting the yields of wheat, rice, maize, coarse grains, cassava, sweetpotato and some grain legumes in developing countries, and sometimes farther afield. It is therefore fitting that ACIAR publish this book highlighting the importance of technological innovation for crop yield increase and world food security.

The book looks beyond just the crops and countries that are of greatest interest to Australia and ACIAR. It considers all the important crops in all major production regions, including those in developed countries. Food security is advanced by increasing production by subsistence farmers for home and local consumption, by boosting commercial smallholder farmer output for national markets, and by raising exportable surpluses from countries and regions with global comparative advantage. By comparing crop yield and current yield increases in the bread baskets of the world, and at the national and sub-national levels, this book reveals both commonalities and considerable diversity in constraints to yield progress. This in turn points to different investment priorities for agricultural development in different regions, but everywhere greater investment in research and development is a necessary condition to lift rates of crop yield increase.

The book is for scientists who daily confront issues concerning the modernisation of world crop production. It is also for those who are more generally interested in agriculture, natural resource management and food security. The book will also inform and inspire tertiary students regarding the challenges and exciting rewards in agricultural research and development. It takes a multidisciplinary approach to the possibilities for continuing crop yield advance, with attention to fields ranging from plant molecular biology and genetics to rural policy and political economics. We hope it will serve as a contemporary and comprehensive guide to a subject that, while lately becoming so topical, has been central to ACIAR's mission since its inception more than 30 years ago.



Dr Nick Austin

Chief Executive Officer
ACIAR

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Preface



More than 200 years have passed since Thomas Malthus, author of 'An essay on the principle of population' published in 1798, and highlighted 200 years later in Evans (1998), argued that world population expansion would outstrip growth in food supply, resulting in starvation. In the intervening period these gloomy predictions have reappeared from time to time, only to be banished again by arable land expansion in the New World, massive growth in global food trade, and (more recently) crop yield increase. The latter effectively buried the dire 1960s predictions from the Club of Rome,¹ and similarly from the Paddock brothers in their book 'Famine–1975!' (Paddock and Paddock 1968).

Nonetheless, L.T. Evans in his introduction to 'Feeding the ten billion' (Evans 1998) pointed to the prevailing excessive complacency over world food supply at that time. And indeed many believe that the Malthusian spectre has returned in the wake of sharp price increases for food commodities in 2008 and 2011; these persistent price increases point to a failure of supply to meet demand.

Renewed concern, even alarm, is reflected in the host of conferences and research publications on world food security appearing in the past 5 years. The popular science book 'The coming famine' (Cribb 2010) captures the mood, raising alarm over shortages of land, water and research products, and over mounting pressure from demand growth and climate change. However, it was our June 2009 participation in an expert meeting at the Food and Agriculture Organization of the United Nations that provided the catalyst for this book—this meeting was entitled 'How to feed the world', and its proceedings were later published (Conforti 2011).

Farm boys from the Antipodes and graduates in agricultural science, we had come together in Mexico in the 1980s at the International Maize and Wheat Improvement Center—known as *Centro Internacional de Maiz y Trigo* (CIMMYT)—but after a number of years working together we went our separate ways. Our distinct experiences are now brought together to bear on the critical issue of crop productivity, as reflected in the title of this book.

¹ The Club of Rome is an international think tank established in 1968 and famous for publicising views on the limits to world growth.

World population surpassed 7 billion in late 2011; population is expected to reach 9.3 billion by 2050, and per-capita demand is likely to increase along with income growth. Across the scientific literature, global food demand is predicted to increase between 50% and 100% over 2000 levels by 2050. At the same time, growth in food production is slowing.

The take-off in crop yield increase in the mid 1960s averted the predictions of widespread famine of the time. This yield increase, until the turn of the millennium, led to steadily reduced real prices of food and a dramatically slower expansion of arable area. If this desirable situation (with respect to price and arable area) is not to deteriorate under the pressure of relentless growth in demand, further substantial increases in crop yield are essential. Real prices cannot be allowed to rise greatly, because (as seen recently) this translates into increased malnutrition and misery in the world's two billion poorer people, and to civil unrest. Meanwhile, in most cases, for environmental reasons, crop area increase is a difficult and undesirable option.

There have been many analyses of this dire scenario, but few contain a balanced and detailed dissection of the central issue—the prospects for further crop yield increase. This topic, considered from now out to 2050, is therefore the subject of our book. It recalls the concluding sentence of an interesting article on the subject of world food security:

'Few things matter to human happiness more than the yields of staple crops.'
The Economist (26 February 2011)

Claims regarding crop yield prospects abound, and range widely, causing much confusion and uncertainty. As an example, in 2008 Monsanto (the multinational crop breeding company) optimistically projected that US maize yields would double between 2000 and 2030, largely driven by new biotechnology (including genetic engineering). This means farm yield would rise from an already high 9.4 t/ha to 18.8 t/ha—equivalent to an unprecedented rate of linear growth equal to 3.3% p.a. of the 2000 yield.

On the other hand, Duvick and Cassman (1999) argued that the potential yield for maize (in the same US Mid West region) has already reached a plateau, despite the huge investment of research dollars targeting this crop. Furthermore, co-author and leading US agronomist Cassman predicts that farm yield is fast approaching this potential yield plateau (K.C. Cassman, pers. comm.). A plateau in yield conjures up visions of an approach to biological limits to yield—long foretold and usually 'disproven even before they are forgotten' as Evans (1993) wryly commented—but there is little doubt such limits exist.

A totally different scenario can be found with maize in Sub-Saharan Africa, where it is widely agreed that farm yields are (at best) no more than one-third of their potential under reasonable assumptions. Bright prospects thus exist for yield progress through closing of the gap between farm and potential yields, although proposed solutions are diverse, challenging and controversial. The other key food crops tend to fall between the extremes highlighted here for maize, and reflect (as with maize) huge variation in

(and understanding of) cropping scenarios around the world. Such variation is totally hidden in the deceptively simple linear growth of world average yield for most crops.

Our approach here is to dissect crop yield growth and its drivers in time and space, and to focus on the world's four most important crops—rice, wheat, maize and soybean—which indirectly (as feed grain) or directly provide around two-thirds of the calories and protein consumed by humans. The dominance of these few crops is unlikely to change but, nevertheless, we also give limited attention to other important crops (e.g. millet, cassava, other oilseeds, sugarcane, oil palm and pulses) especially where these crops play important roles in developing countries.

We also consider climate change, resource use efficiency, cropping sustainability and the environmental effects arising from intensification of cropping. Included is information from the fields of crop physiology, breeding, biotechnology and agronomy, especially regarding its influence on prospects for potential yield. Discussion is further broadened to include other key influences on farmer innovation—rural socioeconomics, institutions, infrastructure and policy. Thus our book ranges from genetics and crop physiology at one extreme to the socioeconomics of agricultural development at the other. The former are fundamental to the limits on yield and resource use efficiency of crops, and the latter is essential for discussing the likely farm-level effects of technological change. At the same time, we have endeavoured to discuss these diverse fields at levels that are understandable to the informed but non-specialist reader.

To conclude, we draw together seemingly disparate threads to articulate unreserved support for sustainable intensification of cropping around the world, and for the increased investment in agricultural research and rural development that this will require. We are cautiously optimistic that increased investment will be forthcoming and that world food security will continue to improve.

Tony Fischer, Derek Byerlee and Greg Edmeades

March 2014



Introduction

1



Key points

- Because of population and per capita income growth, and usage in biofuel, world demand for staple crop products should grow by 60% from 2010 to 2050, with greatest increases in the next 20 years.
- Crop area is likely to grow by approximately 10% over the same period, through net increase in arable area and increase in cropping intensity.
- World wheat, rice and soybean yields have been increasing linearly over the past 20 years, but progress is declining in relative terms to reach 1.0% per annum (p.a.), relative to 2010 yields; for maize the figure is 1.5% p.a.
- In order to hold real grain price increases by 2050 to no more than 30% over the low levels of 2000–06, published modelling suggests that a minimum acceptable rate of yield progress of staple crops is 1.1% p.a. (linear relative to 2010 levels).
- Higher rates of increase (e.g. 1.3% p.a.) would be wiser targets to drive faster reductions in world hunger and guard against unanticipated negative contingencies.
- The subject of this book is the prospect for progress in crop yield to achieve this minimum rate, the conditions required for this to be realised, and the consequences for resource use and the environment.



Introduction

1.1 The problem

The late 19th century author, Mark Twain, noted that 'prophecy is a good line of business but full of risks'. Indeed projecting crop yields—especially as far as 40 years ahead to 2050—is fraught with uncertainty at every turn. Despite the obvious challenges, three stylised facts about world food needs have emerged from several recent studies.

First, given climate change and rising energy prices on the supply side, growing demand for food, feed and fuel on the demand side, and increasing land and water scarcity generally, global grain markets are widely projected to be tighter in the future than over the past 40 years.

Second, future area expansion for agriculture will incur a significant risk to remaining forests and savanna, so agricultural growth must rely more than ever on productivity gains through increased crop and animal yields.

Third, although the absolute rate of cereal yield increase has been remarkably linear over the past 50 years, the high relative rates of yield increase during the green revolution² years—a period of progress that saved the world from serious food shortages—have since been steadily falling as yield rises (Figure 1.1).

Figure 1.1 suggests inevitability about the absolute rate of ~ 53 kg/ha/yr increase in average cereal yield. However, given many factors are involved in yield progress in these (and other) crops, it would be misleading to simply project forward the progress trends of the past 50 years. Thus the major objective for this book is to analyse the likely trends for future crop yields. The following chapters consider whether, as some suggest, a technological plateau for crop yields has or will soon be reached, or whether large unexploited sources of yield gains remain to be accessed immediately 'off the shelf' or from the research pipeline.

2 The 'green revolution' refers to the dramatic increase in wheat and rice yields in Asia beginning in the mid 1960s with the introduction of high yielding semi-dwarf varieties of these crops. This led to widespread adoption (>50%) of these crops within two decades, accompanied by substantial improvements in agronomic management.

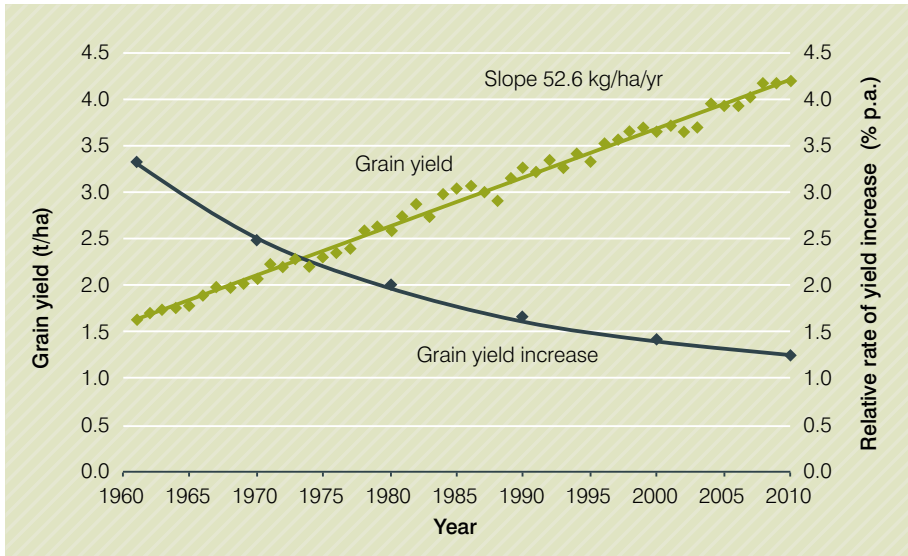


Figure 1.1 World yield of wheat, rice and maize (arithmetic average) and the annual relative rate of yield increase between 1960 and 2010. Standard error of slope = 0.7 kg/ha/yr, $R_{sq} = 0.992$. Source: FAOSTAT (2013)

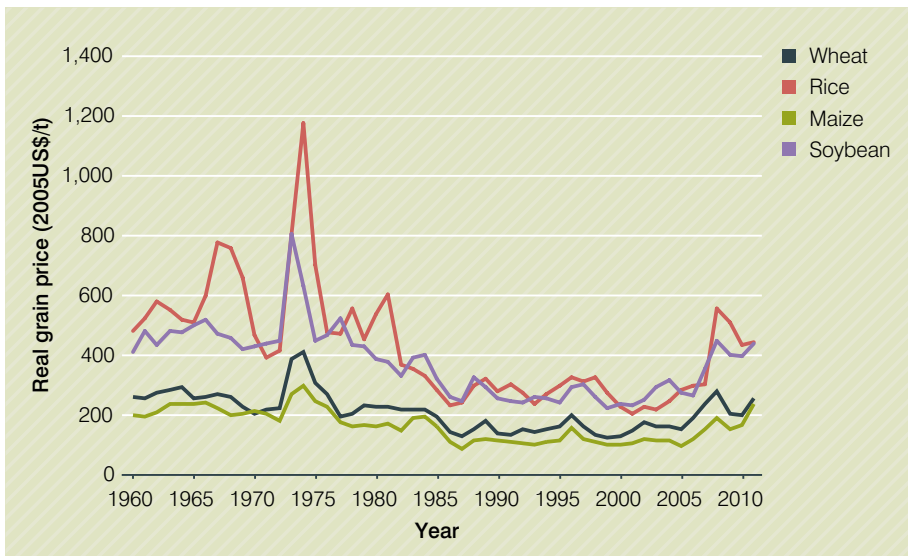


Figure 1.2 Change in real grain prices (2005US\$/t) for wheat, rice, maize and soybean from 1960 to 2011. Source: World Bank (2012a)

Of course food security is not dictated by crop yield alone. Changes in the real price³ of agricultural commodities (Figure 1.2) constitute a key yardstick for world food sufficiency. Generally, real grain prices have declined in the past 50 years, but the sharp peak in prices in the mid 1970s—largely driven by an oil price spike—notably interrupted the decline. However, after the late 1980s the real price declines steadied and record low levels were reached around 2000–06. Since then, there have been rises significant enough to again highlight the question of world food security.

Thus, expanding on the initial question of future yield trends, later chapters in this book consider how quickly unexploited yield progress can be realised: whether the speed of realisation will be sufficient to meet growing demand and limit the kind of rises in real prices that have been experienced in recent years.

1.2 Growing demand for crop products

Demand for crop products is determined by four main forces, with increasing uncertainty moving down the list:

1. population growth
2. increased income per capita
3. biofuels
4. prices.

The **global population** is projected to reach ~9.3 billion by 2050 (United Nations 2011, medium variant). This is a large addition (33%) to the current population of 7 billion—reached at the end of 2011—and reflects a relative growth rate of 1.11% p.a. in 2011.⁴ The relative growth rate has declined from 1.71% p.a. seen between 1960 and 2000, and is projected to decline further to 0.73% p.a. between 2011 and 2050, falling to 0.47% in 2050 (US Census Bureau 2013). The decline in population growth largely reflects the influence of growing per capita income and expanding female education.

A fair amount of uncertainty surrounds **future increases in income**, especially in the current economic environment. Predictions by the World Bank used by the Food and Agriculture Organization of the United Nations (FAO) assume a baseline compound rate

3 Real prices over a period are the actual prices corrected for general cost of living change. They are expressed in constant dollars of a given year when the real and observed prices were assumed to be the same (e.g. dollars of 2005 in Figure 1.2).

4 Population growth rate is always calculated on an exponential basis, even though world population is now growing at a steadily declining relative rate. The average growth rate between two dates is the exponential rate that gives the observed or predicted population change.

of income increase of 1.4% per capita per year to 2050 (Alexandratos and Bruinsma 2012). For high-income countries, and most middle-income countries, per capita direct consumption of cereals declines as incomes rise; the effect is largest for coarse grains and smallest for wheat.

The major effect of higher income is greater demand for feed for livestock, especially in developing countries. Demand for vegetable oils, fruits, vegetables and sugar is also income elastic (highly responsive to income) until countries reach high-income status. It is the combined demand for both vegetable oils and feed grains that stimulates the high increase in demand for soybean, which shows the strongest increase of the four staple crops (see Table 1.1), followed by maize.

Demand for feedstock to produce **biofuels** (and other industrial materials) depends on energy prices, grain prices, biofuel policy mandates and the speed with which second-generation (cellulose-based) biofuels become available. Currently 130 Mt of grain—comprising mostly maize—is used as biofuel. Alexandratos and Bruinsma (2012) project this grain figure will reach 182 Mt by 2020, with further contribution from 118 Mt of other plant products (mostly sugar and palm oil).

Biofuel predictions thereafter are highly uncertain. FAO assumes that demand will stabilise after 2020, but another scenario proposed by the International Institute for Applied Systems Analysis (IIASA), based on continuing delays in the introduction of second-generation biofuels, puts grain demand at 450 Mt by 2050 (G. Fischer 2011). It is even uncertain whether second-generation biofuel feedstock can be harvested without interfering with cropping for other purposes.

In 2010 about 30 Mt of plant oil was used in industrial processes, substituting for fossil fuel. This represents an increase of more than double over the previous 20 years (Carlsson et al. 2011). Predictions are for this figure to increase to 250 Mt by 2030, but this will require large technical breakthroughs in modifying plant oil composition and will depend on prices relative to fossil fuel.

The way in which demand and supply play out in world markets sets **prices**. When demand growth exceeds supply growth, markets are cleared by higher prices. Actual fulfilled demand then depends on the supply side response as well.

FAO (Alexandratos and Bruinsma 2012) provides individual supply and demand predictions, but apparently with real prices assumed constant (Table 1.1). Others—such as the International Food Policy Research Institute (IFPRI) and IIASA—use equilibrium models that balance demand and supply, and hence the balancing price is a key part of their predictions. These latter predictions will be discussed in Section 1.5.

While uncertainties surround the demand predictions, note that even the observed numbers for production, area and yield—largely drawn from FAOSTAT (2013)—carry uncertainty. FAOSTAT figures can sometimes differ from national statistics and can be revised as time passes; thus models can notably differ even in their observed starting statistics (Alexandratos 2011).

Table 1.1 Summary of the Food and Agriculture Organization of the United Nations (FAO) observed and projected world crop demand and supply at 'constant' prices, considering the 44 years before and after the 2005–07 base period

	1961–63	2005–07	2050	Increase (%)	
				1961–63 to 2005–07	2005–07 to 2050
Demand (Mt)					
Cereals ^a (rice as paddy)	919	2,282	3,284	148	44
Production (Mt)					
Wheat	235	614	858	161	40
Rice ^b	230	644	827	180	28
Maize	210	736	1,178	250	60
Soybean	27	217	390	704	80
Harvested area (Mha)					
Wheat	206	222	225	8	1
Rice	118	158	155	34	–2
Maize	106	155	194	46	25
Soybean	24	94	124	292	32
Yield (t/ha)					
Wheat	1.14	2.77	3.82	143	38
Rice ^b	1.94	4.07	5.32	110	31
Maize	1.99	4.74	6.06	138	28
Soybean	1.13	2.31	3.15	104	36

- a 'Cereals' for FAO include wheat, rice, barley, sorghum, millet, oats and rye plus some other very minor crops. The major cereals (wheat, rice and maize) were (in 2007–09) 87% of the production of all cereals (see Table 1.2).
- b It is customary to use 'milled rice' weights (i.e. 67% of the weight of 'paddy rice') on the demand side of the ledger. As this book uses paddy rice weights throughout, the FAO values in Table 1.1 have all been adjusted back to paddy weights to avoid confusion.
- Source: Alexandratos and Bruinsma (2012)

Overall, Table 1.1 shows **a 44% projected increase in demand of all cereals from 2005–07 to 2050**. This is equivalent to a compound growth rate of 0.83% p.a. Because the composition of demand shifts as incomes rise, **the growth in value of total agricultural production is estimated to be closer to 60%** (Alexandratos and Bruinsma 2012); other studies tend to estimate higher values for growth in demand for cereals and for all agriculture (see Section 1.5, below). Total agricultural demand

growth exceeds that of cereals because there is greater demand growth for high-value non-staples; for example, Alexandratos and Bruinsma (2012) project the demand for meat to rise by 76%, sugar by 75% and vegetable oil by 89% between 2005–07 and 2050. Similarly, greater demand growth is projected for other animal products, vegetables and fruit.

Of the staples, the use of maize and soybean for feed and biofuels leads to significantly higher projected demand growth for these commodities, with increases of 60% (maize) and 80% (soybean) from 2005–07 to 2050 (Table 1.1). Across all cereals, rice shows the lowest projected increase in demand. Demand for rice from 2005–07 to 2050 increases by only 28% (less than the world population rise), caused by per capita consumption peaking with income increase in Asia, then declining as incomes increase further, as happened in Japan. However, others argue that this decline may not happen in China, India or Indonesia, and not for a long time in Sub-Saharan Africa where per capita consumption is rising rapidly (e.g. Mohanty 2013a).

Note that the predictions shown in the 2050 columns in Table 1.1 are based on demand growth with no attention to price (termed 'constant' price growth). Also note that very low real prices persisted (Figure 1.2) into 2005–07 (the base period used in Table 1.1). Despite these important points, the FAO predictions shown in Table 1.1 are not expected to lead to elimination of hunger. In fact, predictions suggest that some 318 million people—that is, 4% of world population—will remain hungry in 2050 (Alexandratos and Bruinsma 2012). Furthermore, this unacceptable level could actually be underestimated since real food prices are unlikely to stay as low as those seen 2005–07 (see also Section 1.5). Of course, and as is discussed in Section 13.6, when it comes to world hunger, much also depends on where food is produced (and by whom) and other measures to ensure food access (such as safety net programs).

1.3 Supply side—our major crops

Increases in crop supply—that is, increased production to meet projected demand growth—will come from both **crop area and yield increase** (Table 1.1). Crop area is a function of arable land area and intensity of cropping, where 'arable' refers to land used regularly for crops with a growth cycle of less than one year (Box 1.1 provides further definitions).

Yield progress was more important than area increase in the 44 years between 1961–63 and 2005–07, accounting for 85% of the increase in production of the three major cereals, or 77% of the four staples (calculated from Table 1.1). Table 1.1 also predicts that yield progress—rather than crop area increase—is likely to remain the primary mechanism for production increases until 2050. The validity of this important prediction is the substance of this book.

This book primarily concentrates on **the big three cereals—rice, wheat and maize—and soybean**, now the fourth major grain crop in the world. Cereals account for 58% of annual harvested crop area globally, and directly provide ~50% of world food calories (Nelson et al. 2010). Through indirect paths, cereals provide even more food calories as stockfeed, supporting production of animal products for human consumption. Following cereal calories, the next biggest sources of world food calories for direct consumption are vegetable oils (12%) and sugar (8%) (Nelson et al. 2010).

Globally, per capita calorie and protein intake increased ~27% between 1961 and 2007 (Figure 1.3)—most of that increase was due to even greater relative increases in developing countries. **Rice and wheat** alone accounted for about half of the increased per capita energy intake (Figure 1.3a). **Maize** has been the major source of energy to support the rapid increase in consumption of animal products (Figure 1.3), accounting for more than 60% of energy in commercial animal feeds. **Soybean** greatly contributes to the supply of animal feed in the form of high-protein meal (in turn boosting food protein consumption) and is the second-most important component of the rise in vegetable oil consumption (Figure 1.3) after palm oil. Together the three major cereals are projected to provide ~85% of the increase in food cereal consumption to 2050, and maize and soybean will continue to drive growth in animal food calories and protein supply.

Of course, **the ‘big four’ staples are not the complete solution to world food security**. Diversification of cropping and food production is needed and any comprehensive review should include relevant data from coarse grains, roots and tubers, pulses and oilseeds (Table 1.2). Many of these additional crops are critical for food security in some countries.

These ‘other crops’ have been considered in this book, albeit in much less detail since relevant data are generally sparse. Some of these crops show weak yield trends, while others—such as sugarcane, canola (rapeseed) and oil palm—are booming commercial crops serving multiple uses for food, feed and fuel. Vegetables and fruits contribute less to intake of calories and protein (Table 1.2), but play an important role in providing micronutrients and generating income; however, these crops fall beyond the scope of this book.

The 2008–10 global area and production figures for the world’s main food crops—most of which are considered in this book—are shown in Table 1.2. Data include that portion of production going to biofuel or other industrial uses. Table 1.2 also calculates calories and protein from crop production, but it should again be noted that not all these calories or protein amounts are consumed directly by humans. Large portions of calories and protein are used for animal feed—particularly from coarse grains (like maize) and from meal produced by processing oilseeds. Similarly, large portions are used for industrial purposes (particularly biofuel).

Table 1.2 shows that maize is now first in energy supply, with wheat second and rice third. Meanwhile, soybean is first for protein supply and maize second. For vegetable oil production (a higher energy food not shown in Table 1.2), oil palm is now first and soybean second, palm fruit having higher oil content than soybean grain.

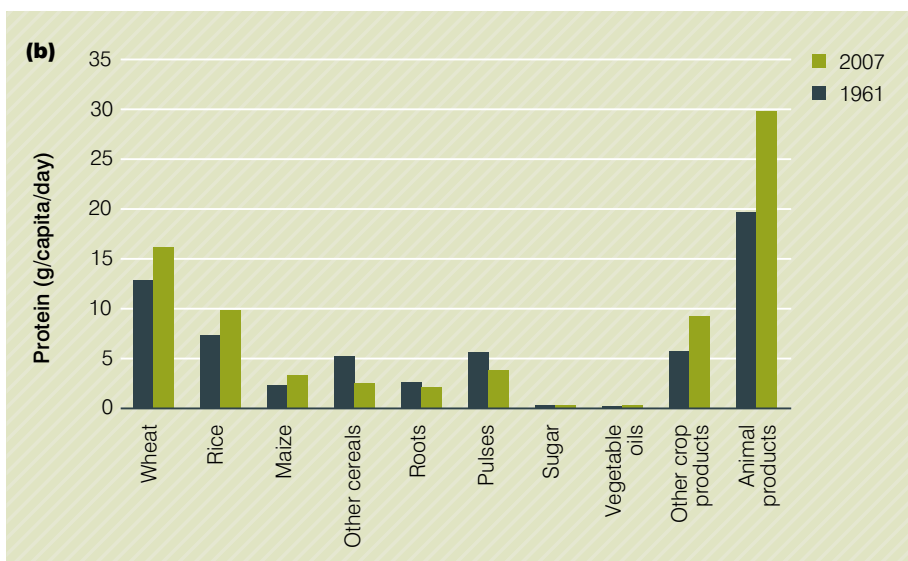
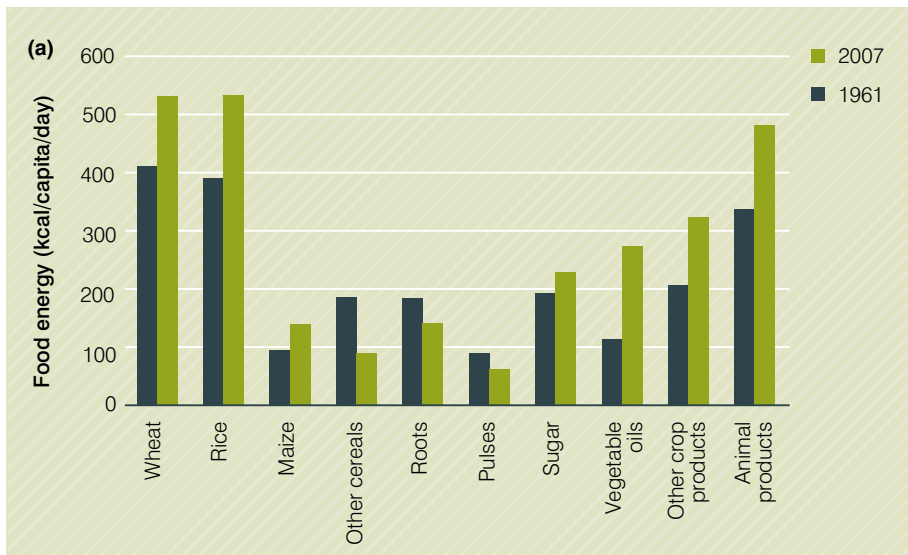


Figure 1.3 Components of average world food supply in 1961 and 2007 for (a) food energy in kilocalories/capita/day and (b) food protein in grams/capita/day. Total supply in 1961 was 2,200 kcal/capita/day and 61 g protein/capita/day; and in 2007 was 2,800 kcal/capita/day and 77 g protein/capita/day. Source: FAOSTAT (2013)

Table 1.2 Production of the world's major crops shown against global harvested area in 1988–90 and 2008–10, area change, and food calorie and protein amounts

Crop ^a	Harvested area (Mha)		Area change (%)	Production 2008–10 (Mt)	Food values	
	1988–90	2008–10	1988–90 to 2008–10		Relative calorie amount ^b	Relative protein amount ^b
Wheat	225.5	221.3	–2	674.4	100.0	100.0
Maize	130.9	161.8	+24	833.4	133.5	107.6
Rice (paddy)	147.4	160.2	+9	691.6	87.2	49.7
Soybean	56.9	99.3	+75	239.8	35.8	124.0
Pulses	68.8	73.2	+7	65.0	9.9	19.4
Fruits	41.1	55.4	+35	599.0	12.3	4.3
Vegetables	31.8	54.1	+70	1,019.4	10.9	17.2
Barley	74.3	52.3	–30	143.4	14.4	14.6
Sorghum	44.2	42.3	–4	60.3	10.0	9.0
Millet	38.3	35.4	–7	31.5	4.2	3.4
Rapeseed (including canola)	17.5	31.5	+80	60.2	13.2	16.1
Cotton (seed only)	33.1	31.2	–6	41.3	5.1	12.9
Sunflower seed	15.8	24.4	+54	33.4	4.5	9.1
Peanut (in shell)	20.2	24.4	+21	38.7	6.6	9.2
Sugarcane	16.7	23.9	+43	1,705.2	22.8	0
Cassava	15.1	19.0	+26	234.7	11.4	2.9
Potatoes	17.9	18.5	+3	332.7	9.9	7.3
Oil palm (fruit)	5.8	15.3	+161	219.4	15.6	6.8
Coconut	9.9	11.4	+15	60.5	3.7	1.1
Bananas + plantain	7.7	10.4	+35	136.0	4.7	1.5
Sweetpotato	9.1	8.1	–11	103.3	4.2	1.0

a Crops ranked by current area

b Values expressed relative to wheat. Calorie and protein amounts corrected for non-food and/or non-feed portions (i.e. husk for rice, barley, peanut, coconut; non-sugar portion for sugarcane; non-kernel portion of fruit in oil palm), with results given relative to the wheat amount set at 100. One kilogram of wheat is assumed to have 3,330 kcal (13.9 MJ) of food energy and 109 g of protein. Food calorie and protein compositions used for other crops are global averages relative to the global wheat average but, in reality, compositions can vary considerably among regions for any given crop.

Source: Calculated from the FAOSTAT (2013) Food Supply Table

1.4 Supply side—crop area and its prospects

For the following discussion of crop area changes, a clear understanding of land definitions is needed; FAO definitions are used and explained in Box 1.1.

Box 1.1 Definitions of crop areas

Arable land: Land under annual (sometimes termed ‘temporary’) agricultural crops, temporary meadows or pastures, market gardens and land temporarily fallowed for less than 5 years. Thus, it is land expected to be often planted to annual crops.

Cropland: Land under crops as the sum of arable land and permanent cropland. This is also sometimes known as ‘cultivated land’.

Cropping intensity: Crop harvested area of annual crops as a percentage of arable land. It may be less than 100% due to resting (fallow or pasture) and crop lost between planting and harvest, or greater than 100% due to multiple cropping (more than one crop per year).

Harvested area: The crop area actually harvested; for annual crops often less than the area planted (due to crop failure), but in some regions can exceed arable area where there is multiple annual cropping. FAO does not publish detailed statistics on crop area sown.

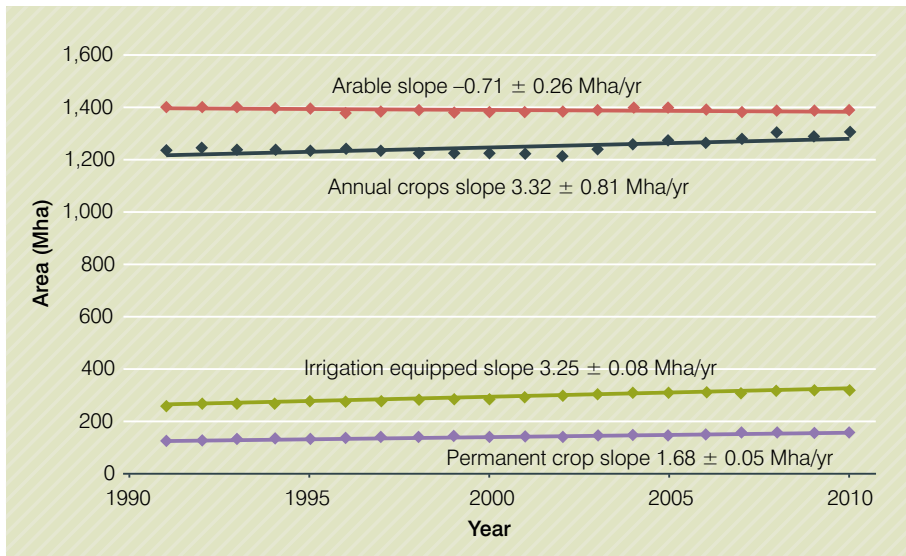
Permanent crops: Long-term crops, which do not have to be replanted for several years (these are tree crops, but plantation forestry is not included for this discussion).

Temporary (or annual) crops: All crops with a less than one-year growing cycle and which must be newly sown or planted for further production after the harvest. Sugarcane and cassava may occupy the land for more than 12 months, but are nevertheless considered as arable-land crops (not permanent crops).

Source: FAOSTAT (2013)

Current crop area and past changes

Considering both **annual** and **permanent crops** for the 2008–10 period, **total harvested area amounted to 1,450 Mha**. Of this figure, permanent crops comprised 150 Mha, while the remaining 1,300 Mha represents the harvest area of annual crops (Figure 1.4).



All slopes significant at $P < 0.05$ or better

Figure 1.4 Changes in global areas for arable land, for harvested area of annual crops and of permanent crops, and for land area equipped for irrigation (1991–2010). For definitions, see Box 1.1. Source: FAOSTAT (2013) but annual (temporary) crop area was from a FAOSTAT file now unavailable; 2009 and 2010 have been estimated by authors

Table 1.2 lists the top 21 food crops; these are mostly annual crops (including sugarcane and cassava; FAOSTAT 2013), but there are also some permanent crops (i.e. oil palm, coconut, bananas and plantain, and some fruits). These top food crops comprise 81% of the total harvested area (annual + permanent crops); the remainder is made up of nut tree crops, industrial (non-food) crops (e.g. jute) and hundreds of other minor food crops.

Figure 1.4 shows that in the past 20 years, **arable land** has decreased very slightly ($<0.1\%$ p.a.), essentially remaining steady at $\sim 1,400$ Mha.⁵ This suggests that—on a global basis—the **opening of new arable land to cropping approximately balances arable land lost** to urbanisation, new tree crops, permanent pastures, degradation, and to plantation forestry and reserves (a likely small part of which may occupy arable land). On the other hand, area for permanent crops has increased

⁵ These absolute numbers sourced from FAOSTAT do not agree exactly with Bruinsma (2011), also from FAO, who reported arable land to be 1,562 Mha in 2005. Bruinsma (2011) agrees that arable area is increasing only very slowly (up 14% since 1961) and the discrepancy arises because he included permanent tree cropland in the 'arable' total (J. Bruinsma, pers. comm. 2012).

by ~30 Mha in this same period by an annual rate of 1.45 Mha or 1% p.a. (Figure 1.4). Contribution from permanent crops has meant that total global cropland has increased to reach ~1,550 Mha; this figure exceeds the total harvested area because the area of arable land exceeds the harvested area of annual crops.

Harvested area of annual crops has increased on average only very gradually at an annual rate of 3.3 Mha (0.25% p.a.) over the past 20 years (Figure 1.4). The trendline, however, disguises a decline in area to 2003, followed by an upturn, giving a jump of ~6% through to 2010 when area reached 1,300 Mha. Over the 18 years from 1990 to 2008, with a steady arable area (1,400 Mha) dedicated to annual cropping, the increase in crop harvested area can be explained by the increase in **cropping intensity** from 88% to 93% (Bruinsma 2011).

Figure 1.4 highlights the **very small net change in world arable area** in the past 20 years. This phenomenon goes back much more than that; arable land area was 1,287 Mha in 1961–63, so the increase in almost 50 years has been only ~100 Mha (or 7%). The area of the ‘big four’ staples has increased by much more than 7% (Table 1.1)—as has the area for some other crops (Table 1.3)—but some of this crop area increase is derived from increased cropping intensity (such as with the increase in rice–wheat double cropping in South Asia and maize–soybean in the Brazilian Cerrado). Other crop area increases have been at the expense of less popular crops, like the coarse grains barley, sorghum and millet (Table 1.2).

Globally, land equipped for irrigation has also increased annually by 3.25 Mha (~1% p.a.) to reach ~300 Mha; although in 2005–07 **observed operated irrigated land** was only 257 Mha. Irrigated lands have an average cropping intensity of around 127%, which points to a significant portion of irrigated land under double cropping.⁶ Irrigation permits higher cropping intensity and yields, so although irrigation comprises only 17% of cropland, irrigated areas deliver 42% of all cereal production and also of all crop food production (Bruinsma 2011).

Small net area changes in global arable land disguise both gains and losses. Annual declines of 2.9 Mha in cropland from 1990—comprising 2 Mha from the transitional countries (those of the former USSR) and 0.9 Mha from other developed countries—were more than outweighed by annual increases of 5.5 Mha in developing countries. Expansion was concentrated in Sub-Saharan Africa, Latin America, and South-East Asia, but there was also notable recovery specifically in the sunflower area of the Russian Federation and Ukraine. Soybean, maize, canola, rice, oil palm, sunflower and sugarcane were the key commodities driving expansion, amounting to a total harvested area increase of 125 Mha over 20 years (Table 1.3).

6 Bruinsma (2011) calculated cropping intensities in 2005–07 to be 79% (rainfed), 134% (irrigated) and 87% (overall), but as pointed out in footnote (4), his figures consider the sum of arable land and permanent cropland. The area of permanent crop that is irrigated is not readily available, but allowing for, say, 50% irrigated, the annual cropping intensity on rainfed arable land (as defined here) is slightly underestimated, and that on irrigated arable land is overestimated by a few per cent.

Expanded trade in agricultural commodities led to shifts of production. Countries that had potential to increase cropland (such as Argentina and Brazil) could increase production to meet booming demand from China and other emerging economies. During this same period, plantation forests (which are not included in the FAO definition of permanent crops) also expanded relatively rapidly (2.2 Mha p.a.) to reach 139 Mha in 2007; one-third of this expansion was in China.

Table 1.3 Key commodities driving global crop expansion from 1990 to 2007

Commodity	Area change 1988–90 to 2008–2010 (Mha)	Major contributors (% of net increase)
Soybean	42.4	Argentina (33), Brazil (28), India (19)
Maize	30.9	China (29), USA (29), Brazil (9)
Canola	14.0	Canada (32), India (15), France (8)
Rice	12.8	Myanmar (38), Thailand (21), Indonesia (18)
Oil palm	9.5	Indonesia (50), Malaysia (26), Nigeria (11)
Sunflower	8.6	Russian Federation (41), Ukraine (38), Myanmar (10)
Sugarcane	7.2	Brazil (47), India (29), China (9)

Source: FAOSTAT (2013)

In summary, the historically low rate of arable area increase points to the role of yield progress as the primary driver of past production gains, with a small contribution from increased cropping intensity. However, despite past trends, we cannot ignore future possibilities for increasing crop area, or threats to current arable area.

Prospects for crop area increase

Predictions of **future increases in annual crop area driven by demand** are quite variable. Table 1.1 indicates FAO thinking on extra harvested area (including biofuels), with projected future expansion to 2050 of ~39 Mha for the staple cereals, entirely due to maize, and 32 Mha for soybean alone. Considering all annual crops collectively, Alexandratos and Bruinsma (2012) projected ~134 Mha extra harvested crop by 2050—an increase of 9% from 2005–07 harvested area. Further projected small increases in cropping intensity would meet half of this projected crop area increase; **the remainder would be met by ~70 Mha net increase (+ 5%) in arable land.**

Another estimate for crop area increase, this time from Deininger and Byerlee (2011), includes plantation forests (which are not included by FAO). Each year, >6 Mha of new land is expected to be brought into production globally until 2030 (a total of 120 Mha). Improved world trade would encourage greater production from low-cost producers and could double the amount of new land (Deininger and Byerlee 2011).

The Deininger and Byerlee (2011) estimates agree with the recent synthesis by Lambin and Meyfroidt (2011), as shown in Table 1.4. **The low estimate for additional land for crops, biofuels and plantation forests was projected to be 181 Mha from 2000 to 2030** (equating to 120 Mha from 2010 to 2030 pro rata). The high estimate given in Table 1.4 is little more than double the minimum estimate.

Table 1.4 Projected increases in global land uses from 2000 to 2030

Additional land use	Low estimate (Mha)	High estimate (Mha)
Crops other than biofuels	81	147
Biofuels	44	118
Industrial (plantation) forests	56	109
Total	181	374

Source: Lambin and Meyfroidt (2011)

The estimates in Table 1.4 are generally higher than those of FAO, which projected to 2050 a net increase in arable area of 70 Mha, or a net increase in total cropland of 113 Mha (Alexandratos and Bruinsma 2012)—a 7.3% increase from the 2007–09 figure of 1,550 Mha. The main reason for the difference is that FAO refers to net increase in arable land (net of arable land losses); the other authors refer to new (or additional) cropland, which must therefore add up to the needed arable land increases plus the arable land losses.

Loss of arable land is occurring from:

- urban and infrastructural encroachment (as seen in China, India and many high-income countries)
- land degradation
- conversion of marginal areas to forestry
- conservation of other areas in protected reserves.

For example, Nelson et al. (2010) projected declines in arable land from 2010 to 2050 of ~20 Mha in China and ~10 Mha in India—essentially irreplaceable losses because little new land is available. For the period between 2000 and 2030, Lambin and Meyfroidt (2011) projected minimal global estimates for loss of cropland totalling ~100 Mha; this comprised urban expansion (48 Mha), land lost to degradation (30 Mha), and land converted to protected areas (26 Mha) and plantation forestry (56 Mha). Note that some or much of the projected losses to protected areas and plantation forestry are unlikely to come from current arable land.

A key question in this issue is how much (if any) **suitable land remains available** to bring under cultivation? Based on the IASA agroecological zones, FAO estimated

that some 1,400 Mha of currently uncultivated land—that is not currently forested or protected—is suited to crop production (Alexandratos and Bruinsma 2012).

Using the same IIASA database, Deininger and Byerlee (2011) provided a more conservative estimate of available land (Table 1.5). Their estimate of 449 Mha of worldwide available land—which is based on land that is non-forested and non-protected, with a population density of <25 persons/km²—is equivalent to ~30% of current global cropland. However, this available land is concentrated in just seven countries—Sudan, Brazil, Australia, Russian Federation, Argentina, Mozambique and the Democratic Republic of Congo—and is often far from ports and roads. This global estimate also probably overlooks other micro-level constraints on land and is an upper estimate of available land (Lambin et al. 2013), as seems to be the case in Australia, but it is the best top-down global estimate available. Table 1.5 also reveals that little new land is available in East and South Asia, the Middle East and northern Africa.

Table 1.5 Potential availability of uncultivated land around 2010 in different world regions with suitability to crop production

World region	Current cropland area (Mha)	Uncultivated area suited to crop production (Mha) ^a
Sub-Saharan Africa	221	201
Latin America and Caribbean	164	123
Eastern Europe and Central Asia	254	52
East and South Asia	454	15
Middle East and northern Africa	97	3
Rest of world	360	52
(of which, Australia)	(46) ^b	(26) ^b
World total	1,550	446

a Based on data from the International Institute for Applied Systems Analysis (IIASA). Data refer to uncultivated land with high agroecological potential in areas with population density of <25 persons/km² and which is not forested or protected. Cropland area equals arable land as defined by the Food and Agriculture Organization of the United Nations (FAO) plus permanent crops, noting that some of the arable land may not be cultivated every year.

b In Australia only about 70% of cropland is cultivated annually (FAOSTAT 2013). The remainder is in temporary pasture, but new arable land is probably less than 1 Mha according to local sources (Linehan et al. 2013).

Source: Deininger and Byerlee (2011)

The numbers on available new land in Table 1.5 can be compared with the earlier discussion of projected crop area increase matching 2050 demand and supply. Regardless of the variation among predictions (see Section 1.5), the demand for additional arable land is relatively small (~70 Mha) compared with the potentials shown

in Table 1.5. This conclusion does not change even though the projected crop area increase is net of land loss (which would perhaps total 100 Mha by 2050 and increase **the needed amount of new arable land to ~200 Mha**). However, to open 200 Mha of new cropland—even that which can meet criteria for potential land as shown in Table 1.5—would carry environmental costs that many would wish to avoid (see also Section 10.5 on greenhouse gases and Section 11.6 on other off-site effects of cropping intensification).

Expansion of irrigation also needs to be considered here. Despite the current slow increase of global irrigation area and the high investment costs involved, Alexandratos and Bruinsma (2012) projected a further expansion of 20 Mha (8%) from 2005–07 to 2050, occurring entirely in developing countries. This is a net expansion and the prediction assumes that losses of existing irrigated land due to water shortages or degradation (from salinisation and/or waterlogging) will be sufficiently compensated by rehabilitation and substitution of other areas.

In addition, Alexandratos and Bruinsma (2012) projected a small increase in irrigation cropping intensity (from 127% to 132%), which together with area expansion would lift irrigated crop area by 12% relative to that in 2005–07. The projected **increase in the percentage of irrigated crop area relative to total crop harvested area is unfortunately so small (<1%) as to have an insignificant effect on global yield increase (+0.44%) to 2050**. An additional observation here is that in irrigated lands, some lower value staples (e.g. wheat and maize) may gradually lose area to higher value crops (e.g. vegetables).

In concluding this discussion of the pressure for crop area increase—including likely arable land losses and the availability of suitable new land—the predictions of Alexandratos and Bruinsma (2012) for 134 Mha of global crop area increase by 2050 are accepted as accurate, even if the values for maize in Table 1.1 seem high. Such crop area increase will arise by cultivating more arable land more intensively, and **amounts to an increase of approximately 10% on the 2008–10 annual average harvested area** of 1,300 Mha, or about 3 Mha/yr over the 40-year period.

Figure 1.4 shows that the FAO projected rate of 3 Mha/yr crop area increase is about the same as the average increase over the past 20 years. Even though this means opening of new arable land at about twice this rate (to allow for arable land losses), land availability and arable land losses are unlikely to be constraints on such a rate of crop area increase.

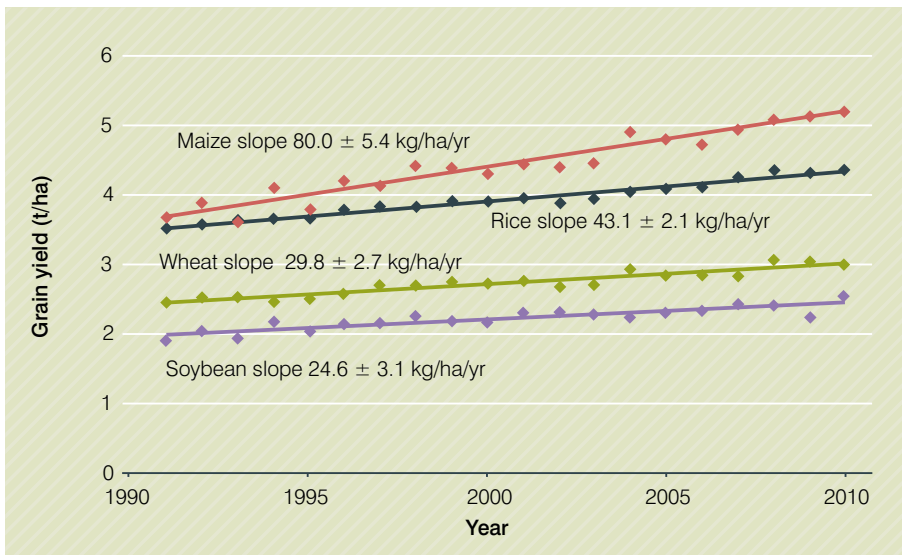
Although projected crop area increase somewhat lessens the pressure for yield increase alone to meet production demands by 2050, yield increase will remain as the driving force behind the majority of production gains in the future. Based on the FAO numbers given for the 'big four' staples in Table 1.1, projected crop area increase would account for only one-quarter of the projected production increases to 2050.

1.5 Supply side—crop yield, price questions and trade

Given the key role that further crop yield increase must play in meeting the expected increase in demand to 2050, this book closely examines crop yield prospects. The following chapters trace sources of yield increase, focusing on the last 20 years because of the greater relevance of this recent period to the future.

Recent increases in yield

Figure 1.5 shows current trends for global yield of staple crops over the last 20 years. As was foreshadowed in Figure 1.1, yield increase has been strongly linear for the key crops. Expressed as a percentage of the estimated yield in the last year of the series (2010), **the relative rates of gain are 1.0% p.a. for each of wheat, rice and soybean, and 1.5% p.a. for maize.**



*** $P < 0.01$ or better

Figure 1.5 Linear trends in global yield of wheat, (paddy) rice, maize and soybean for last 20 years (1991–2010). Slopes of the linear relationships and the standard error of slopes are given. Source: FAOSTAT (2013)

Figure 1.5 appears to suggest that yield increase at a fixed linear rate is an inexorable force, easy to project forward but difficult to move to a new higher trend rate. This is deceptive, however, as the global average for a crop aggregates many diverse rates of progress from different regions, as discussed in the commodity chapters of this book. Nevertheless, because a linear model adequately fits most of these trends, linear slopes are calculated and presented, while noting their statistical significance. These annual linear rates are expressed as a percentage relative to the most current yield in order to allow for differences in yield levels among crops and regions and provide a better basis for comparisons.

Because linearity with respect to time predominates in crop yield change, forward predictions given in this book are considered to be driven by the linear rates (not the relative ones). This contrasts with most agricultural economics research publications (at least until the late 2000s) in which increases are considered to be compound or exponential, implying a constant relative or annual percentage increase.⁷ Exponential growth in crop yield is now rare.

Future yield increase and prices

A key question in relation to food security is: what level of yield increase will be required to meet future food demands? The FAO 'constant' price predictions of Alexandratos and Bruinsma (2012) in Table 1.1 indicate that after allowing for modest crop area increase, the projected 2050 demand in the 'big four' staple crops would be met by an overall yield increase (relative to 2005–07) of 33% (Table 1.6). Broken down by crop, the FAO percentage yield increase needed to 2050 is shown, followed by conversion to linear annual rates of yield gain and then as per cent per annum, expressed relative to the 2005–07 yield base used in Table 1.1:

- wheat = 38% or 24 kg/ha/yr (0.86% p.a.)
- rice = 31% or 28 kg/ha/yr (0.70% p.a.)
- maize = 28% or 30 kg/ha/yr (0.64% p.a.)
- soybean = 36% or 19 kg/ha/yr (0.82% p.a.).

These FAO projected rates represent a significant decline in both relative and absolute terms when compared to the 44 years from 1961–63 to 2005–07 (see Table 1.1), and the rates of yield increase recorded for the 20 years from 1991 to 2010 (Figure 1.5). These future rates of yield increase are quite modest, and in the case of maize and soybean are low, because of the predicted substantial crop area increase shown in Table 1.1.

⁷ The difference between the relative and linear rates can be seen by the example of 40% yield increase from say 2010 to 2050; this result can be achieved with exponential increase of 0.84% p.a., or with linear increase starting at 1% p.a. of the 2010 yield.

Because the overall FAO predictions to 2050 are based on the assumption of ‘constant’ price, they need to be compared to the results of equilibrium modelling. Using its IMPACT partial equilibrium model to explore scenarios under real price changes that balance supply and demand, IFPRI has already pointed to the notable sensitivity of real price outcomes in 2050 to assumptions regarding yield predictions (e.g. Rosegrant et al. 2008). Several other more recent studies are reported in Table 1.6 and briefly discussed along with the FAO predictions.

Table 1.6 Summary of predictions of world staple grain and/or agricultural demand and supply growth to 2050^a

Source ^b	Commodities	Base year	Change relative to base year (%)			
			Demand	Crop area	Crop yield	Real price
1	Big four staples ^c	2005–07	+47	+11	+33	Not considered
2	All agriculture	2000	+79	0	+57	+44 ^d
3	Big four staples ^c	2010	+36	–8	+47	+25 ^e
4	Cereals	2000	+59	+21	+31	+30
5 ^f	Cereals	2007	+42	–9	+56	+13
6 ^g	All crops	2006	+102	+18	+72	+10

- a Demand and yield relate to quantities of commodities, not values; also biofuel is included and climate change excluded in all cases.
- b 1 Alexandratos and Bruinsma (2012) (FAO); 2 Tweetin and Thompson (2009); 3 Nelson et al. (2010) (IFPRI); 4 G. Fischer (2011) (IIASA); 5 Linehan et al. (2013); 6 Lobell et al. (2013b)
- c Wheat, rice, maize and soybean
- d Relative price increase at equilibrium assumed by authors to be twice the demand less supply gap relative to demand
- e Excluding soybean and using a modelled 2010 real price somewhat lower than observed
- f Reference scenario S1
- g Scenario S2 in which climate change is perfectly countered by extra research

Tweetin and Thompson (2009), in a relatively simple approach, paid most attention to extrapolating current linear yield increase across commodities, weighted by their share of diet, to reach an aggregate yield (supply) figure of +57% by 2050. This fell short of predicted demand growth (+79%) and real prices were estimated to rise 44% (Table 1.6). This high demand growth prediction has been surpassed by only Tilman et al. (2011) and Lobell et al. (2013b); the latter is shown in Table 1.6. Tilman et al. (2013) used the past association of food demand with per-capita income across seven categories of economically similar countries to predict their future per-capita demand in response to ongoing per-capita income growth, along with their population growth, to estimate total food demand in 2050 to be 105% above the 2005 level. Various supply scenarios were investigated (not shown in Table 1.6, but see Section 10.5 on greenhouse gas emissions).

The results of Nelson et al. (2010) may be more reliable than Tweetin and Thompson (2009), since Nelson et al. (2010) used the IMPACT partial equilibrium model. In the absence of climate change—because climate change scenarios were also studied—they balanced projected demand forces to 2050 with a 36% increase in production of the 'big four' staples (Table 1.6). The balance required real prices of the cereals to increase by 2050 (relative to their estimated 2010 baseline) by 23% for wheat, 20% for rice and 32% for maize (soybean is not calculated) for an average increase of 25% (Table 1.6). Because these authors used greater per capita economic growth rates (2.5% annual increase) than assumed by FAO (1.4%) and incorporated greater constraints to crop area increase (including area loss in China and India), their supply growth relied on greater yield increase than that assumed by FAO (except for rice). Thus the rates of yield increase (calculated as above, relative to 2010 values) were 1.5% p.a. for both wheat and soybean and 1.0% p.a. for maize, but only 0.8% p.a. for rice.

The sensitivity of balancing price to yield increase in Nelson et al. (2010) is especially striking when a mere 5% reduction in the predicted global cereal yields for 2050 (caused by a 'climate change' scenario compared with 'no climate change') is predicted to boost real price increases (again relative to 2010) to 55% for each of wheat and rice, and 101% for maize (not shown in Table 1.6).

At IIASA, G. Fischer (2011) also performed equilibrium modelling of future cereal production growth. G. Fischer predicted that 2050 cereal production would be 59% above the 2000 total, which is somewhat greater than the Nelson et al. (2010) result mentioned above, accompanied in the IIASA case by large crop area increases (Table 1.6). The strong tendency for real prices to increase is emphasised by the similarity between G. Fischer's (2011) prediction of 30% increase in real cereal price and the 25% predicted increase of Nelson et al. (2010).

Linehan et al. (2013) used the agrifoods partial equilibrium model of the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) and the assumption of strong linear cereal yield increase (equivalent to 1.3% p.a. relative to 2007 yields). Linehan et al. (2013) came up with quite modest real price increases (Table 1.6), and a notable shift of consumption to higher value products (meat, dairy, vegetables and fruit). The outcome was sensitive to the yield increase assumption: 10% lower yield increase lifted real cereal prices in 2050 to 25% above the base year.

Finally in Table 1.6, Lobell et al. (2013b) projected large increases in yield and production of all crops, and modest changes in real prices (+10% over 2006) in what is effectively a baseline scenario of strong productivity growth. However, in a climate change scenario, when circumstances affecting crop productivity were changed such that yield increase slowed to +60% of 2006 yields, real prices jumped to +32% of 2006. This latter scenario again illustrates the high sensitivity of price to yield.

The latest effort with IMPACT comes from Rosegrant et al. (2013) who modelled demand, supply and prices—but only from 2010 to 2025. They allowed for 300%

increase in crop-based feedstock for biofuel and a 40% increase in real oil prices (M. Rosegrant, pers. comm. 2013). This modelling exercise assumed a 2% growth in real per capita income and achieved supply and demand balance by 2025 with a 20% increase in cereal production between 2010 and 2025, and a 13% increase in real price above a 2009–11 base. Rosegrant et al. (2013) predicted that 93% of the projected gains in production could be achieved from annual yield increases, which amounted to linear rates of cereal yield increase of 1.24% p.a. (relative to 2010 yields). Even so, real cereal price rose to 13% above the 2009–11 base.

Although the target date for prediction differs, the Rosegrant et al. (2013) numbers (when extrapolated to 2050) are in reasonable agreement with Nelson et al. (2010). However, because the Rosegrant et al. (2013) prediction period is shorter, the results are less uncertain, and the real price increases are clearer given that the price base is the observed average 2009–11 price. Note that this price base already represents a substantial increase on the lowest real prices that occurred around 2000–06 (Figure 1.2), and the decrease (2010 to 2025) in the number of people at risk from hunger is small (<5%) relative to the total of around 800 million people. In a sensitivity analysis, Rosegrant et al. (2013) also showed that if yield increase for cereals could be lifted by 0.6% p.a. to reach 1.84% p.a. linear (relative to the 2010 yield), their real price increase would be held to only ~5% above the 2009–11 base, and the number at risk from hunger in 2025 would be reduced 13% (but would still be around 700 million people in 2025).

The results discussed here highlight **the sensitivity of real prices to assumptions regarding yield increase, and the tendency for real prices to increase in all scenarios**. None of the models include a future rate of yield increase high enough to hold real crop prices anywhere near the lows of 2000–06. Earlier Rosegrant et al. (2008) did find that an exponential yield increase somewhere between 1.0% and 1.4% p.a. from 2000 to 2050 would hold real cereal prices constant. However, 1.0% and 1.4% exponential would be equivalent, respectively, to 1.3% and 2.0% linear relative to 2000 yields, over the whole period. These are much higher than current rates.

The somewhat conflicting predictions on demand and supply to 2050 in Table 1.6 make it difficult to settle on **a minimum satisfactory target for future crop yield increase**. The Alexandratos and Bruinsma (2012) predictions in Table 1.6 can be considered as somewhat conservative for several reasons: the low economic growth rate used, cropland expansion providing nearly half of maize and soybean production increase, and the lower assumption on use of grain for biofuels (compared with other estimates, such as those by G. Fischer 2011). Alexandratos and Bruinsma (2012) also noted that their predictions of demand growth to 2050 are generally less than those that appear in recent scientific literature (some mentioned here). However, the FAO figures provide some advantage to this discussion, as these are most thoroughly documented. Further, the other equilibrium modelling estimates from IFPRI and IIASA corroborate Alexandratos and Bruinsma (2012) in terms of predicted demand growth.

Disagreement also continues over what should be considered as the minimum satisfactory tolerance limit for hunger risk and child undernourishment. The above modelling attempts to estimate the effect on this of real prices (e.g. changes in numbers 'at risk of hunger' in Rosegrant et al. 2013)—because it is inversely linked to real prices of staple foods. However, the relationship is not strong, with hunger influenced by other factors as well. The equilibrium modelling suggests that the yield increases in Table 1.6 will neither prevent real price increases, nor the persistence of high levels of world hunger (Nelson et al. 2010; Rosegrant et al. 2013). Even Alexandratos and Bruinsma (2012) admit their predictions leave around 350 million undernourished people in 2050.

Given that ~900 million undernourished people remain in the world now (Alexandratos and Bruinsma 2012)—and given the commitment enunciated in 2000 in the UN Millennium Development Goals to halve hunger and undernutrition—it is assumed here that real price increases need to be no more than 30% above the 2000–06 minimum. This suggests that **the minimum supply increase for staples to 2050 would be 60%** (relative to 2010) with a somewhat higher increase for high-value non-staples. Allowing for 10% increase in staple crop area (Section 1.4), to achieve the projected 2050 minimum staples supply will require that 45% of the supply increase be derived from future yield increase. This means **the minimum target for global yield increase for staple crops should be 1.1% p.a. relative to 2010 yield.**

Undoubtedly, however, it would be most beneficial for all lower income consumers if the world aimed for higher target rates of yield progress (e.g. 1.2–1.3% p.a.). Higher targets would also protect against rare but unanticipated factors that may mean the minimum yield target has been underestimated. These include:

- population growth at the upper estimate (e.g. 10.6 billion by 2050)
- further policy-driven biofuel demand
- constraints or prohibitions on further land clearing
- land loss due to sea level rise or nuclear contamination
- widespread exceptionally adverse weather events (perhaps accompanied by a return to protectionism and greater trade barriers).

In addition, higher target rates of yield progress would prepare the world for rare but unanticipated factors that could create brakes to achieving the minimum target for yield progress specified here. These include:

- worse than anticipated adverse climate change effects
- loss of irrigation water
- another energy crisis (such as that which occurred in the mid 1970s)
- widespread disease epidemic in a major crop
- banning of genetically engineered (GE) crop varieties.

Achieving rates of yield progress beyond the minimum required yield increase would thus buffer the world against the risk of price spikes and food-price driven civil disorder (Rosegrant et al. 2013). Rates of yield increase greater than 1.1% p.a. were common between 1960 and 2000 (Figure 1.1). However, the current rates of 1.0% p.a. for wheat, rice and soybean sit below the minimum target required to attain world food security by 2050. The current rate for maize is higher at 1.5% p.a.

Finally it is worth noting that in meeting future demands, the biggest challenge will come over **the next 20 years to around 2030**. After that point, most of the developing world outside of Africa and South Asia will see only modest increases to consumption of livestock products; global population growth will have slowed to near 0.6% per year; and use of grains for biofuels should have peaked as newer, more efficient cellulosic technologies become commercially viable.

Beyond 2050, the rate of increase in demand will be very much reduced and would not be difficult to supply—at least in a global aggregated sense (Alexandratos and Bruinsma 2012)—were it not for the predicted constraints on yield increase that climate change may pose by then. Note that none of the predictions shown in Table 1.6 considers climate change, because in Chapter 10, which concerns climate change, it is argued that climate change is unlikely to have large negative effects on yield increase before 2050.

Trade in agricultural commodities

In a globalising world, in which the advantages of trade are more widely accepted, many countries will increasingly depend on trade to provision their food needs, as has been the trend in the past. In 2010, a total of ~400 Mt of staples was traded internationally—comprising 38 Mt of rice (in paddy rice equivalent), 161 Mt of wheat, 108 Mt of maize and 93 Mt of soybean—and equivalent to about one-sixth of the aggregate supply. Such dependency will thereby encourage production in the lowest cost regions and increased trade (barring significant trade barriers). This is in accord with the modelling discussed here (e.g. Nelson et al. 2010) and in Chapter 13 'Policies and farmers'. World price is strongly linked to yield and yield prospects, and nowadays as trade expands, national prices are in turn more strongly linked to world price.

However, there are situations where trade will be inadequate to assure food supplies. The 'mega-countries' of China and India have little choice but to domestically produce most of their staple foods (especially rice) given relatively small world markets in relation to their huge domestic markets. In many countries of Africa too, poor infrastructure, landlocked locations, lack of foreign exchange and low incomes necessitate that much of the food be produced near where it is to be consumed. The 2008 food price spike (Figure 1.2)—induced in part by export bans—will likely lead many countries to put a greater premium on local supply. Increase in yield (and sometimes crop area) assumes even greater importance in these countries.

1.6 Yield progress and prospects—the focus for this book

Clearly further yield progress is critical for food security, and the faster the progress the better the outcome for food security. Unfortunately, many scientific publications on food security do not provide much detail on yield or the yield predictions they necessarily make. Further, many recent research publications have been overly optimistic, with limited references to the biological limits to yield.

Because of the limitations of existing research publications, the primary subject for this book is yield and yield increase, and to this end, both local and global assessments of crop yield have been used. This book explores current crop yield progress across many commodities in considerable depth (Chapters 3 to 7) before considering future yield prospects (Chapters 8 and 9).

With its focus on crop yield, this book cannot consider many of the other important aspects of the current broader debate about world food security, such as access to food, food nutritional quality, diet control, post-farm-gate food systems and food wastage. For a broader picture, the reader is referred to a valuable comprehensive global scientific review of the United Kingdom Government Office of Science, entitled 'Foresight. The future of food and farming' (2011).

Looking towards 2050, there are obviously many uncertainties, but there are also some fairly reliable physiological relationships that underlie progress in and limits to crop performance (see Chapter 2 'Definitions, procedures and underlying crop physiology')—this is the rationale behind the emphasis on crop physiology, where appropriate, in the book.

The penultimate topic of interest is the potential for productivity growth (see Chapter 11 'Resource use efficiency' and Chapter 12 'Trends in total factor productivity'), as this reduces food prices and improves the welfare of people with lower incomes—it is closely linked to (but not the same as) yield increase. Input efficiency is discussed as a critical component of productivity, leading to consideration of the sustainability of more-intensive cropping and of the minimisation of its environmental footprint. Finally attention is given to the investments and other changes needed to boost agricultural productivity growth (Chapter 13 'Policies and farmers').

The conclusion is that greater rates of yield increase are possible through further intensification of agriculture, especially in Sub-Saharan Africa where intensification has barely begun and the scope for closing the yield gap is large. This will mean a much greater effort in research, development and extension, especially in the developing world. The increased (and hopefully more efficient) use of inputs will be challenging for scientists and farmers alike, especially in high-potential, high-input environments where innovations to reduce environmental impact are required. If world governments seriously commit to this vital objective, substantial increases in capital investments in agriculture will be needed.

Definitions, procedures and underlying crop physiology

2



Key points

- This book aims to measure and understand crop yield increase in key crops and regions in terms of the development and adoption of new varieties and agronomic technologies.
- Farm yield (FY), potential yield (PY) and water-limited potential yield (PY_w) are defined as fundamental concepts in this chapter. The difference between PY and FY is known as the yield gap. FY is increased as the consequence of PY increase (resulting from the invention of new technology) and/or through a decrease in the yield gap (resulting from the adoption of the technology).
- FY increase is calculated from the linear regression of yield **against year** over the past 20–30 years. The linear slope is expressed as a percentage relative to the estimated FY **in the most recent year**.
- Many confounding factors, apart from adoption of new technology, can cause FY change over time. These include:
 - changes in crop location within a region
 - changes in cropping intensity or emphasis on grain quality, not yield
 - trends in levels of carbon dioxide and ozone
 - trends in the weather and the natural resource base of farming
 - shifts in regulatory policy, costs and/or prices.
- PY is measured in well-managed trials under representative environmental conditions, often conducted by breeders. PY increase is calculated as the linear regression of variety yield **against the year of variety release**, again considering releases only in the past 20–30 years. The linear slope is expressed **relative to the estimated PY of the most recent varieties**. Breeding, novel agronomic practices, and their interaction with variety, all increase PY.
- The relative progress in PY is assumed to apply to FY change for the same varieties and practices, if and when adopted on-farm. However, the maximum economically attainable FY defines a minimum yield gap of about 30% of FY.
- Key concepts in crop physiology are briefly explained since they are fundamental to explaining PY increase and understanding the limits to crop yield and input use efficiency.

Definitions, procedures and underlying crop physiology

2.1 Yields and yield gap definitions

Despite the rich general literature on measures of yield and yield progress, these terms have often been loosely used. To aid clarity throughout this book, this chapter defines the following key terms and their interpretation:

- crop yield
- farm yield (FY)
- potential yield (PY)
- record and contest-winning yields
- water-limited potential yield (PY_w)
- theoretical yield
- attainable yield
- yield gap.

The discussion relies largely on Byerlee (1992), Evans (1993), van Ittersum and Rabbinge (1997), Evans and Fischer (1999) and Connor et al. (2011).

Crop yield

'Crop yield' is the weight of grain or other product, at some agreed standard moisture content, per unit of land area harvested per crop. Standard moisture content varies between countries and crops but is 8–16% in grains. This is usually the maximum limit for marketing of grain and may vary slightly among countries—typical values are wheat (12–14%), paddy rice (14%), maize (15.5%), soybean (13%) and canola (8%). When harvest moisture exceeds the maximum limit, grain must be dried after harvest and before

delivery; where harvest weather is dry, grain moisture can be 1–2% below the maximum limit. In all cases, moisture content is calculated on a fresh weight basis.⁸ Complications abound (as already seen in rice). These are discussed in following chapters relevant to particular commodities. The term ‘crop yield’ is used in this book when greater specificity is not required.

Farm yield

The central yield figure used throughout this book is the field, district, regional or national average yield given in kilograms or metric tonnes per hectare (kg/ha and/or t/ha). This figure is reported in surveys and/or local or national statistics, and is referred to throughout this book as ‘farm yield’⁹ (FY). FY and many related crop statistics for all countries are collated annually by the Food and Agriculture Organization of the United Nations (FAO) and are disseminated through the publically accessible database FAOSTAT.¹⁰ FY is expressed relative to harvested land area, noting that this area can fall well below planted area in some situations (e.g. after winter kill in winter wheat).

Although FY is quoted and used widely, it may not be as accurate as it appears, due to poor data collection, uncertain grain admixtures and other complications with data processing. With survey data, sampling error and bias can also arise.

In warm climates, more than one crop may be grown each year, so that yield per year or per day can be more important than individual crop yield. For example, Indonesian rice systems may produce three crops per year, a situation in which ‘cropping intensity’ (defined as the harvested area of all crops each year as a per cent of the cultivated area) is given as 300%.

Potential yield

At the high end of the yield scale it is critical to define ‘potential yield’¹¹ (PY). PY is the yield to be expected with the best-adapted variety (usually the most recent release), with the best management of agronomic and other inputs, and in the absence of manageable abiotic and biotic stresses. Evans and Fischer (1999) provide this definition, although they use the term ‘yield potential’. Many complications are hidden within this apparently simple definition but PY remains a key yardstick for understanding yield change. It may be difficult to measure, but PY and its surrogates are frequently

8 Grain dry weight is given by grain weight multiplied by $(100 - \% \text{ moisture})/100$.

9 Some call this ‘actual yield’ (e.g. Connor et al. 2011). In addition, where FY is determined from the average of a population of fields or farms, this has interesting statistical properties related to distribution (normality, standard deviation, quantiles, skew, etc.), some of which arise in later chapters. Where the average comes from aggregated districts, states or countries, it is always the area-weighted average.

10 <faostat3.fao.org/home/index.html>

11 In this book ‘yield’ is retained as the noun, and ‘potential’ as adjective, to avoid confusion with the term ‘yield potential’ which appears often in published literature with various meanings.

reported in the general crop science literature—although often without adequate attention to complications.

PY is usually determined in field plots, but to be applicable to the surrounding district, the natural resource base (climate, soil type and topography) of the plots needs to be comparable (not superior) to the district. This includes consideration of any long-term management improvements (e.g. liming or tile drainage). Water supply must be adequate for PY to be determined otherwise it is necessary to instead consider 'water-limited potential yield' (PY_w), which is described further in a subsection on PY_w below. Adequate water can come from well-distributed in-crop rainfall sufficient to satisfy most or all of the crop potential evapotranspiration (crop water use from sowing to harvest without water limitation) or from full or supplemental irrigation. Similarly, pests, weeds and diseases must be held at negligible levels through use of biocides if necessary. Finally, crops experiencing relatively rare weather damage (such as crop lodging or unseasonal frosting) are excluded from PY measurement.

Since PY is usually measured in plots, sampling errors will occur. Also, edge effects arising from extra solar radiation reaching border plants—or extra soil moisture in the case of PY_w —must be avoided, ideally by discarding the plot edges (up to a width of 25 to 100 cm, depending on crop height). If adjacent plots are harvested without discarding longitudinal edges, at the very least interplot path area must be included in the yield calculation.

PY as defined here is obtained from two sources: comparative variety trials and single variety experiments. The first source of PY data, variety trials, typically comprises well-managed experiments for the purpose of comparing new varieties against previously leading varieties (usefully called 'vintage trials'). All varieties may be present in all locations and/or years (termed a 'balanced trial'). Alternatively, multiyear unbalanced trials in which varieties gradually change over time—the situation for many breeding programs—are another source of PY information. The most useful comparative trials measure yields with fungicide protection—a good example is the wheat trials conducted by the UK Home Grown Cereals Authority (e.g. HGCA 2011). Yields from variety trials can only be considered as a true measure of PY where protection has been used, but around the world fungicide protection is not yet a common treatment in such trials. However, visible disease levels are usually reported, and if not negligible or too serious, this information can be used to correct PY.

The second source of PY data comes from careful field experiments conducted by crop physiologists, often to calibrate and/or validate crop simulation models that are largely driven by solar radiation, temperature and water supply applied to key crop physiological processes. Crop modelling is then often used to predict PY in other environments (e.g. different sowing dates, years and/or locations) and is especially useful for estimating PY across a relevant sample of seasons. Modelling accuracy has steadily improved for such purposes, but significant errors are still revealed when different models are compared (e.g. Palosuo et al. 2011). Models need to be updated for the latest varieties every few years, since breeders are steadily altering varieties (e.g. changing phasic development and improving PY). In this book, it is only when reliable

measurements are unavailable that modelled yields are used to estimate PY. Thus, the primary estimates of PY and PY_w in this book are based on measured yields. However, in discussing the broader implications of these results, analyses based on modelled PY values are often cited.

Record and contest-winning yields

Sometimes crop contest-winning yields or record crop yields are considered in the scientific literature to be synonymous with PY. Even if verified independently, these yield values need to be treated with caution because they refer to very favourable circumstances (e.g. soils, weather and/or management) relative to the district or regional average conditions. With cautious interpretation, record and contest-winning yields can provide useful information, and some key examples are discussed in Section 5.2 on the US Corn Belt and Section 9.5 on modelled predictions of PY.

Water-limited potential yield

Much of the global grain crop is grown in rainfed situations where water supply from stored soil water at the start of the crop season, plus precipitation during the crop season, is much less than potential evapotranspiration (where crop water use is unlimited by water shortage). Thus for the purposes of measuring yield, it is useful to define a water-limited potential yield (PY_w). This is the yield obtained with no other manageable limitation to the crop apart from the water supply. Obviously crop yield will depend on the amount of available water, so PY_w is usually plotted relative to water supply (or use). The slope of the relationship is considered to reflect the potential 'crop water use efficiency' (or 'water productivity'), commonly reported in kilograms of grain yield per harvested hectare per millimetre of water (kg/ha/mm).

Complications can arise from variation in rainfall distribution with respect to crop development stages, but PY_w (defined as a linear function of the water supply) is a valuable and simple benchmark as argued in an in-depth review (Passioura and Angus 2010). Simulation modelling has been especially useful in dealing with expected deviations caused by variation in the distribution of water supply.

Theoretical yield

Models, such as dynamic crop simulation models, are also used to calculate yields that would result if certain physiological processes could be altered favourably within realistic bounds: such yields are here called 'theoretical yields'.

Attainable yield

In any given region, 'attainable yield' is another important yield benchmark between FY and PY (or PY_w). It is defined here as the yield attained by a farmer from average natural

resources when economically optimal practices and levels of inputs have been adopted while facing the vagaries of weather.¹²

Since risk of financial loss almost always forms part of a farmer's decision to invest in increased inputs, the attainable yield definition must temper 'optimum level' with 'prudent attention to risk'. As an example this could mean input investments must be expected to return a risk premium over and beyond the cost of capital. This premium is usually low in developed countries and/or where water supply is assured, but is higher in developing countries and under rainfed conditions.

Of course attainable yield will reflect the economic circumstances of the crop and region—particularly grain prices relative to input costs, all measured at the farm gate. Although it is not easy to establish an appropriate attainable yield, general experience suggests that it will be ~20–30% below PY in situations where world prices and reasonable transport costs operate. Where this does not occur—for example, in much of Sub-Saharan Africa where infrastructure and institutions are weak—attainable yield (as defined above) may be much lower. Alternatively, where inputs and grain prices are heavily subsidised, it could more closely approach PY.

Yield gap

Because of the uncertainties surrounding attainable yield, it is easier to discuss the yield gap in terms of that between FY and PY, bearing in mind that even in the most advanced cropping situations in developed economies operating at close to world prices, FY will remain significantly below PY because of farm economic considerations surrounding attainable yield. Also it is more appropriate to **express yield gap as a percentage of FY** because when it comes to discussing food security, observed world grain production and likely increases are directly linked to FY (not PY). Other ways of estimating yield gaps are presented in Box 8.1.

General literature suggests that there is a minimum yield gap when FY equals attainable yield (as defined above), depending largely on prices. Assuming that future prices will be reasonably favourable for the farmer, this book considers that the **minimum yield gap to be 30% of FY**, meaning attainable yield is 23% below PY.¹³ Any larger gap is often defined as an 'economically exploitable yield gap'. However, as shown in following chapters, the expected exploitation can be as much a task for national and local governments and agribusinesses, as one for farmers.

¹² 'Attainable yield' is a term also defined by FAO and Connor et al. (2011), and somewhat differently by van Ittersum and Rabbinge (1997). The definition used in this book aligns more closely with that of FAO.

¹³ Here, if FY equals 100, and the minimum yield gap is 30%, then PY must equal 130. Thus, the difference as a percentage of PY is $30/130 = 23\%$.

2.2 Measuring progress in farm yield and potential yield

Yield progress can be measured in terms of improving FY and PY.

Farm yield progress

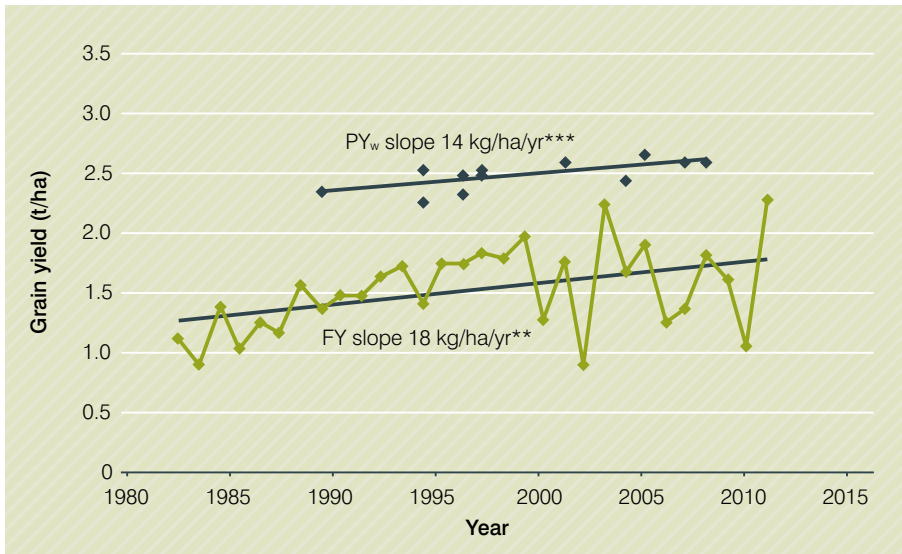
It is common to plot FY, the dependent variable, against year for given regions, states or nations. Economists look at exponential or compound rates of change (or the linear fit of log FY vs. time) expressed as annual per cent change. In contrast, crop scientists tend to calculate the linear fit of FY vs. time, coming up with a slope in kilograms (or tonnes) per hectare per year (kg/ha/yr or t/ha/yr). As change in FY over time in most cases resembles a linear relationship more closely than an exponential one (Figure 1.5), this book uses the linear slope as the basis for calculating and reporting annual rate of FY progress.

Over the last century, bilinear fits were adequate for major grain crops in most countries (Evans 1993; Calderini and Slafer 1998; Hafner 2003). Thus, slow or zero initial FY increases were replaced by rapid linear increases that often commenced in the 1950s or 1960s with the onset of modernisation of agriculture (e.g. the 'green revolution' in rice and wheat yields in Asia). Recently, many rising yields have slowed and some have even shown another break—this time to zero ongoing FY improvement, such as has occurred with wheat yields in parts of western Europe (Lin and Huybers 2012) including France (Brisson et al. 2010; see Section 3.8 on wheat mega-environment 11 (WME11)). In one case, maize in the USA, there has been a recent acceleration in the linear FY increase (see Section 5.2 on the US Corn Belt).

Since this book considers potential for yield gain into the future, progress is calculated using only the past 20 years (or 30 years if the data are very noisy, as with rainfed crops and/or small growing regions). This approach largely avoids the previous period of most rapid yield improvement, but also reduces the chance of picking up abrupt changes in slope (as in Lin and Huybers 2012). Linear relationships are fitted because in no case was a quadratic relationship significantly better.

Figure 2.1 illustrates a typical situation for FY progress. The linear slope and its level of significance are reported. The **standard for statistical significance** adopted throughout this book is:

- not significant (ns) for $P > 0.10$ —although sometimes the observed P -value is given for the estimated slope of observed data if it is close to 0.10
- significant (*) for $0.05 < P < 0.10$
- highly significant (**) for $0.01 < P < 0.05$
- very highly significant (***) for $P < 0.01$.



** $0.01 < P < 0.05$, *** $P < 0.01$

Figure 2.1 Typical plot of progress in farm yield (FY) and water-limited potential yield (PY_w) using example of spring wheat yields in Western Australia. FY is plotted against year and PY_w is plotted against year of variety release. Source: Source: PY_w from NVT (2009); FY from ABARES (2012) (see also Section 3.5)

In order to estimate the relative rate of change of yield (and crop area), throughout this book, **the linear slope (yield or area change per year) is expressed as a per cent of current FY**, estimated from the trendline in the last year for which there are statistics (usually 2009 or 2010).¹⁴ This percentage is abbreviated to per cent rate of yield progress wherever the meaning is self-evidently an annual rate. The statistical significance is assumed to be the same as that of the linear slope, and is usually not repeated. These rules are applied also to slopes and relative rates of change obtained or calculated from other scientific literature.

Using the estimated FY for the latest year as the denominator to calculate the relative rate of progress reduces the influence of weather-induced fluctuations in FY. In the

¹⁴ Note that when FAO Crop Statistics refer to a given year, it is the year of harvest for all crops everywhere, with the exception of the Southern Hemisphere where it is the year of sowing of autumn-sown crops whose harvest can spill into January to February of the following year. In the US Department of Agriculture (USDA) and Australian systems, (year n to $n + 1$ notation), the first year (n) is the year of harvest of all crops except: (1) again for some late harvested southern hemisphere autumn-sown crops; and (2) for southern hemisphere summer crops, when the second year ($n + 1$) is the year of harvest. The FAO dating system is used throughout this book.

example used as Figure 2.1, the estimated FY (shown by the black trendline) in 2010 was 1.8 t/ha and thus—calculated from $(18/1800) \times 100$ —the rate of progress is 1.0%. A slope expressed relative to recent yield will also prove far more relevant to the future than a rate of progress inflated by a lower selected denominator: either the average yield of a time series or, worse still, the yield in the first year, is often used in research publications. For the same reason, where progress is linear the relative rate of increase will not be constant as in compound growth; rather, a given relative rate of progress will inevitably decrease as FY increases.¹⁵

Calculations in this book make no allowance for outliers or for heteroskedasticity in fitting the data, as have some authors (e.g. Finger 2010). Heteroskedasticity in this case refers to changing variance of yield with year, which is likely to be small over 20–30 years; not allowing for it should not bias the determination of slope.

Potential yield progress

PY (or PY_w) is plotted **not against year (as for FY), but against year of variety release** (see Figure 2.1). This is the first year in which farmers could avail themselves of the potential offered by that variety.¹⁶ As with FY, the linear slope of PY vs. year of release is calculated by linear regression and shown in a figure. The rate of PY progress is given by this slope expressed as a per cent of estimated PY in the latest year of variety release (which is hopefully close to the present). In the example shown in Figure 2.1, estimated PY from the trendline was 2.6 t/ha in 2008 and the rate of progress is 0.5%—calculated from $(14/2,600) \times 100$. Again, recently determined data have been sought to relate variety releases during the past 20 years. Where such data could not be found, longer release periods have been considered with attention to the duration of the linear relationship (i.e. consideration of whether the relationship remains linear through to the latest year of variety release).

As previously described, vintage trials—in which newer varieties are compared alongside older ones—represent the simplest situation in which to measure PY progress. Unbalanced multiyear trials have also been used to measure rate of progress, relying on recurrent control varieties that appear every year, and against which the yields of non-recurrent varieties are expressed as ratios or percentages. These ratios are then regressed against year of release. Both approaches assume that the older varieties, or the recurrent control varieties, always react in the same manner to any environmental changes over time (e.g. new disease races in unprotected trials). Obviously if varieties become more susceptible to disease with time, the rate of progress will be overestimated (see Section 3.8 on WME11, for example).

15 A 50% increase in yield over the next 50 years (e.g. from 3 to 4.5 t/ha), requires a linear increase of 30 kg/ha/yr throughout. Another way of describing this progress would be a relative rate of progress starting at 1% and falling to 0.7% in the final year.

16 Sometimes researchers use year of first entry in widespread trials, perhaps 2–3 years before official variety release.

More recently, new statistical techniques can calculate effects from the unbalanced multiyear datasets now more common. With regular variety turnover (old varieties replaced by newer ones) over long time series, very few of the potential number of pairwise comparisons are present (e.g. <10% in Mackay et al. (2010) using multiyear Home Grown Cereal Authority (HGCA) data in the UK). Using linear mixed-model regression statistics, a coefficient for year of release can be directly fitted (e.g. Nalley et al. 2008), or variety effects can be determined and then regressed against year of release in a two-step process (e.g. Mackay et al. 2010). These procedures do not entirely reduce risk of bias due to breakdown of disease resistance with age in unprotected trials (again see Section 3.8), but bias is lessened as the residence period of varieties in the trials shortens. Again, some authors in this situation have allowed for heteroskedasticity (e.g. Nalley et al. 2008) but others do not consider this to be a significant issue (I. Mackay, pers. comm. 2012).

As explained, PY trials need to be performed under conditions representative of the target region, and such trials usually receive the best agronomic practices of the day. Advancing agronomic practice has generally contributed to PY progress, usually to the same extent as breeding,¹⁷ and a positive interaction between the two has often delivered a major part of the progress (de Wit 1992; Evans 1993; Evans and Fischer 1999; Fischer 2009). For example, to cover two of the major interactions in modern agriculture (see Box 2.1), the rate of PY progress is higher in wheat when measured at high nitrogen levels (e.g. Ortiz-Monasterio et al. 1997), and higher in maize when measured at high plant density (Duvick 1997).¹⁸ The balanced vintage trials mostly used for PY progress in this book were all conducted under recent environmental conditions and with the latest agronomy, even if some of the varieties involved were released (sometimes more than) 20 years ago. As a consequence, agronomy-by-variety interactions, if significant, become part of the measured 'breeding progress' in vintage trials, and are referred to in this book as such; however, the analysis misses any effect of changed agronomy on older varieties (see Box 2.1).

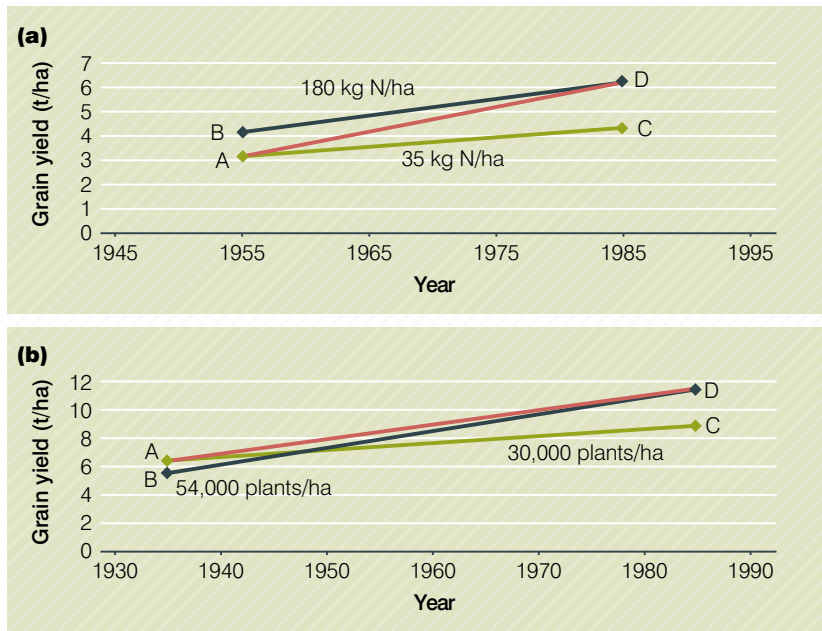
In the linear mixed-model approach with unbalanced datasets (see above) the agronomy-by-variety (and year-by-variety) interactions are in fact ignored and stay in the error term, but progress due to both breeding and to year (= agronomy plus any weather trends) are estimated and their sum gives PY progress correctly (see also Box 2.1). This approach is now becoming more popular; several are cited in the book, wherever possible specifying the separate components.

¹⁷ Note that throughout this book 'agronomy' refers to crop management, as distinct from crop breeding.

¹⁸ Note that it is impossible to mathematically separate the breeding and agronomic contributions in such interactions, an important point often overlooked in the attribution of progress. However, the effort taken to breed higher PY is clearly more than that required to raise the level of an agronomic input like nitrogen or seed; an entirely new agronomic intervention like conservation agriculture is, however, no effortless endeavour!

Box 2.1 Variety-by-agronomy interaction and potential yield progress

Ideally, vintage trials should be conducted under old and modern agronomy, because the examples used in the figure below show that estimates for PY progress under only modern agronomy miss the response of older varieties to changed agronomic conditions. This response could be either positive, shown in part (a) of the figure, or negative (part b). In both examples, point A represents the old variety under old agronomy, and point D represents the new variety under new agronomy: thus line AD measures true PY progress. But a vintage trial under modern agronomy would measure progress represented by BD, a lower slope than AD for the wheat example (figure part a) but a higher slope for the maize example (part b).



(a) Wheat potential yield (PY) progress at two levels of nitrogen per hectare, and (b) maize PY at two plant population densities. In each case an old and a modern variety are shown. Note: line AC represents the response to variety under old agronomy, line BD the response under modern agronomy and line AD the overall progress in PY. Source: (a) Ortiz-Monasterio et al. (1997), (b) Duvick (1997)

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Continued

Since PY trials are usually conducted under the best available agronomy for the latest varieties, yield results of latest varieties are likely to sit close to the top of their response curves. Thus when previously 'new' varieties become 'older' varieties in subsequent trials at a later date, these varieties are unlikely to respond greatly to higher agronomic input; hence the difference (or error) between lines AD and BD is unlikely to be large. It is not easy in modern agriculture to envisage an agronomic innovation that could lift yield of both old and new varieties by the same amount. However, this may be the response to increased carbon dioxide (CO₂) (see below in Section 2.4 on confounding factors), an effect that is missed by the measure of PY progress given here. To the extent that such PY progress estimation does miss agronomic innovation lifting all yields, this method underestimates PY progress and overestimates the rate of yield gap closing.

The situation is different in multiyear variety trials because yield increases not only through variety improvement but also better agronomy (and any positive interactions). This is because the trial is a measure of PY of the year of trial, not year of variety release. Linear mixed-model regression analysis can be used to separate the year effect (agronomy and/or environment change assuming no substantial change in trial locations) from the breeding effect (year of release). Again, the work of Mackay et al. (2010) with 59 years of Home Grown Cereal Authority (HGCA) variety trials in the UK provides a valuable example of this approach.

To date, however, progress through variety-by-agronomy interaction in such trials has not been separated in any of the cases cited in this book. The Mackay et al. (2010) analysis found no evidence for agronomic progress in UK winter wheat trial yields between 1982 and 2007, suggesting no significant variety-by-agronomy interaction contributing to the identified variety progress; this is common in other such analyses. However, Mackay et al. (2010) found both variety and agronomic progress between 1949 and 1981 when nitrogen levels increased notably. In this case the likely positive interaction would contribute to the estimates of both components of progress.

The estimated current values of FY and PY determined above also form the basis of the yield gap calculation. Using a current estimate for PY means that an inevitable part of yield gap is the time taken for the latest varieties (and any accompanying novel agronomy) to dominate in farm fields. Even in the best situations this lag time probably equates to around 5 years: with PY progress of 0.5% per annum (p.a.), this would inevitably lead to a small yield gap of ~2.5%. For many reasons the lag in new variety adoption can be longer—as is also common for the adoption of new agronomy—and this can partly explain much larger exploitable yield gaps reported in later chapters.

Yield gap with respect to delayed and variable variety adoption has been incorporated into some analyses of progress. For example, Silvey (1981) and Bell et al. (1995) took the breeding yield progress contained in each variety grown (relative to a standard control variety), then weighted it by the proportion of the region grown to the variety. In this way these authors built a **variety weighted index of PY** for the mix of varieties in farm fields in any year. The index was then plotted against time to estimate the relative progress that might be expected at the farm level from variety change. This process required statistics on which varieties are grown—data that are not often available—but the method does eliminate uncertainty arising from assuming that the best varieties are always adopted (after an appropriate lag). This approach is used in Section 4.2 for rice in some South-East Asian countries.

2.3 New technology, farm yield progress and yield gap closing

Many factors can be involved in the change in FY over time. The importance of each factor will change with region and crop (see Section 2.4 on confounding factors in FY change). The premise in this book is that the main driver of FY progress is the adoption of steadily improving technologies: new varieties, new agronomic or management techniques, and better timeliness and decisions by the farmer (e.g. Cardwell 1982; Bell et al. 1995). PY trials are conducted under the best current management and should therefore capture the latest in technical progress.

Furthermore, this book proposes that FY progress can be usefully divided into two components: increasing PY and closing of the yield gap between PY and FY. Figure 2.1 might indicate that the rate of increase in FY (18 kg/ha/yr) can therefore be considered the sum of the rate of increase in PY (14 kg/ha/yr) and the rate of yield gap closing (4 kg/ha/yr). This may be mathematically correct but **it is more realistic to assume that the relative rather than absolute rate of increase of PY applies to farm fields**. Thus the annual rate of FY progress of 1.0% is more usefully disaggregated into the rates of 0.5% PY increase and 0.5% yield gap closing, noting that gap closing is a negative rate of change. The critical assumption is that the relative change in FY to be expected from full adoption of PY varieties and practices is the same as the relative change in PY. This assumption has been confirmed by most on-farm testing where relative yield gains with new technologies (particularly new varieties) appear to hold up even where some management deficiencies exist. Note that this is not necessarily the case if management deficiencies are major, especially in the area of weed control. Note also that in the methodology used in this book, PY progress is always measured independently of any factors that change with time (for example, weather trends or CO₂ increase). FY remains subject to all factors that change with time (see Section 2.4), but such time trends can be used to correct changes in FY to better determine the contribution to yield progress from adopted technologies.

2.4 Confounding factors in farm yield change

Besides the major role of the discovery, development and uptake of new technologies, the following potentially confounding factors need to be considered when examining change with time in FY:

- crop area and location
- grain quality
- cropping intensity
- carbon dioxide (CO₂) and ozone
- seasonal weather
- change in the natural resource base
- government policy
- input costs and grain prices.

Crop area may change within regions, bringing the possibility of crop shifts within a region to poorer or better environments, even if there is no change in total crop area. These changes arise as land is newly cropped, old land retired, or when one crop replaces another. A key change in land use that can confound yield is the adoption of irrigation, and it is often impossible to disaggregate yield data into rainfed vs. irrigated yields. In New Zealand, for example, national wheat yields have doubled in the past 20 years but the main cause has been a shift from zero to 80% irrigated area over the period. The adoption of irrigation is better considered a land-use change, not a yield gap closing technology.

The importance of **grain quality**, through price signals to the breeders and farmers, means there can be progress in economic output with relatively less (or even without) yield progress. Economists consider this a 'product mix' contribution to productivity growth. This often arises because of the common negative relationship between PY and several aspects of grain quality that originate from either genetic (e.g. protein content in wheat) or agronomic (e.g. rice eating quality in Japan, as discussed in Section 4.5) influences.

Farmers switching to earlier maturing varieties can increase **cropping intensity** (crops grown per year). Although crop yield may not increase through increased cropping intensity, productivity may benefit (e.g. many Asian paddy rice systems). Farmers who abandon intercropping practices would record higher yields for the main crop without any other change in technology. This has happened with wheat–mustard intercropping in north-western India because of rising labour costs.

At least two atmospheric gases, **CO₂ and ozone**, may cause yield change over time. The atmospheric concentration of CO₂ in parts per million (ppm) is steadily

increasing, and over the past 20 years has risen at ~ 2 ppm/yr or 0.5% p.a. The influence of increased CO₂ on yield has been widely studied and, although the crop yield response depends somewhat on growing conditions (moisture, temperature and nitrogen), it is reasonable to assume that the yield of crops with C₃ photosynthesis (see Section 2.6 under 'Crop growth, photosynthesis and respiration') is currently increasing at $\sim 0.2\%$ p.a. due to CO₂ rise (Horie et al. 2005a; Tubiello et al. 2007); C₄ crops are assumed unaffected (see also Section 10.3 on direct measurement and crop modelling). Results presented in this book have not been corrected for CO₂ increase, so that observed gap-closing progress in C₃ crops (FY change less PY change) must be discounted by 0.2% p.a. to determine true technical progress on-farm.¹⁹ Changes in ozone concentration in the lower atmosphere are much more variable in time and space, but can be high enough to reduce crop yields in some locations where modern industrial activity is intense, and thereby counter yield trends from other causes; alternatively, reducing ozone levels (e.g. with pollution control) could bias upwards estimates of yield progress resulting from technology (see Section 10.3).

Variation in **seasonal weather** causes deviations from any yield trend. Seasonal variations can also change the slope of the trendline if the changed weather correlates with year. This effect can be critical for FY determination (e.g. see Section 3.2 on WME1 and Section 10.2 on time series and climate change). Crop simulation models or simple empirical relationships permit correction for such weather changes to improve estimates of the yield slope and thus permit a better estimate of true technological change. Such weather trends may or may not be associated with human-induced climate change.

Gradual **change in the natural resource base** of cropping in a region can influence yield change. This is commonly the result of soil deterioration due to fertility or structural decline or salinisation—but equally, cropping soils can be gradually improved (e.g. through liming, applying phosphorus in excess of removal, and/or reducing tillage). Availability and quality of irrigation water can decline with overuse or poor system maintenance. Pressure from weeds, disease and pests can change as a result of new pest arrivals, pest evolution or changes in farming practice (e.g. the appearance of herbicide-resistant weeds). These changes are by definition gradual and their occurrence is often invoked as indicators of sustainability of the natural resource base of cropping when no other explanation for yield change is evident. The possibility of such impact should not be ignored, but definitive proof of such change is hard to secure. By the definitions used here, these are causes of exploitable yield gaps and are therefore manageable by proper use of technology. Often, however, the period of poor management has been decades. In such cases, management to reverse the degradation may take more than a year. Further, any particular farmer is unlikely to have caused some types of resource degradation (e.g. aquifer overuse, exotic pest invasion), and it is therefore difficult (or impossible) for one farmer to change their farm's management practice to overcome the problem.

¹⁹ In reality, in C₃ crops CO₂ rise lifts both PY and FY at 0.2% p.a. and does not directly affect the yield gap. The rates of change in PY estimated here do not include this effect but those in FY do, leading to the apparent yield gap closing effect due to CO₂ rise.

Farm yield can also be influenced by change in **government policy directly impacting farm practices** such as regulations and/or incentives. Limitations on the use of nitrogen fertiliser, or subsidies for low-input farming, are examples now found in western Europe (see Section 3.8 on WME11).

Farmer decision to adopt a new technology or practice is generally slow but can be strongly influenced by **input costs and grain prices** (both calculated at the farm gate) and also by availability and cost of credit. However, the allocation of already-in-use inputs by farmers responds more quickly to price shifts at the farm gate than the adoption of entirely new technologies. Economists refer to this as the price elasticity of yield (Chapter 13 'Policies and people'). Hertel (2011) estimates this elasticity as 0.2 for maize in USA, meaning that a 1% rise in prices would lift yield by 0.2%. Elasticity may be greater if input use is lower.

Finally it should be noted that when PY progress is plotted against the year of release, the PY values refer to the soil, weather and management levels under which the variety comparisons were conducted—normally meaning those of recent times. It is possible that plant breeding has unwittingly adapted varieties to some of the gradual changes discussed above (e.g. to take greater advantage of CO₂ increase, or to resist increasing salinity or ozone concentration). In analyses presented in this book, this effect is simply lumped into another positive variety-by-environment interaction contributing to breeding progress. Properly measured and calculated PY progress is not, however, inflated by the direct effect of increasing CO₂ on yield of C₃ crops, because all variety comparisons are made in the same years; if multiyear unbalanced data are used, these are corrected for the effect of year in the statistical analysis.

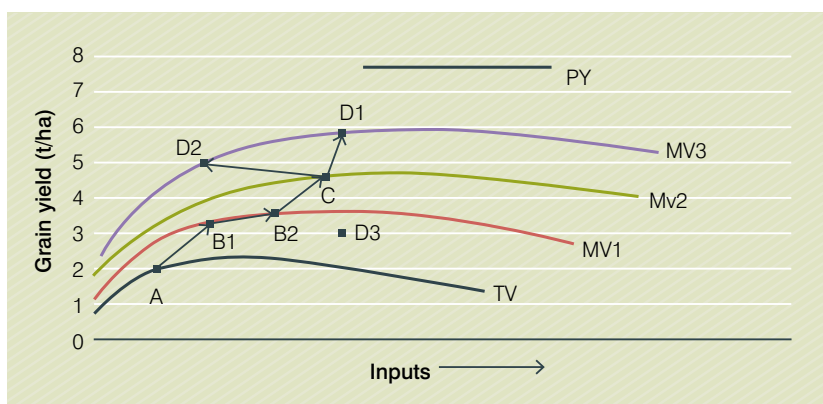
2.5 Other measures of efficiency and productivity under technical change

The next seven chapters (Chapters 3–9) deal with changes in FY and PY, the common currency of breeders and agronomists. Economists and farmers, however, look beyond yield to also consider efficiency, productivity and profit. Thus, in a finite world it is also essential to pay attention to yield per unit input, whether the input is nutrients, energy, water or labour—issues that will be covered in Chapter 11 on resource use efficiency.

Another economic measure, total factor productivity (TFP), considers productivity across all inputs. This measure is mainly useful because changes in TFP drive long-term price trends. TFP is a measure of physical output in relation to the aggregate quantity of all inputs. In this way, changes in agricultural production are disaggregated into one component relating to change in the amount of inputs, and a second relating to change in productivity. TFP is explained in Box 2.2 and further in Chapter 8 'Yield gap closing' in connection with efficiency gaps between farmers, and Chapter 12 'Trends in total factor productivity'.

Box 2.2 Efficiencies, profit maximisation and total factor productivity (TFP) under technical change

Economists define efficiency as the average cost for producing a given yield relative to the lowest cost option with the best current technology. They generally distinguish technical and allocative efficiencies. 'Technical inefficiency' refers to failure to operate at the yield frontier. 'Allocative inefficiency' refers to failure to meet the marginal conditions for cost minimisation where the marginal returns of applying an additional unit of input (the marginal return divided by the price of the input) are equal for all inputs. Profit is maximised when this marginal return is equal to the marginal cost across inputs, as determined by grain to input price ratios at the farm gate. The box figure illustrates a useful framework for identifying these economic measures as farmers adopt new varieties and practices.



Stages in the adoption of technology by farmers and effect on yield.
Source: Derived from Byerlee (1992)

The figure is derived from Byerlee (1992) using an example of the green revolution in South Asia—where, in the mid-1960s, high-yielding semi-dwarf wheat and rice varieties were first introduced. The figure plots yield against the sum of inputs (such as nutrients, seeding density, water and biocide) used after suitable adjustments for costs. TFP is the slope of the line joining any point in the figure to the origin, which will here lie to the left of the y-axis (because fixed inputs are not included). Four technical frontiers in time are shown, starting with the era before the green revolution shown by the curve TV for 'traditional variety', and passing to the curves MV1–3 for 'modern varieties' and technologies.

Continued next page

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The PY corresponding to the final technical frontier (which is shown by line MV3) is shown some 30% above the line for MV3.

Initially, an innovative irrigated wheat or rice farmer (i.e. 100% technically efficient) could have moved from position A (on curve TV) to position B1 (on curve MV1, representing the first semi-dwarf modern varieties). Then, in what can be termed the first post – green revolution phase, the farmer could have intensified input use to attain position B2 on curve MV1, thus seeking greater allocative efficiency. The FY progress from A1 to B2 might involve an improved variety, improved fertiliser input, or their positive interaction.

In consecutive waves of technology—such as improved second and later generation semi-dwarf varieties of the 1980s and beyond (represented by frontier MV2 and finally MV3)—the farmer could move to position C and then position D1. The 100% efficient farmer could also increase TFP (input efficiency) by moving closer to the y-axis (point D2), but if D1 represents profit maximisation, a shift to reduce inputs to point D2 will sacrifice allocative efficiency, yield and profit.

Technically inefficient farmers will occupy positions below the prevailing technical frontier, and their efficiency is measured by the ratio (or per cent) of their yield relative to the frontier yield at their level of inputs. For example, the farmer at position D3 has the same level of inputs as another at position D1, but operates at about one-half the technical efficiency.

Establishing the technology frontier is not easy and, just as with yield gaps, site specificity and seasonal conditions influence efficiency gaps. These tend to be ignored by economists, leading to overestimations of inefficiencies (e.g. Ali and Byerlee 1991). Of course the frontier moves upwards with new technologies, but it may also shift downwards if there are serious long-term problems of resource degradation.

Yield gaps and efficiency gaps are often measuring the same things, but efficiency gaps may exist even in the absence of yield gaps. As with yield gaps, factors related to farmer characteristics and system-wide constraints explain variation in efficiency across farmers and fields. Technical efficiency relates largely to timing and technical skills in input use, and is often explained by farmer-specific knowledge and skills. However, system-level factors (such as management of irrigation systems) can also explain technical inefficiency. Allocative inefficiency can be caused by similar factors, as well as by differential risks of input use, input market failures and financial constraints.

2.6 Weather and soil parameters and physiological determinants of yield

To better understand crop yield progress—and in particular, future prospects for yield progress—this book relates yield to a number of common crop physiological concepts, considered alongside standard weather and soil parameters. Defined and described briefly below, these concepts and parameters form the building blocks for crop simulation models, to which reference is often made.

Weather parameters

The key weather parameters driving crops, and their units (and means of measurement, where appropriate) are:

- air temperature in degrees Celsius ($^{\circ}\text{C}$)
- humidity as vapour pressure deficit (vpd) in units of kilopascals (kPa)
- solar radiation in units of megajoules per square metre per day ($\text{MJ}/\text{m}^2/\text{d}$)
- precipitation as depth of liquid water in millimetres (mm) accumulated over a given interval.

The range in **daily air temperature** is seen in the maximum (T_{max}) and minimum (T_{min}) daily temperatures. Temperature is generally summarised as **daily mean temperature** (T_{mean}), which is the average of T_{max} and T_{min} , and sometimes as **diurnal temperature range (DTR)**, which is the difference between T_{max} and T_{min} .

More detail can be obtained with hourly temperatures, which (if not measured) can be interpolated from T_{min} and T_{max} . Temperature sums over time above a defined base temperature (T_{base}), below which development stops, are often calculated in units of 'degrees Celsius days'. Temperature sums can be calculated using either T_{mean} or a daily sum that is produced by dividing the sum of hourly temperatures above the base by 24. The duration of given development periods (see below) is often a cultivar-dependent number of **growing degree days (GDD)**.

Air humidity refers to moisture in the air, usually reported as **vapour pressure deficit (vpd)** given by the measured water vapour pressure of the air subtracted from the saturated vapour pressure at air temperature. Saturated vapour pressure increases as an exponential function of temperature.

Since water vapour pressure is fairly steady over the course of a day, vpd peaks at T_{max} . The dewpoint is the temperature at which the air becomes saturated with the water vapour it contains; in the absence of measurement of vpd, it is often assumed that T_{min} is the dewpoint. One important aspect of micrometeorology is that leaves can modify

temperature and vpd within the crop canopy. Also, transpiring leaves can be cooler (and non-transpiring leaves warmer) than the air.

The **daily solar radiation** is the total incoming solar radiation incident on a horizontal surface (R_s) given in units of megajoules per square metre per day ($\text{MJ}/\text{m}^2/\text{d}$). Leaf photosynthesis over short intervals is often expressed as a function of irradiance, meaning the perpendicular component of solar radiation reaching the leaf surface expressed as power in watts per square metre (W/m^2) in which one watt is equivalent to one joule per second ($1 \text{ W} = 1 \text{ J/s}$).

Measured above Earth's atmosphere, perpendicular to the Sun's rays, average solar irradiance is $1,360 \text{ W}/\text{m}^2$ (Connor et al. 2011). However, at ground level and even when the Sun is high in a very clear sky, peak irradiance is only about $1,000 \text{ W}/\text{m}^2$ for a leaf perpendicular to the solar beam. On a clear day most of the radiation is direct beam radiation from the Sun, with a small proportion ($< 15\%$) arriving as diffuse radiation (i.e. scattered solar radiation from the rest of the sky). The proportion of the total irradiance that arrives as diffuse radiation increases with cloudiness, with important positive consequences for crop photosynthetic efficiency (see below in the section 'Crop growth, photosynthesis and respiration'). Not determined by weather, the angle of the direct solar beam is also important for crop photosynthesis; the solar elevation angle is expressed relative to the horizontal and varies predictably by time of day, date and latitude.

About one-half of the solar radiation energy (direct and diffuse) occurs in wavelengths that can be used by photosynthesis—this portion, termed **photosynthetically active radiation (PAR)**, can also be measured in units of megajoules per square metre per day ($\text{MJ}/\text{m}^2/\text{d}$). The assumption made in this book is that the ratio of PAR to daily solar radiation (R_s) is 0.50 (Mitchell et al. 1998; Sinclair and Muchow 1999).

Photoperiod is determined by date and latitude, and is measured in hours and minutes. Critical for influencing the rate of development of many crops, photoperiod is closely related to day length (the interval from sunrise to sunset), but is somewhat longer because twilight, which is sensed by plants, is not included in day length.

The sum of all water reaching the ground (rain, hail and snow) is termed **precipitation (P)** and is measured as the depth of liquid water in millimetres (mm) accumulating over an interval (which could be a day, month, crop growing season or year). One millimetre per hectare is equivalent to 10 m^3 or 10 kL of water. Irrigation is often measured in megalitres per hectare (ML/ha), with one megalitre equivalent to a depth of 100 mm of water over a hectare.

An important aspect of weather in the water balance of crops is **potential evapotranspiration (ET_p)**, measured in millimetres per day (mm/d), or per growth interval. ET_p refers to the water that evaporates from a green crop surface completely covering the ground and well supplied with water. The value of ET_p is a moderately complex function of daily solar radiation (R_s), temperature (T), vpd and wind speed; crop type exerts little effect.

Soil properties

Soil provides physical support to crops and supplies roots with nutrients and water. Nutrients are found mostly in the topsoil (top 10–30 cm). They are largely supplied from breakdown of soil organic matter, which is measured as **soil organic carbon (SOC)** and expressed as per cent of soil dry weight (weight of soil organic matter is about 1.67 times that of soil organic carbon).

Topsoil texture is important and depends on the proportions of sand, silt and clay. Sandy topsoils are termed 'light textured' and have a low maximum water-holding capacity—that is, ~5% moisture by weight of dry soil, or only ~7 mm per 10 cm of soil depth (considering a sandy topsoil might have a density of 1.4 g dry soil/cm³). At the other extreme, clay topsoils are termed 'heavy' and can hold much water—that is, up to 50% moisture by weight of dry soil, or ~70 mm per 10 cm of soil depth.

Total water-holding capacity of the soil profile is a critical consideration for rainfed cropping. For these purposes, water-holding capacity is usually considered in terms of **plant available water-holding capacity (PAWC)**, measured in millimetres (mm). PAWC is the maximum amount of water that a crop (with a fully extended root system) can extract from a fully wetted and drained soil. Thus PAWC is specific not only for soil type, but also for crop type because root depth and density vary. PAWC is always less than the maximum water-holding capacity to the full root depth, because even dense root systems in the topsoil physically cannot extract all the soil water, and there are never enough roots at depth to extract all the available water. PAWC for annual crops can range from 50 mm in poor water-holding, shallow, sandy soils to >250 mm in deep silty soils (e.g. Loess soil).

Solar energy reaching the soil surface—especially when the surface is wet—causes **soil evaporation (E_s)** measured in millimetres (mm). Microbiological processes in the soil can also result in the release of important greenhouse gases such as CO₂ and nitrous oxide (N₂O) to the air, as well as nitrogen (N₂) and ammonia (NH₃). These gases are usually measured in grams per hectare per day (g/ha/d) or kilograms per hectare per day (kg/ha/d), but N₂ release is very difficult to measure.

Crop development

Crop development and growth are distinct and important processes. Development refers to the occurrence in time of major morphological events and periods in the life of the crop. Crop development is often termed 'crop phenology' and the life periods termed 'phenophases'. The designation of periods of crop development is influenced somewhat by whether the crop is a monocot or dicot. Crops that first emerge above the soil with a single leaf are termed 'monocots' and examples include cereals and sugarcane. Crops that first emerge above the soil with two leaves are termed 'dicots' and include all broadleaf crops.

Table 2.1 summarises the development of cereals. The events and periods marked in bold are critical to the determination of yield in cereals, and divide the life cycle of all such crops (sowing to physiological maturity) into three general periods:

1. **true vegetative period** from sowing to floral initiation
2. **reproductive period** from floral initiation to anthesis (literally the release of pollen)
3. **grain-filling period** from anthesis to physiological maturity.

Table 2.1 Major events and periods in the development of cereal crops

Event or process	Definition	Comment
True vegetative period		
Sowing^a	Beginning of water uptake by seed	Assume soil moist
Germination	Appearance of radicle (first root) from seed	na
Emergence	First appearance of leaf above soil	na
Leaf initiation	Regular appearance of leaf primordia (microscopic bud) on apex of the main stem or shoot	Needs dissection to detect
Leaf appearance	External appearance of leaves on main stem at regular rate between emergence and last leaf appearance	Fixed number of leaves on main shoot, between 6 and ~25
Tillering	Appearance of new stems in axils of leaves on main stem (and on other tillers)	na
Reproductive period		
Floral initiation	First appearance of floret primordia (microscopic buds) on main shoot apex (needs dissection to detect); signals end to leaf initiation on main shoot	In maize the tassel is formed at the shoot apex, the cob in a leaf axil several leaves below the final leaf
Onset stem elongation	Internodes (interval between nodes or joints) on main stem begin to elongate	na
End of floret initiation	Last floret primordia appears at apex of shoot	Many florets are initiated; few grow to complete florets
Onset inflorescence growth	Beginning of rapid accumulation of dry matter in inflorescence (spike, panicle, tassel or cob) structure	na
Meiosis	Production of haploid nuclei for pollen (in anthers) and ovule (in carpel) in developing florets	Pollen are the male equivalents, carpels the female
Final leaf emergence	Appearance of last leaf on main stem	In wheat called the flag leaf
Spike (head) emergence	Appearance of the main shoot inflorescence	Tassel in maize, panicle in rice

Continued next page

Table 2.1 Continued

Event or process	Definition	Comment
Anthesis or flowering	Appearance of first burst anthers, shedding pollen, and occurrence of pollination of the ovules (except maize)	Often known as flowering (or pollen shed in maize)
Silking (maize only)	External appearance of styles (silks) from female flowers on maize cob, receptive for pollen	Under stress in maize, silking may be significantly later than pollen shed on the same plant
Grain-filling period		
End of inflorescence growth	Soon after anthesis and pollination	In maize the cob grows more after pollination than before
Onset grain-filling	Beginning of rapid dry matter accumulation in grain	Always some lag between pollination and onset of rapid grain growth
Grain-filling	Period of rapid grain growth	na
Physiological maturity	End of grain growth, as can be seen by changes within grain	Upper leaves may or may not still remain green
Harvest ripeness	na	Crop dry enough to mechanically harvest

- a Bold text represents major events
na = not applicable

Unfortunately there are complications and confusions in the naming of these periods of crop development—sometimes the period from sowing to anthesis is termed ‘vegetative’ and grain-filling is considered ‘reproductive’ (a practice avoided in this book). Importantly, key periods for the determination of yield can be more sharply defined for individual crops and can overlap the key events of floral initiation and anthesis. Table 2.1 refers to development on the first or main shoot of the cereal plants. Many cereals have tillers, which are shoots or branches formed in leaf axils. The development stage of the tiller apices is initially a little behind that of the main shoot, but by the flowering development stage, differences between main shoots and tillers are usually small (a few days), and are negligible by physiological maturity.

Two additional periods are defined for the purposes of this book (see Chapter 9 ‘Increasing potential yield’), which largely determine:

1. number of grains (GN) measured per square metre of crop ($\#/m^2$)
2. potential grain weight (GW) measured in milligrams (mg).

Depending on the crop, these two periods can occur either side of (but always close to) flowering. Note that in North America, GN and GW are often referred to as 'kernel number' and 'kernel weight', respectively.

The picture outlined in Table 2.1 is for cereals, which are determinate monocot crops—'determinate' because a floral structure terminates the main stem (and each tiller, if present). The situation is somewhat different in dicot crops, with the exception of modern sunflower, a strictly single-stemmed and determinate plant. Most other dicots—such as soybean, pulses, canola and peanut—have an indeterminate habit in which branching, leaf appearance and internode elongation overlap with stages of flowering. Branches or flowers arise as axillary buds of leaves. Floral initiation, flower appearance and anthesis can occur over an extended period (even if flowers eventually terminate the shoots); however, there are clear development events for first floral initiation and first flower opening. Reproductive development of the indeterminate dicots is thus quite asynchronous; pods form and begin to grow slowly, but flowering finishes only with a sharp onset of pod growth and seed-filling across all pods. Physiological maturity occurs relatively synchronously over all seed pods.

Finally there are root and tuber crops for which flowering is not a part of yield formation; rather, for these crops, flowering is incidental and best avoided to maximise yield. The onset of yield formation—the swelling of storage roots in cassava (and lower stem or tap root in sugar beet) and the formation of tubers in potato—usually occurs early in the life of the crop and follows similar environmental signals as (but independent from) flowering.

The **rate of crop development** is the reciprocal of the duration of specific development periods. It is driven strongly by a linear response to temperature, such that durations are usually a constant GDD sum above the appropriate base temperature for a given crop variety. The duration of crop development at a given temperature can, however, differ notably among crops (and among crop varieties), as many genes control the response to other environmental factors—notably photoperiod and vernalising cold (hours below $\sim 15^{\circ}\text{C}$). Longer photoperiod generally speeds development in some crops (long-day plants like wheat and barley) and slows it in others (short-day plants like rice, soybean and maize), but within short-day plants, some varieties are unaffected by photoperiod (these varieties are termed 'day neutral'). In some varieties of wheat, barley, rapeseed (including canola) and sugar beet, exposure of the plant to vernalising cold can shorten specifically the true vegetative period by accelerating the onset of floral initiation. In so-called 'winter varieties' the need for vernalisation is obligate, because without vernalisation there is no flowering; in 'facultative varieties', floral initiation is merely accelerated. Genes can also influence the GDD sum independently of photoperiod and vernalising cold.

Suffice it to say here that unfavourable photoperiods for floral initiation will prolong the vegetative period; the number of leaves formed around the main stem will increase, and crop development will be delayed both during the vegetative and reproductive periods. The lack of vernalisation in sensitive genotypes also increases the number of leaves,

but usually does not delay development after the true vegetative period. Grain-filling duration shows much smaller differences among varieties of any crop and no response to photoperiod or vernalisation.

Crop development rates become especially important when considering the effects of higher temperature as may arise with climate change. Chapter 10 on climate change expands somewhat on this subject since there are limits to the linear response of development rate to increasing temperature.

Crop growth, photosynthesis and respiration

Crop growth refers to the accumulation of dry matter (DM), which sometimes known as 'biomass' and is measured in weight per unit area (g/m^2 , kg/ha or t/ha). DM is the sum of carbon compounds from net daytime photosynthesis plus a small proportion of other elements from the soil, less night-time respiratory loss of carbon compounds. Nitrogen and minerals from soil usually comprise less than 6% of DM, but the proportion is greater for high protein grains because of the nitrogen therein (Connor et al. 2011).

Crop growth rate is determined as DM accumulation per day ($\text{g/m}^2/\text{d}$). Since roots are difficult to measure and unless stated otherwise, DM refers to above-ground parts of the crop.

Photosynthesis is the conversion of CO_2 to simple sugars by green leaves (and other green tissues) driven by energy from PAR. It is usually expressed as **net photosynthesis** because respiration (the breakdown of sugars into CO_2) continues in leaves even in sunlight. **Respiration** is an essential process for building the simple sugars from photosynthesis into the multitude of compounds found in plants (complex carbohydrates like cellulose and starch, and proteins and lipids), and for maintaining and defending the integrity of living cells. It continues day and night and for this reason is sometimes known as 'dark respiration'.

Respiration has two components: growth respiration and maintenance respiration.

Growth respiration can be quantitatively related to the compounds being synthesised. Thus 1.2 g of glucose is required to synthesise 1 g of carbohydrate, 2.5 g of glucose to synthesise 1 g of protein (starting with nitrate nitrogen), and 2.7 g of glucose to synthesise 1 g of lipid (Connor et al. 2011). **Maintenance respiration** is less well understood but relates to maintaining cellular processes. It is approximately proportional to the amount of living DM and highly sensitive to temperature (approximately doubling for each 10°C increase).

Crop plants are divided into two groups according to their initial photosynthetic product. C_3 crops include wheat, barley, rice and almost all dicot crops, while C_4 crops are largely confined to tropical monocots such as maize, sorghum, millet and sugarcane. Between these two groups (C_3 and C_4), there are substantial differences in the response of leaf net photosynthesis to PAR. As seen in Figure 2.2, C_3 crops reach PAR irradiance saturation at about 200 W/m^2 , but C_4 crops mostly never quite saturate in sunlight and have a higher **maximum value of net photosynthesis** (P_{max}) at full irradiance, given

in grams of CO_2 per square metre per day ($\text{g CO}_2/\text{m}^2/\text{d}$).²⁰ The light response curve for C_4 leaves also has a higher initial slope above about 25°C . Notwithstanding Figure 2.2, there is considerable variation in P_{max} within the C_3 and C_4 groups of crop species.

Differences between C_3 and C_4 leaves reflect processes that evolved in C_4 plants over the last 40 million years to eliminate the apparently wasteful so-called **photorespiration** of C_3 leaves. In photorespiration, Rubisco (the central photosynthetic enzyme) takes up oxygen at the same site in the enzyme as CO_2 , but the fixed oxygen eventually cycles back to be released in photorespiratory CO_2 , thereby reducing net CO_2 uptake. C_4 crops eliminate this apparently wasteful photorespiration by a unique leaf anatomy termed 'kranz anatomy'. For initial fixation of CO_2 , C_4 crops use a different enzyme, phosphoenol pyruvate (PEP) carboxylase, which has no affinity for oxygen. Rubisco remains the ultimate fixer of CO_2 in C_4 leaves, but the kranz anatomy ensures that the Rubisco is surrounded by high CO_2 concentrations released from the product of PEP carboxylation. This means C_4 Rubisco can fix CO_2 efficiently without photorespiratory wastage, as was presumably the case when C_3 photosynthesis first evolved several billion years ago, under high CO_2 and low oxygen levels.

There are other important differences between C_3 and C_4 crops. C_4 crop leaves are better adapted to higher temperatures (above $\sim 15^\circ\text{C}$, C_4 leaves tend to achieve higher photosynthetic rates than C_3 ones), less responsive to increased external CO_2 and more efficient with respect to photosynthesis per unit water lost (transpired) and per unit nitrogen invested in the leaf.

The last two mentioned differences between C_3 and C_4 photosynthesis serve to introduce the important (but here simplified) concepts of stomatal and mesophyll (or internal) conductance to CO_2 diffusion. 'Conductance' is the reciprocal of resistance to diffusion in gas physics. In photosynthesis, CO_2 diffuses from the air across the leaf boundary layer, through the stomatal pores into the air-filled leaf intercellular spaces, and then to the primary 'fixing' enzyme: Rubisco in C_3 plants and PEP carboxylase in C_4 plants (both located in the loose green mesophyll cells of every leaf). If the CO_2 movement in the mesophyll is assumed to also behave according to diffusion, and the CO_2 concentration is assumed to be zero at the site of initial CO_2 fixation, then the law of diffusion means that the intercellular CO_2 concentration is controlled by the stomatal relative to the mesophyll conductance. There is also a small influence of the boundary layer surrounding the leaf, but this influence can be ignored here for the sake of simple explanation.

Thus C_4 plants—with more efficient mesophyll photosynthetic machinery (i.e. higher mesophyll conductance) and a tendency for lower stomatal conductance—have under full irradiance markedly lower intercellular CO_2 concentrations of around 150 ppm (vs. 280 ppm with C_3 plants) when air CO_2 concentration is 370 ppm. This is the basis

²⁰ The most common unit for P_{max} these days is micromoles of CO_2 per square metre per second ($\mu\text{mol CO}_2/\text{m}^2/\text{s}$) obtained by multiplying grams of CO_2 per square metre per day ($\text{g CO}_2/\text{m}^2/\text{h}$) by 6.31.

of the higher innate transpiration efficiency of C_4 crops. It is achieved with a lower investment in nitrogen-rich photosynthetic enzymes, the reason for higher nitrogen efficiency of C_4 photosynthesis. These concepts are also important for understanding the smaller, but possibly more important, genotypic differences within crops.

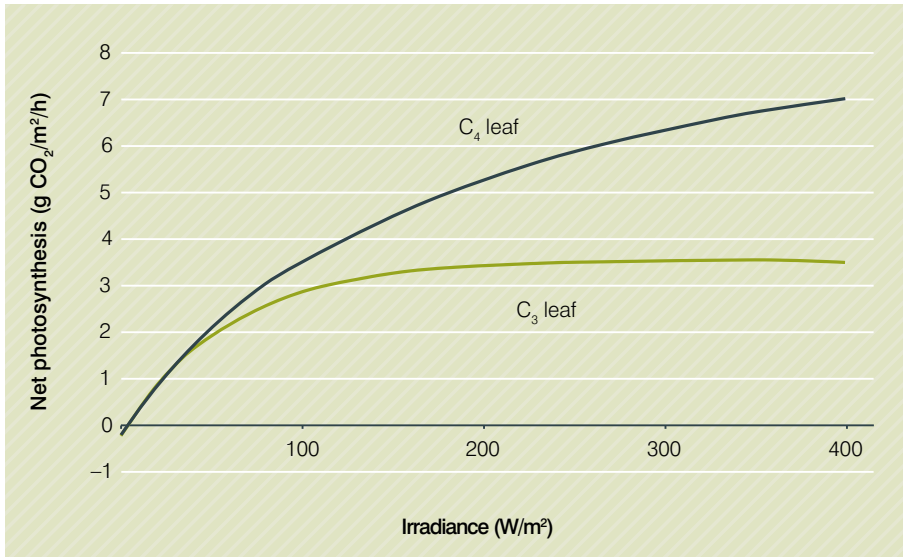


Figure 2.2 Response of leaf net photosynthetic rate to photosynthetically active radiation (PAR) expressed as irradiance. Source: adapted from Connor et al. (2011)

The leaf net photosynthetic rate vs. PAR irradiance response curve in Figure 2.2 is the principal building block for determining the photosynthesis of any crop canopy. However, the canopy comprises many leaves of different age and nutrient status (hence different photosynthetic capacity, as reflected in different P_{max} values), orientated at many angles to the vertical and illuminated by various angles of direct solar beam, which change with time. Moderately complex models can integrate all these factors if they can be measured, but crop physiologists usually take a simpler approach to the problem. To understand this, several aspects of the leaf canopy require definition.

A simplified quantification of the crop canopy is contained in the measure known as **leaf area index (LAI)**, which is the dimensionless ratio of the area of green leaves to the area of ground (m^2/m^2); if other green parts like stems and spikes are included, this measure can be called 'green area index'. Further, the penetration through the green canopy by solar PAR fits well a physical law: the proportion of PAR not intercepted at the bottom of the green canopy is an exponential function of the LAI (equation (1)).

equation (1) Interception of photosynthetically active radiation (PAR) by crop canopy

$$F_{\text{PAR}} = 1 - \exp(-K \times \text{LAI}) \quad (1)$$

where

F_{PAR} is the fraction of incident PAR intercepted by the canopy

K is the extinction coefficient (a unitless parameter between 0.3 and 1.0)

LAI is the leaf area (or green area) index (m^2/m^2).

The **extinction coefficient** increases with more horizontal leaves (i.e. with lower leaf elevation angle or inclination). The more erect the display of the leaves, the greater the LAI needed to maximise PAR interception. An LAI of 4–5 is sufficient for 90% interception of daily PAR in typical monocot crops at middle latitudes ($K = 0.5$, $F_{\text{PAR}} = 0.9$). Where $\text{LAI} > 4\text{--}5$, the crop is considered to have reached 'full light interception' because any greater LAI captures little extra PAR—thus, LAI would have to double in order to reach 99% interception (or $F_{\text{PAR}} = 0.99$). Adding greatly to the use of equation (1) was the advent of portable instruments that facilitate the measurement of F_{PAR} by green canopies.

Monteith (1977) proposed that crop growth rate be related to daily intercepted PAR, and crop DM accumulation to the cumulative daily intercepted PAR, finding that the slope of this relationship tended to be a stable number across the crop life cycle and reasonably stable for any crop across environments. This slope is defined as the **radiation use efficiency (RUE)** measured in grams of dry matter produced per megajoule (g DM/MJ). Notwithstanding limitations fully discussed in Mitchell et al. (1998), Monteith's (1977) ideas have subsequently become the basis of much relatively simple modelling of crop growth and yield under non-water-limiting conditions (equations (2) and (3)).

equations (2) and (3) Daily crop growth rate and accumulated crop growth. Source: Monteith (1977)

$$d\text{DM}/dt = \text{PAR}_i \times \text{RUE} \quad (2)$$

where

$d\text{DM}/dt$ is the dry matter accumulated daily ($\text{g}/\text{m}^2/\text{d}$)

PAR_i is the daily intercepted photosynthetically active radiation; in other words, daily incident PAR given by $(0.5 \times R_g)$, multiplied by F_{PAR}

RUE is radiation use efficiency measured in grams of DM produced per megajoule of PAR intercepted (g DM/MJ).

$$\text{DM} = \sum \text{PAR}_i \times \text{RUE} \quad (3)$$

where

DM is dry matter accumulated (g/m^2) over some period

$\sum \text{PAR}_i$ is the accumulation in daily time steps of intercepted PAR over the same period

RUE is as given in equation (2).

With progression from CO₂ uptake in photosynthesis to DM accumulation in RUE, dry weight of the initial sugar product (from photosynthesis) will be only 68% of the mass of CO₂ fixed because of oxygen released by photosynthesis. In addition, (dark) respiratory losses must be subtracted and minerals added. Finally, since RUE usually refers to above-ground DM, no account is made for net translocation of DM to roots. Early in the crop life cycle, DM investment in roots is significant—starting at root/shoot DM ratios of 0.5 to 1.0—but by anthesis in grain crops, this ratio is usually less than 0.15, after which there is little root growth.

Despite these caveats, many measurements subsequent to Monteith (1977) confirmed that RUE is a relatively robust crop-specific parameter (Mitchell et al. 1998; Sinclair and Muchow 1999; Stöckle and Kemanian 2009) very useful in crop modelling. Obviously canopy net photosynthesis—and by inference, RUE—is equal to the sum of net photosynthesis across all leaves in the canopy, but only some are exposed to the full solar beam perpendicular to the leaf surface (giving P_{max}). Many leaves in a canopy receive low levels of irradiance because they are at oblique angles to the solar beam and/or due to degrees of shading within the canopy. The situation under cloud, when diffuse radiation dominates, is even more complex.

It is obvious that leaves in a canopy operate at various levels of efficiency with respect to PAR depending on where they sit on the curve in Figure 2.2 and that this efficiency changes throughout the day. Nevertheless, three important general points are apparent:

1. Canopy photosynthesis does not saturate at high light—unlike individual leaves (Figure 2.2)—therefore canopies reach higher net photosynthesis rates per square metre than sunlit leaves (e.g. up to 10 g/m²/h).
2. Canopy RUE responds to change in P_{max} of the constituent leaves, other things equal. Detailed canopy models suggest that if leaf P_{max} increases by 1%, RUE in a wheat canopy at LAI = 6.5 will also increase but by a lesser relative amount depending on solar elevation (~0.2–0.4% according to Day and Chalabi 1988).
3. Most sun angles in most cropping environments are such that canopies with erect leaves are likely to achieve higher RUE, other things equal.

Thus C₄ crops, with higher P_{max}, show generally higher RUE values than C₃ crops. For growth before grain-filling under optimal conditions, the following general average RUE²¹ values and ranges were reported by Mitchell et al. (1998) and confirmed in Sinclair and Muchow (1999):

- maize (C₄) 3.3 g DM/MJ (range 2.3–4.1)
- wheat (C₃) 2.7 g DM/MJ (range 2.4–3.1)
- rice (C₃) 2.2 g DM/MJ (range 2.0–2.5)
- soybean (C₃) 1.9 g DM/MJ (range 0.9–2.7).

21 Note this refers to above-ground DM and was more correctly termed as the 'radiation conversion factor' in the thorough review by Mitchell et al. (1998). However, RUE is now the accepted term, and RUE is always expressed in this book relative to PAR.

Ranges in crop RUE, or within-crop variation, may seem to challenge the validity of RUE as a concept—especially as all the reported ranges related to well-managed and well-watered crops. Such challenge is countered by ease of RUE measurement and application of RUE in simple models to disaggregate crop growth into major and independent components (as in equation (3)). Also there is a reasonable (if empirical) understanding of RUE variation, attributed largely to environmental factors (i.e. higher RUE values with a higher proportion of diffuse radiation, or lower vpd). There have been few reports of effects due to variety in side-by-side comparisons, except that RUE tends to decline during grain-filling in older varieties. The generally lower RUE for soybean probably reflects the larger respiratory load associated with nitrogen fixation, and (during grain-filling) the higher energy content of soybean seed arising from high oil and protein content.

Regarding RUE and leaf inclination, again detailed canopy photosynthesis models provide evidence favouring erect leaves. Photosynthesis of a leaf at high irradiance is at or close to PAR saturation and thus uses PAR inefficiently (Figure 2.2). Erect leaves reduce the angle of incidence of the solar radiation—and hence the effective irradiance seen by the leaf—so PAR is used more efficiently. An early example is the canopy modelling of Loomis and Williams (1969), which shows the advantage of vertical leaves (leaf angle 90°); LAI needs to be greater than 3 to benefit from this effect, otherwise F_{PAR} may be too low. An ideal canopy would have erect leaves at the top, with less-erect leaves at depth. Small leaves and green structures, with relatively larger penumbral effects, also have the beneficial effect of scattering sunlight deeper into the canopy.

Crop growth, partitioning of dry matter and determination of potential yield

As the crop canopy is built, the products of photosynthesis are distributed by a process called ‘partitioning’, by which DM is distributed among major crop parts. Figure 2.3 illustrates this for irrigated spring wheat in north-west Mexico. Crop development (or phenology) is shown on the x-axis to set the temporal framework within which partitioning occurs.

As well as total DM production, Figure 2.3 shows the **partitioning of DM** into key crop parts. Thus crops first produce leaves (with an area to DM ratio of 200–300 cm²/g DM, depending on crop) in an exponential phase of growth until 100% PAR interception is approached (40–60 days after sowing under irrigation and high fertility). After the crop has reached full light interception, total DM accumulation becomes strictly linked to incident PAR and RUE—that is, extra leaves produced beyond this point will not much increase the proportion of light interception, because interception is already above 90%, a situation which continues until leaves start to senesce towards the latter half of grain-filling.

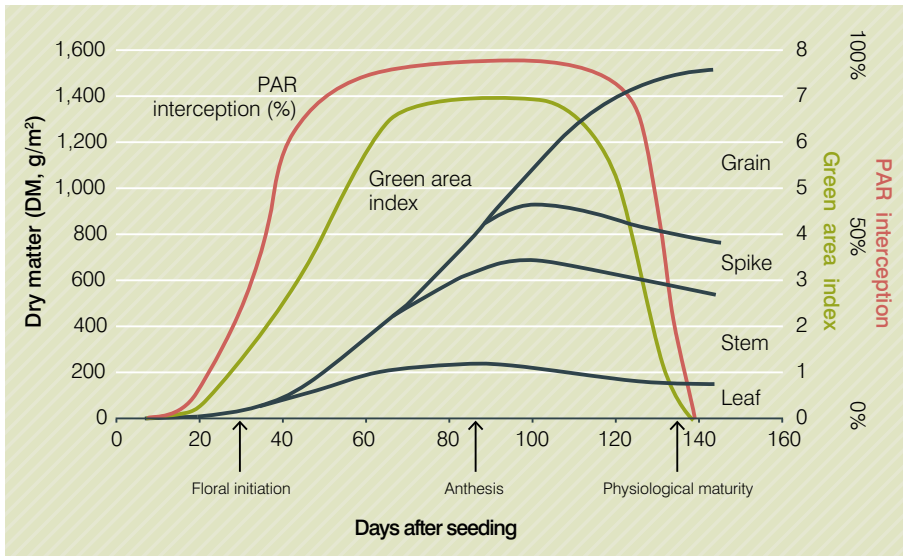


Figure 2.3 Evolution of green area index, photosynthetically active radiation (PAR) interception (%) and dry matter (DM) accumulation in crop parts as a function of days after seeding in spring wheat. Example for spring wheat grown under irrigation and high fertility in north-western Mexico. Crop parts are shown as the cumulative dry weights of leaf, stem, spike and grain. Source: adapted from Fischer (1984)

Stems begin to grow soon after floral initiation and then (some 20 days before anthesis) the spike (or inflorescence) also becomes an important sink (destination) for DM. Accumulation of grain DM begins soon after anthesis in Figure 2.3, reflecting the warm environment of north-west Mexico. Towards the later stage of crop development (in the latter half of grain-filling), the downturn of trendlines for stem and leaf suggests sources for some of the final grain DM. Studies with radiocarbon (^{14}C)-labelled carbohydrates confirm that DM accumulation in later grain-filling occurs largely through translocation of stored carbon compounds to the grain. This process is known as the contribution of pre-anthesis stored carbohydrate (and protein) to grain yield, commonly expressed as a percentage of total DM at anthesis or, alternatively, percentage of the grain yield.

A key outcome in Figure 2.3 is the **harvest index (HI)**, which is the ratio of grain DM, or yield (g/m^2), to final total crop DM above ground (g/m^2) at physiological maturity (often called 'biomass') expressed as a percentage or dimensionless ratio. As with RUE, HI is a robust crop parameter. HI depends on crop and variety, but less on environment under good management. HI is easy to measure, provided all senesced crop parts can be collected at physiological maturity, and provides a measure of breeding progress to which it is frequently referenced.

As with crop development, the exact pattern of crop growth varies among crops and varieties under the influence of the genetics-by-environment interaction, but the general pattern is similar for all grain crops. Thus the simple relationship of PY to DM and HI becomes useful to understanding yield changes in all grain crops (equations (4) and (5)).

equations (4) and (5) Potential yield (PY) as a function of dry matter (DM) accumulation

$$\mathbf{PY = DM \times HI} \quad (4)$$

in which DM (final dry matter in this case) can be substituted by equation (3) to give:

$$\mathbf{PY = \sum PAR_i \times RUE \times HI} \quad (5)$$

where

PY is potential yield in grams per square metre (g/m^2) at zero grain moisture in this equation

$\sum PAR_i$ is the cumulative intercepted photosynthetically radiation given in megajoules per square metre (MJ/m^2)

RUE is radiation use efficiency given in grams of dry matter per megajoule of PAR intercepted (or simply g/MJ)

HI is the harvest index, the ratio of grain dry weight to crop dry weight (above ground) at physiological maturity.

Equation (5) is the most common simple model of PY, and it is used as the basis for discussing breeding and agronomic progress in this book. Reference is also often made to P_{max} (and sometimes stomatal conductance) as surrogates for RUE when the latter may not have been measured.

Numerical components of grain yield

Before leaving the general physiology of PY determination, it is useful to present another simple model for grain crops that is used by many physiologists as equation (6).

equation (6) Potential yield (PY) as a function of numerical yield components

$$\mathbf{PY = GN \times GW} \quad (6)$$

where

PY (commonly in this case) is grain dry weight in grams per square metre (g/m^2)

GN is grain number, the number of grains per square metre of land area

GW is grain weight, the dry weight of individual grains in grams (g), but also often reported in milligrams (mg).

As with equation (5), the relative physiological independence of the components (in this case, GN and GW) makes equation (6) useful for understanding causality of PY; GN is usually the dominant determinant. An added advantage is the ease with which GW can be measured, and that grain number can be estimated from yield divided by GW (provided that errors are small). There is little advantage, however, in dissecting GN into its traditional numerical components (e.g. plants per square metre, inflorescences per plant and/or grains per inflorescence) because of their strong interdependence.

As mentioned, there is a **critical period for grain number determination**: that period of 20–30 days leading up to and shortly following flowering. Potential GW is determined by events at and after flowering. The critical GN period is demonstrated by the increased sensitivity of GN to environmental change (e.g. solar radiation) during this stage of crop development, and further aids yield analysis by linking GN to equation (2) and Figure 2.3. Thus grain number has been related to one or more of the following traits:

- crop growth rate in the critical period for grain number—that is, from 20–30 days before flowering to 10 days afterwards in determinate crops or, in maize, from 15 days before silking to 15 days afterwards
- ability of the variety to partition photosynthetic products to the developing reproductive organs in this critical period—along with crop growth rate, partitioning ability determines dry weight of inflorescences
- ability to build many fertile florets per unit inflorescence dry weight.

It is notable that the critical period for grain number (at least in wheat and rice) is also when the aforementioned water-soluble carbohydrates are being accumulated in stems for later translocation to the growing grains. Therefore grain number and grain weight in such crops may not be as independent as originally proposed because carbohydrate availability per floret around flowering also affects the survival of florets (Slafer et al. 2009) and potential weight of grains, at least in wheat (Calderini et al. 2001).

Determination of key yield components in relation to flowering holds well for determinate crops (like wheat, rice or maize), but may seem less clear-cut in indeterminate crops (like soybean, rapeseed or pulses) with long flowering periods. Nevertheless, the determination of grain number in soybean (e.g. Slafer et al. 2009) and canola (Mendham and Salisbury 1995) does seem to fit this model relating grain number to DM accumulation during flowering.

Reference to grain number raises one final important notion with respect to photosynthesis: that of **source–sink relations**, a term commonly used by crop physiologists. The source is considered to be the photosynthetic tissue (but can also include temporary storage tissues), while the sink is the growing organ to which the products of photosynthesis are being translocated. During grain-filling the sink clearly comprises the grains growing to reach some given potential size. It is often argued that during this period, crop photosynthesis can actually be limited by the grain sink (or demand) for the products of photosynthesis. This appears to be the case when there is a large photosynthetic area relative to the number of grains; artificially decreasing the photosynthetic area can increase the photosynthetic rate of the remaining leaves, or

artificially increasing grain number in novel experiments can have the same effect. It remains uncertain whether sink limitation of photosynthesis can occur before grain-filling. The relative stability of RUE before grain-filling suggests that such sink limitation at that time is unlikely, but RUE is often observed to decline during grain-filling.

Determination of water-limited potential yield

Some changes to the above schema for PY determination are needed to deal with performance under water-limited conditions (i.e. PY_w). Water limitation implies insufficient supply of water for crop evapotranspiration (ET) to reach the maximum for the particular crop (i.e. ET_p). For water-limited crops, total ET may lie between 5% and 80% of ET_p .

For PY_w determination, again it is easiest to relate DM production to the limiting resource, which in this case is water. A simple expression, coming originally from Passioura (1977), facilitates this and lies behind much of the simulation modelling of PY_w (equation (7)).

equation (7) Simple expression of water-limited potential yield (PY_w). Source: Passioura (1977)

$$PY_w = T \times TE_1 \times HI \quad (7)$$

where

PY_w is the water-limited potential yield measured in kilograms per hectare (kg/ha)

T is transpiration (amount of water transpired by the crop) measured in millimetres (mm)

TE_1 is transpiration efficiency, measured in kilograms dry matter (DM) produced per hectare per millimetre of transpiration (kg/ha/mm)

HI is the harvest index.

Furthermore, a simple but useful and robust variant of equation (7) was developed for wheat crops in South Australia by French and Schultz (1984) (equation (8)).

equation (8) Water-limited potential yield (PY_w) from water supply, transpiration efficiency and harvest index. Source: French and Schultz (1984)

$$PY_w = (ET - E_s) \times TE_1 \times HI \quad (8)$$

where

PY_w is the water-limited 'potential' yield in kilograms per hectare (kg/ha), using kg units to accommodate the common units for transpiration efficiency (TE)

ET is evapotranspiration (crop water use) measured in millimetres

E_s is soil evaporation in the crop from seeding to physiological maturity

TE_1 and HI are as defined for equation (7). Note that French and Schultz (1984) originally called $TE_1 \times HI$ the 'maximum water use efficiency', but this term has since come to mean many things and is not used in this book.

ET is equal to transpiration (water consumed through the plant) plus evaporation from the soil (E_s). ET of a field crop is only weakly dependent on crop leaf area index (LAI) as long as the soil surface is wet. This is because the solar radiation that reaches an unshaded wet soil surface (i.e. in the absence of a growing crop, crop residue or mulch) will drive as much soil evaporation as would have occurred as transpiration if the soil surface had been shaded by leaves. Thus transpiration and soil evaporation are relatively independent, but the latter decreases markedly when the soil surface dries. Note that transpiration (T) in equation (7) equates in equation (8) to ET less E_s .

French and Schultz (1984) set E_s at 110 mm, a reasonable assumption for many soils and annual crops. E_s is essentially a loss to the crop. For wheat in southern Australia at the time, French and Schultz (1984) found that the maximum slope ($TE_1 \times HI$) for yield vs. ET attained by the best crops was ~ 20 kg grain/ha/mm. Note, however, that the original French and Schultz equation (from which equation (8) is derived), defines a 'grain yield frontier' (at 12% grain moisture) attained by farmers with the best varieties and management; strictly speaking, this 'frontier' is the water-limited attainable yield (as defined in Section 2.1), which may lie somewhat ($\sim 30\%$) below true PY_w as defined for this book.

Equation (8) was developed to demonstrate a target water-limited attainable yield for farmers, but, as reviewed by Passioura and Angus (2010), the equation proves valuable as a simple model for understanding PY_w given that the three components (i.e. $(ET - E_s)$, TE_1 and HI) remain relatively independent. Equation (8) emphasises the notion that water supply is central to PY_w , as reflected in the ET term (discounted by E_s). Thus equation (9) offers a description of ET.

equation (9) Determination of evapotranspiration (ET) by water supply

$$ET = \Delta S + P - \text{losses} \quad (9)$$

where

ΔS is equal to the change in millimetres (mm) in soil water between seeding and physiological maturity, thereby picking up the contribution of any soil water stored in the fallow period prior to seeding. ΔS can reach (but never exceed) the plant available water-holding capacity (PAWC) for the particular crop–soil combination if seeding occurs into a 'full' profile of soil water

P is precipitation in millimetres (mm) during the crop cycle

losses refer to precipitation in millimetres (mm) lost to deep drainage below the root zone or surface run-off during the crop cycle.

In concluding discussion of crop physiology through simple equations, determination of transpiration efficiency (TE) is now explored. Apart from water supply, TE is the main factor in equation (8) that links PY_w to climate. Crops transpire water largely through open stomata in their leaves. This is an inevitable consequence of opening stomata to permit CO_2 uptake for photosynthesis, a process that exposes the water-saturated

inner leaf surfaces to water loss to the atmosphere. TE is linked to the ratio of CO₂ taken up to water lost, but the CO₂ uptake is converted to weight of carbohydrate photosynthesised to calculate TE. As for RUE, TE is also subject to upper limits. The limit is higher for low intercellular CO₂ concentration of the photosynthesising leaves, and is separately modified by the relationship between transpiration rate and the prevailing dryness of the air (equation (10)).

equation (10) Inverse relationship between transpiration efficiency (TE) and the prevailing dryness of air in crop canopies. Source: Tanner and Sinclair (1983)

$$TE_2 = k/vpd \quad (10)$$

where

TE₂ is the dimensionless ratio between weight of dry matter accumulated to that of water transpired (reciprocal of the longstanding transpiration ratio).[†]

k is a crop-dependent efficiency factor between vpd and TE₂, given in pascals (Pa). It is negatively related to the intercellular CO₂ concentration in the leaf, which (being less than ambient CO₂ concentration) determines the rate of diffusion of CO₂ into leaves.[‡]

vpd is vapour pressure deficit given in pascals (Pa). It refers to the appropriate daytime average vpd (when stomata are open) and is about two-thirds of the daily maximum vpd (Stöckle and Kemanian 2009). Since the intercellular spaces of the leaves are always saturated with water vapour, vpd determines the gradient for water diffusion out of the leaf.

[†]Dimensions given to TE in equation (7) (kg/ha/mm) conveniently convert to a dimensionless weight ratio simply by dividing by 10,000 (because 1 mm of transpiration over 1 ha is 10,000 kg of water). Thus 50 kg/ha/mm (a typical value for DM production) becomes 0.005 kg/kg or simply 0.005 (a transpiration ratio of 200).

[‡]Apart from being higher for C₄ than C₃ crops, k is considered to be relatively stable for each crop and hence is a valuable term for crop models.

The lower intercellular CO₂ in C₄ leaves means a greater gradient for CO₂ diffusion into the leaf, causing higher k and TE₂, other things equal. Thus the value of k is about 9 Pa for maize and sugarcane, 6 Pa for wheat and rice and 5 Pa for soybean (Sinclair 2010). Since the original work of Tanner and Sinclair (1983), it has been recognised that stomata tend to close in response to increasing vpd—this decreases intracellular CO₂ concentration and thus k increases as daytime vpd increases across the whole range of values encountered (e.g. 0.5–3.0 kPa). Therefore, the decline in TE₂ with rising daytime vpd is somewhat less than equation (10) would predict (Kemanian et al. 2005). This is not the same as stomatal closure in response to soil water shortage, which also increases TE₂ (other things equal), but it can be difficult to distinguish between the two responses.

Important general considerations for crop transpiration efficiency are the spatial variation in vpd (increasing markedly from humid to arid regions), and the seasonal march in vpd (lowest in mid winter or in the wet season; highest in midsummer or the dry season).

Harvest index (HI)—the last component in the water-limited conditions shown in equation (8)—becomes less stable and tends to be lower because water becomes scarce during grain-filling. Thus transpiration is often constrained at a time when TE is lower due to vpd increase during grain-filling, and grain growth and HI suffer in a reasonably quantifiable way (Sadras and Connor 1991). Other aspects of water limitation bearing on HI, such as the sensitivity of grain number to water shortage, are introduced in Section 9.6.

Agronomic studies often refer to water productivity or water use efficiency (WUE), given as yield per unit of water use (kg/ha/mm). It is important to define water use in this context: it is commonly ET but can refer to other measures (e.g. water supply such as rain or irrigation).

2.7 Concluding remarks

To cover the broad principles of crop physiology in a few pages inevitably cuts many corners, but the aim is to provide a foundation for much of the following discussion of yield progress and prospects. The interested reader is referred to Sadras and Calderini (2009) and Connor et al. (2011) for greater detail. The terms introduced here (and a few others that appear elsewhere in this book) are listed in the Glossary.

Chapters 3–7 move to looking at the yield performance of individual crops to seek the genetic, agronomic and socioeconomic factors behind yield progress. This is facilitated by defining (at the outset of each single commodity chapter) the **major mega-environments** around the world in which the commodity is grown. This is a term developed by the International Maize and Wheat Improvement Center—otherwise known as *Centro Internacional de Mejoramiento de Maíz y Trigo* (CIMMYT)—to facilitate research targeting maize and wheat, but it is a useful tool for all crops. Mega-environment is a commodity-specific term, and refers to broad (but not necessarily contiguous) areas facing similar agroecologies in terms of weather, abiotic and biotic stresses, and cropping system requirements for the crop under consideration.

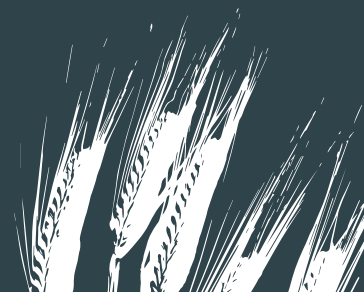
Wheat

3



Key points

- World wheat production in 2010 approached 675 Mt. Harvested area has remained steady, but global average farm yield (FY, at close to 3 t/ha) is increasing at a current rate of 1% p.a. (relative to 2010 yield).
- For each of the major wheat mega-environments (WMEs), detailed case studies presented in this chapter have explored farm yield (FY), potential yield (PY) and yield gap, and their respective rates of change over the past 20–30 years. Twelve of these case studies contributed to the values quoted in the key points below.
- The current rate of wheat FY increase ranged between 0.3% per annum (p.a.) and 1.7% p.a. (relative to FY around 2010); northern France at 0.3% p.a. was the only non-significant ($P > 0.10$) slope.
- The current rate of wheat PY increase showed a global average of 0.6% p.a. (relative to PY around 2010); it ranged between 0.3% p.a. and 1.1% p.a. and was significant ($P < 0.10$ or better) in all cases. Progress rates did not appear to vary between dry and humid environments, or for spring vs. winter wheat.
- The global average wheat yield gap was 48% of FY. The range was surprisingly narrow (26–69% of FY), but the gap was clearly smaller in developed countries (especially western Europe, with a low average of 30% of FY).
- Wheat yield gaps appear to be closing very slowly; the global average rate of change is -0.2% p.a. (range -1.0% p.a. to $+0.8\%$ p.a.). Notable adoption of yield-increasing agronomic technologies has been observed in only some cases (e.g. Western Australia and parts of China). In western Europe, wheat yield gaps are increasing where regulations may be slowing FY progress.
- The results emphasise the importance of raising PY as the primary means for future wheat FY increase. Further FY increases from yield gap closing through adoption of better agronomy will be possible (especially in developing countries) but will involve complex incremental changes in multiple technologies.
- Increased PY in wheat is associated with increased grain number (GN) and harvest index (HI) and, lately, increased grain weight (GW) and total dry matter (DM). There have also been several reports of increases around spike emergence in radiation use efficiency (RUE), leaf photosynthesis (P_{\max}) and stomatal conductance, and greater stem-stored carbohydrate at anthesis.



Wheat

3.1 World wheat and its mega-environments

In 2008–10, annual world production of wheat (bread wheat, *Triticum aestivum*, plus durum wheat, *Triticum turgidum*) was 674 Mt (Table 3.1)—a 24% increase from 544 Mt 20 years prior. The major producers shown in Table 3.1 are listed in order of dominance, with China leading (at 17% of global production), followed by India (12%), the United States of America (USA) (9%) and the Russian Federation (8%).

Table 3.1 Annual wheat production, harvested area and yield in 2008–10 for major producing countries and annual rates of change from 1991 to 2010

Country	Average 2008–10			Rate of change ^b (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^a (t/ha)	Area	Yield
World	673.7	221.5	3.04	ns -0.1	1.0
China	114.3	24.1	4.75	-2.0	1.7
India	80.0	28.1	2.85	0.7	0.9
USA	62.8	20.7	3.04	-1.6	0.9
Russian Federation	55.7	24.8	2.22	ns 0.3	1.6
France	38.5	5.4	7.20	0.5	ns 0.3
Canada	26.2	9.3	2.81	-2.5	1.1
Germany	25.1	3.2	7.74	1.4	0.7
Pakistan	22.8	8.9	2.55	0.5	1.7
Australia	21.7	13.6	1.60	2.3	ns -1.0
Ukraine	21.2	6.7	3.15	ns 0.6	ns -0.4

a What FAOSTAT calls 'yield' this book calls 'farm yield' (FY); see Chapter 2 on definitions.

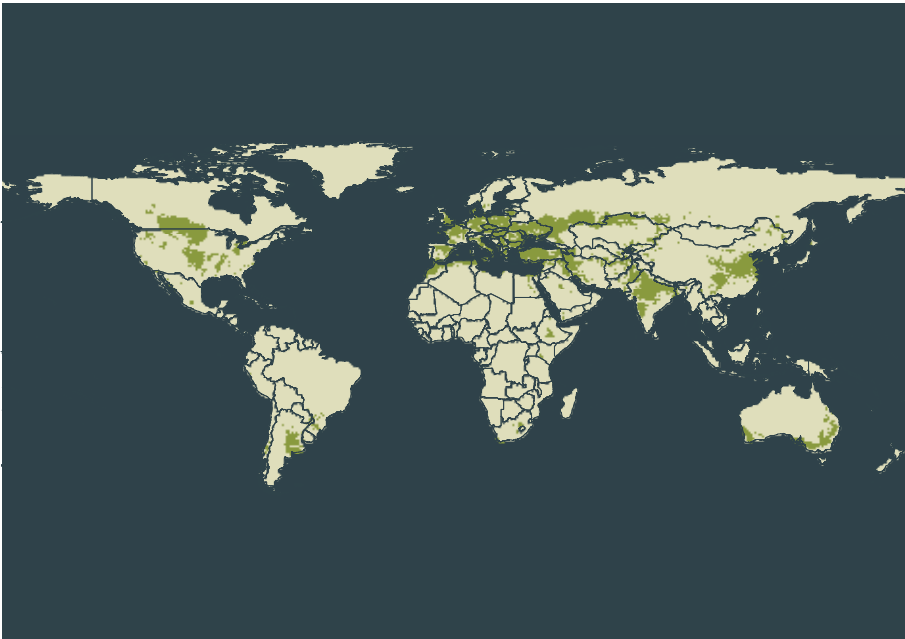
b Relative to 2008–10 average; ns = not significant at $P > 0.10$; all others significant at $P < 0.10$ or better

Source: FAOSTAT (2013)

The distribution of world wheat area around 2000 is shown in Map 3.1. World wheat area peaked in 1981 at 239 Mha, then fell steadily to a low of 208 Mha in 2003, after which began a slow rise to 222 Mha in 2008–10. Over the past 20 years there have been significant declines in wheat area in Canada, China and the USA, partly balanced by rises in India and Australia (Table 3.1).

Among the major producers, average wheat yield ranges from <2 t/ha to >7 t/ha. Of special interest over the last 20 years is the apparent absence of significant yield increase in France, Ukraine and Australia (Table 3.1); the situation for Australia and France will be discussed in Sections 3.5 and 3.8, respectively.

Wheat is widely traded, with exports amounting to 134 Mt (2008–10) or 20% of global production. Major net exporters according to FAOSTAT (2013) are the USA (27 Mt), France (18 Mt), Australia (16 Mt), Canada (15 Mt) and the Russian Federation (14 Mt). Although traditionally a large exporter, Argentina has fallen to eighth place, with only 6 Mt of exports in 2008–10.



Map 3.1 Global distribution of wheat area circa 2000. Source: Harvest Choice project, International Food Policy Research Institute; data from You et al. (2009a)

The global wheat mega-environments (WMEs) presented in Table 3.2 are derived from those delineated in the 1980s for developing nations by the International Maize and Wheat Improvement Center—otherwise known as *Centro Internacional de Mejoramiento de Maíz y Trigo* (CIMMYT)—to assist targeting of its wheat breeding program. The WMEs have been refined several times since (e.g. Lantican et al. 2005; Braun et al. 2010) and are presented in Table 3.2 in an updated and slightly modified form to include the whole world.

The growth habits of wheat varieties form the basis of the WME system. Thus spring wheats show little or no need for (or response to) vernalising cold ($T_{\min} < \text{about } 15\text{ }^{\circ}\text{C}$) to switch from vegetative to reproductive growth (see Section 2.6 on weather and soil parameters). At the other extreme, winter wheat varieties have an obligate need for many hours of vernalising cold, while facultative cultivars are intermediate in habit, responding notably to vernalising cold. Thus WME1 to WME5 comprise late autumn to early winter sown spring wheat environments, with T_{mean} between $5\text{ }^{\circ}\text{C}$ and $17.5\text{ }^{\circ}\text{C}$ in the coolest month for WME1 to WME4, but greater than $17.5\text{ }^{\circ}\text{C}$ for WME5, which is found only between latitudes $25\text{ }^{\circ}\text{S}$ and $25\text{ }^{\circ}\text{N}$. WME6 follows with spring-sown spring wheats at high latitude. Then finally in Table 3.2, there are autumn-sown facultative (WME7 to WME9) and winter wheats (WME10 to WME12) grown at middle latitudes.

Several WMEs in Table 3.2 arise from divisions made according to moisture supply, where low to moderate rainfall (WME4 and WME12) limits average crop evapotranspiration (ET) to less than about two-thirds of potential evapotranspiration (ET_p)—less than $\sim 350\text{ mm}$. Note that the contribution of irrigated and high rainfall WMEs to global production will be more than the area proportion shown in Table 3.2 because of their higher yields (see the section ‘Estimated wheat yield and yield change by wheat mega-environment’, below).

Some major producing countries contribute to several major WMEs. China, the world’s largest wheat producer, has 64% of its wheat area in WME10 and 26% in WME1. The Russian Federation has about 50% in WME6 and 50% in WME11. The US wheat area includes contributions in WME1 (2%), WME6 (30%), WME11 (16%) and WME12 (52%).

The shaded cells in Table 3.2 highlight the ‘breadbasket’ regions vital to wheat food security. Yield progress and prospects in representative cases within each region are discussed in detail according to WME categories (WME1 to WME12) later in this chapter. Where WME separation has not been possible, some lumped national statistics are presented. Attention is given to the latest reports, preferably with varieties from the last decades for up-to-date estimates of yield potential progress. Readers are referred to Lantican et al. (2005) for a global listing of wheat breeding progress studies up to the late 1990s.

Table 3.2 Wheat mega-environments (WMEs), relative areas and major producing regions

WME	Moisture ^a	Latitude ^b	Global wheat area (%) ^c		Major regions	
			Developing	Developed ^d	Developing	Developed ^d
Spring wheat						
1	Irrigated	Low	17	0	Mexico, Indo-Gangetic Plain, southern China, Egypt	
2 ^e	High rainfall	Low	5	0	Wet northern Africa, southern Brazil	
4	Low–moderate rainfall	Low	8	7	Dry northern Africa	Australia, Mediterranean Europe
5	Irrigated	Low, hot	2	0	Bangladesh, Sudan, Brazilian Cerrado	
6	Low–moderate rainfall	High	2	18	North-eastern China	Canada, Finland, northern Asia
Winter (and facultative) wheat						
10 ^f	Irrigated	Middle	5	1	North China Plain	
11 ^f	High rainfall	Middle	1	22		Eurasia, eastern USA
12 ^f	Low–moderate rainfall	Middle	6	5	Anatolia, Iran	Great Plains and Pacific North-west (USA)
Total			47	53		

a 'Low–moderate' rainfall is 200–500 mm; 'high' rainfall is >500 mm.

b 'Low latitude' is less than about 35°–40°; 'middle latitude' is about 35°–50°; 'high latitude' is greater than about 45°; 'hot' refers to environments with $T_{\text{mean}} > 17.5$ °C in the coolest month, January in the northern hemisphere and July in the southern.

c Shaded areas refer to major wheat regions (or 'bread baskets') vital to wheat food security.

d 'Developed' includes countries of the former USSR ('transitional economies')

e WME2 includes WME3, which has an acid soil component but is otherwise similar to WME2.

f In this simplified analysis, WME10, WME11 and WME12 include WME7, WME8 and WME9, respectively, where facultative rather than winter wheats tend to be grown.

Source: CIMMYT Wheat Program (e.g. Braun et al. 2010, see text), but updated with percentages of the global 2008–10 wheat harvested area (average 222 Mha)

3.2 WME1—Yaqui Valley, Mexico

Introduction

Irrigated spring wheat of WME1 occupies ~34 Mha in the developing world (especially in northern South Asia, southern China and Egypt; Table 3.2) and is probably the most important WME for world food security. The Yaqui Valley in the state of Sonora in north-west Mexico (Map 3.2) is representative of WME1 and has been the site of the wheat breeding operations of CIMMYT and its predecessor organisation for more than 50 years.

3



Map 3.2 Yaqui Valley irrigation area in Sonora, Mexico, and *Centro Experimental Norman E. Borlaug* (CENEb) research station

Irrigated spring wheat is the main crop in the Yaqui Valley and is grown each winter–spring season (i.e. November–April, when average total rainfall is only 60 mm). The region is near a seaport, and grain and input prices now appear close to world parity. However, there are several differences between this wheat environment and other regions of WME1:

- Overall, the climate of the Yaqui Valley is somewhat more favourable than most other WME1 areas—proximity to the coast provides a cooler grain-filling spring environment and the desert environment means higher solar radiation.

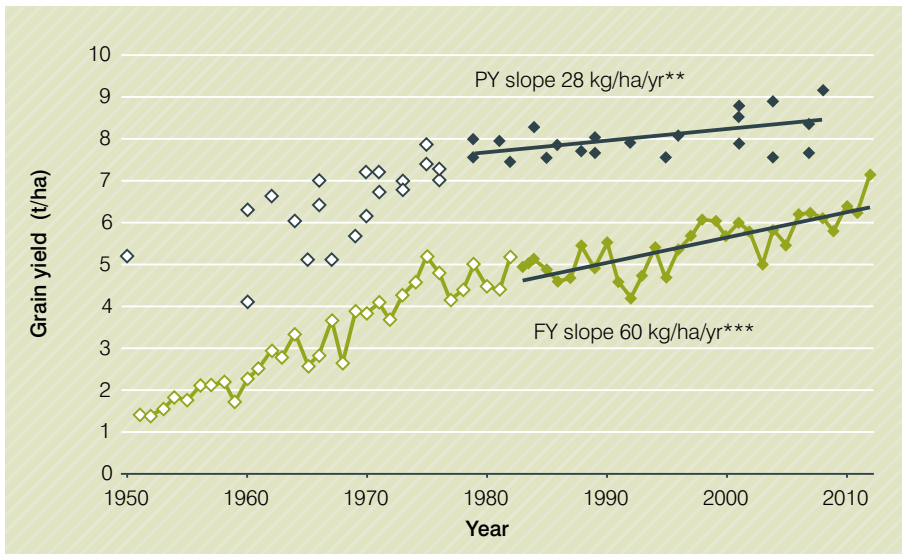
- By the standards of developing-world irrigated areas, farm size ranges from medium to large—average farm size is about 20 ha, with a range from less than 10 ha to more than 150 ha. Typical field size is about 10 ha (Lobell et al. 2007).
- Unlike Asia—where wheat is usually double cropped with summer paddy rice—there has been little summer cropping in the Yaqui Valley since 1996 because of lack of irrigation water.

The Yaqui Valley has been heavily targeted by wheat research and development since the late 1940s and is the birthplace of the wheat varieties of the green revolution (see Section 1.1). Moreover, wheat performance in the valley has been well documented in the past 20 years, including a recent substantial publication on both this and related agricultural issues of the region (Matson 2012).

The Cajeme Irrigation district (latitude 27 °N) dominates irrigated cropping in the Yaqui Valley and its statistics are those to which this section refers under the heading 'Yaqui Valley'. The district is relatively uniform topographically, with a current annual wheat area of 150,000–180,000 ha. From 1945, wheat there became the object of substantial research and development effort by Dr Norman Borlaug and the *Oficina de Estudios Especiales* (Office of Special Studies), later merging into the CIMMYT Wheat Program in 1966. This program has continued ever since, operating at the central Yaqui Valley research station, *Centro Experimental Norman E. Borlaug* (CENEB),²² in collaboration with the Mexican government agricultural research institute—known as *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias* (INIFAP).

The impact of the green revolution can be seen quite clearly when Yaqui Valley farm yield (FY; see Chapter 2 on definitions) is plotted from 1950 to the present (Figure 3.1). FY increased dramatically in the first 30 years, from 1.4 t/ha in 1950 to almost 5 t/ha in 1980 (equivalent to >4% p.a. exponential growth). FY increase occurred more slowly thereafter, although 2011–12 delivered a record yield of 7.2 t/ha. Progress in potential yield (PY; see Chapter 2) in the valley has been measured many times in sets of historic and new varieties grown side-by-side at the CENEB research station. Figure 3.1 presents measurements between 1990 and 2010, as explained in the caption, using optimal agronomy and fungicide for complete disease control. Figure 3.1 combines bread wheat (BW) and durum wheat (DW) varieties, the latter assuming major importance in the last 30 years in the valley, caused especially by higher durum prices. These recent changes in FY and PY, and the gap between them, are now examined in considerable detail because the Yaqui Valley is a critical bellwether for world wheat, especially in WME1.

²² Before 2010, CENEB was known as *Centro de Investigaciones Agrícolas del Noroeste* (CIANO).



** $0.01 < P < 0.05$, *** $P < 0.01$

Figure 3.1 Wheat farm yield (FY) plotted against year, and potential yield (PY) plotted against year of release, in the Yaqui Valley, Mexico, from 1950 to 2012. PY values are for both bread and durum wheat varieties (see text) determined in numerous on-station protected vintage experiments from 1990–91 to 2009–2010, under optimal agronomy (K.D. Sayre and R.A. Fischer, unpublished data 2010). Results were corrected for year of experiment by use of a common control cultivar (Siete Cerros 66). Regressions refer to the past 30 years only (shown as solid symbols) and are given for 1983–2012 for FY and 1979–2008 for PY. Source: FY values for the Cajeme Irrigation District from SIAP (2012)

Wheat farm yield and potential yield progress in the Yaqui Valley

Modern semi-dwarf varieties first appeared in 1962 and in less than 5 years occupied the whole district. Bell et al. (1995) analysed sources of progress from 1968 to 1990 when varieties were further improved. They concluded that variety improvement contributed 28% of FY increase and increased use of nitrogen fertiliser—which rose from 80 to 230 kg N/ha—contributed 48%.

The average annual rate of FY increase has clearly slowed since 1950 (Figure 3.1). Because of surprisingly large annual fluctuations for an irrigated crop, **current FY progress is estimated over the past 30 years** (rather than 20 years as generally

shown throughout this book). The rate of FY progress from **1982 to 2011 was 60 kg/ha/yr, or 0.9% of the estimated 2011 FY of 6.4 t/ha**. However, persistent weather changes in the Yaqui Valley—warming (Bell and Fischer 1994) and later cooling (Lobell et al. 2005a)—can confound the interpretation of yield change over time.

Remarkably, average minimum temperature (T_{\min}) (January to April) fell from about 10.2 °C to 8.2 °C across the 30-year period 1983 to 2012 (slope -0.070 °C/yr; $R^2 = 0.393$; $P < 0.01$); average maximum temperature (T_{\max}) and solar radiation (R_s) showed no significant trend. Wheat yield usually increases when T_{\min} declines (Fischer 1985a), which suggests that FY progress in Figure 3.1 ought to be corrected for this unusual cooling.

Lobell et al. (2005a), using the first difference method, determined a slope between the annual anomalies in yield and those in T_{\min} of about -456 kg/ha/°C for the Yaqui Valley FY from 1988 to 2002. Sensitivity to T_{\min} was confirmed by their independent simulation modelling, but there appeared to be no significant effect of T_{\max} or R_s fluctuations on yield. For the longer regression period 1982–2011 of Figure 3.1, the first difference analysis showed a slope of -368 kg/ha/°C change in T_{\min} . Applying this number to the steady decline in T_{\min} in the 1982–2011 period suggests a yield increase of 26 kg/ha/yr in the Yaqui Valley **due to cooling alone. By difference this leaves only 34 kg/ha/yr (or 0.5% p.a.) progress in FY from other factors, including technical progress.**

PY progress was initially rapid, estimated at greater than 1% p.a. (Fischer and Wall 1976; Bell et al. 1995; Traxler et al. 1995; early years in Figure 3.1). Traditionally, BW and DW varieties have shown similar PY to each other, but when the varietal releases over the past 30 years are analysed separately, BW varieties showed a lower slope of progress of 10 kg/ha/yr ($P < 0.10$) or 0.1% p.a. of their estimated 2007 release PY of 8 t/ha, while DW varieties achieved a higher slope of 38 kg/ha/yr ($P < 0.01$; 0.4% p.a.), while reaching a 2008 release PY of 9 t/ha. Since the Yaqui Valley presently grows both BW and DW, for the purposes of this book, **a combined PY slope of 28 kg/ha/yr (0.3% p.a.) is used as the estimate of current PY progress at CIMMYT in the Yaqui Valley (Figure 3.1).**

Nalley et al. (2010), using the same BW data source as in Figure 3.1 to estimate PY, derived a slope of 38 kg/ha/yr, or 0.4% p.a. of the estimated 2001 release PY. The somewhat higher slopes may reflect the inclusion of older varieties (releases between 1962 and 2001) and of plots without (as well as with) fungicide. Lopes et al. (2012) reported yield progress for the best CIMMYT advanced BW lines tested in the Yaqui Valley and at three other high-yielding WME1 locations: taking lines released during 1994–2008 gave a PY slope of 0.6% p.a. of the estimated 2008 release PY. Other recent independent estimates of PY progress at CENEB show 0.4% p.a. PY increase in BW varieties released between 1966 and 2009 (Aisawi 2011), and 0.4% p.a. for 1966–2012 BW and DW releases together, with a somewhat higher rate for BW compared with DW (K.D. Sayre and B. Goevarts, unpublished data 2012). All these estimates are slightly more than that derived from Figure 3.1, probably because they have not met all the conditions applied to calculating the PY value (0.3% p.a.) settled above.

Considerable attention has been given here to estimating the current rate of PY progress in the Yaqui Valley because the CIMMYT wheat breeding effort, focused *inter alia* on this target, is one of the largest and most critical for WME1. It is noteworthy that all estimates point to slower progress now than in the past, but also that this slow progress does not support the claims (without supporting evidence) that progress has ceased.

Wheat yield gap in the Yaqui Valley

Calculation of yield gap requires confidence in the PY estimate. Certainly experimental management at CENEB for the PY data in Figure 3.1 was appropriate for PY estimation. However, when a single central site (the CENEB experiment station) is used to estimate the PY, it needs to be representative of the Cajeme District. The station's soil type (compacted clay) is less favourable to wheat than the district average. Farm yields across soil types in the district (Lobell et al. 2002) and the proportions of each soil type suggest that, other things equal, compacted clay would yield 6% less than the overall district average. Given this and the fact that Cajeme District grew 80% durum wheat in 2009–12, **it is concluded that the relevant PY for 2012 is probably close to 9 t/ha. With FY estimated at 6.4 t/ha, this gives a yield gap of about 2.6 t/ha (or 41% of FY)**; Figure 3.1 also indicates that the yield gap is closing very slowly. Although recent FY and PY values have been favoured to some extent by unusually low T_{\min} values, this does not affect the yield gap estimate.

High-resolution satellite images of the Yaqui Valley (two to four measurements of green groundcover per wheat season) offer a unique approach to understanding the yield gap. When combined with an algorithm using observed R_s and temperature, the images permit a reasonably accurate estimation of crop yield at high resolution (pixels 30 m × 30 m), from which the yield of each field can be calculated (Lobell et al. 2002; 2003). Aspects of the FY distributions for all wheat fields in the Yaqui Valley are shown for three years in Table 3.3. Field FY showed negative skewness (i.e. more low yields than expected from a normal distribution). This is common with such samples and is attributed, in favourable environments, to the existence of a maximum district yield, which limits all farmers (e.g. Park and Sinclair 1993). Lobell et al. (2002) concluded that the spatial yield variation was dominated annually by management variation between fields (see below), while soil class effects were relatively small.²³

²³ Later analyses have looked at the temporal variation in yield (across years in given fields, controlled for change in annual average regional yield), which is smaller than the spatial variation across fields in any year (Lobell et al. 2007). More striking is the gap of about 2.5 t/ha in any year between the maximum and average yields. As more years are added to the sample for these same 'maximum' fields, this value declines at a rate equal to what would be expected if field-to-field yield variation were random (Lobell et al. 2009). Surprisingly, therefore, successful management influences do not appear to persist in a given field, possibly because the 'best' management changes with the observed weather of each year, which is difficult to anticipate.

Table 3.3 Wheat potential yield (PY) and key statistics of remotely sensed individual FY of each wheat field in the Yaqui Valley, Mexico, in 3 years

Yield measure	Year and yield (t/ha)				Average relative to mean FY (%)
	1993–94	1999–2000	2000–01	Mean	
PY ^a	8.88	8.72	9.49	9.03	159
Average FY ^b	5.40	5.66	5.98	5.68	100
90th percentile FY ^c	6.92	7.05	7.37	7.11	125
Median FY ^c	5.72	5.99	6.27	5.99	106
10th percentile FY ^c	3.80	4.31	4.53	4.21	74

a Measured at CENEB in the same given year (12% moisture), under best agronomy and weighted by varieties grown by farmers that year in the Yaqui Valley

b Same source as Figure 3.1

c Remotely sensed; 90th percentile means 90% of fields have a lower FY than this value
Source: Remote-sensing results from Lobell et al. (2002)

Table 3.3 indicates an average yield gap (as defined here) of 59% of average FY, a figure that is somewhat higher than that estimated earlier for 2012 (41%). It also suggests several yield intervals comprise this yield gap, for example: (1) from average FY to the 90th percentile FY, which varied across the 3 study years from 23% to 28% of average FY; and (2) from the 90th percentile FY to PY, which varied from 30% to 36% of average FY. In addition, inspection of the results of Lobell et al. (2002) reveals that in each of the 3 years the absolute maximum FY of any field is no more than 0.7 t/ha above the 90th decile yield, and still about 1.2 t/ha below PY. Since the study area is quite uniform in its natural resource base, management probably dominates this yield variation. Thus the average gap of 1.4 t/ha from average FY to the 90th decile FY (or 25% of average FY) should be readily exploitable with better management. However, this may not be the case for the gap of 1.9 t/ha (0.7 + 1.2 t/ha) from the 90th percentile FY to PY (or 33% of average FY).

The gap from the 90th percentile FY to PY should reflect rational on-farm economic constraints plus the small factors discussed in Chapter 2, which can give an upwards benefit to on-station trial yields. As mentioned in the first paragraph of this section, the soil type itself probably does not benefit yield in the CENEB research station, but beneficial factors could include:

- use of small plots (although adequate edges were always removed)
- faster irrigation and drainage (less temporary waterlogging)
- more careful harvesting
- lodging protection (although, according to surveys, lodging is not a very significant constraint in the valley)

- extra agronomic inputs, including:
 - legume summer crop before the wheat (up to 2001–02) plus chicken manure (up to 2004–05)
 - preventative (prophylactic) fungicide application
 - usually five or six post-germination irrigations (compared with the recommended three or four).

For economic reasons, farmers of the Yaqui Valley use almost none of the special practices employed at the research station, except in fairly rare situations when varietal resistance to leaf rust breaks down and farmers resort to fungicide application. Crop rotation could be one desirable option but is currently not in practice due to few non-wheat options. Adopting the notion from Section 2.1 (on yield and yield gap) that the attainable yield is 23% below the PY, this value is 7.0 t/ha for the years studied in Table 3.3. This is only 0.1 t/ha below the average 90th percentile FY and gives some support to the idea of the 90th percentile as a useful predictor of the attainable yield.

Farm yield constraints for wheat in the Yaqui Valley

FY constraints can be revealed by associated variation in yield and practices between fields in any year and across years. In this respect a great deal is known about the Yaqui Valley. There have been regular field surveys (D. Byerlee and D. Flores, unpublished data 1981; R.A. Fischer, unpublished data 1990, 1991; Meisner et al. 1992; D. Flores, unpublished data 2001), and more recently these have been combined with the powerful new tools of remote sensing (Lobell et al. 2005b).

The turnover of wheat varieties has always been rapid in the valley and adoption lag has never been a significant constraint, while agronomic improvement was rapid early on (Bell et al. 1995), and has continued. For example, since 1980, nitrogen fertiliser rates have increased from 175 kg N/ha to ~300 kg N/ha (D. Flores, pers. comm. 2013). Phosphorus fertiliser rates have increased to ~50 kg P/ha and use of herbicide and pesticide has also increased. But these recent changes may not have contributed much to FY increase. Nitrogen and phosphorus rates appear very adequate, while the switch to integrated pest management (IPM) for aphid control and almost complete adoption of bed and ridge planting since 1980 may have been more significant in reducing costs than increasing yield. Tillage practices appear to be unchanged, with little adoption of reduced tillage on permanent beds, despite the demonstration of its cost-saving advantages.

One clear change has been the disappearance of cotton and soybean from the crop rotation due to lack of water and to pest problems. Up until the mid 1990s most of the wheat followed a broadleaf crop; now more than 90% follows wheat and a short summer fallow (I. Ortiz-Monasterio, pers. comm. 2012). This sort of rotational change could facilitate the carryover of soil diseases and wheat pests. One indicator of the state

of the soil, soil organic matter, appears low but stable (~0.5% organic carbon), while soil salinity has been controlled through a system of deep drains to the sea.

Turning to the large yield variation among farmer fields so evident in Table 3.3, the following agronomic variables have been found to be important, and are discussed in more detail below:

- timing of planting
- water
- nitrogen
- weeds
- other factors.

Although the Yaqui Valley is totally mechanised, **some fields can still be planted late**, mainly due to untimely rain at planting. Ortiz-Monasterio and Lobell (2007) used satellite images to estimate both planting dates and yields. Despite 30–50% of crops being planted after the optimal planting window (15 November to 15 December) in the study periods 1999–2000, 2001–02 and 2002–03, the only significant yield loss attributed to late planting (averaging 11% of FY) occurred in 1999–2000. Year-to-year variability in response to late planting is not unusual, but many experiments—and modelling with historic data (Fischer 1985b)—suggest that, on average, yield will peak when flowering occurs around 1 March, and will fall sharply if flowering occurs after 15 March (equivalent to a late planting, i.e. after 15 December).

Thus a significant proportion of the area planted after 15 December would significantly lower average yield; some such delays have been indicated by the ground surveys, while Ortiz-Monasterio and Lobell (2007) across 3 years with satellite images estimated on average 35% of area planted with an average delay of 1 week. Later, Lobell and Ortiz-Monasterio (2008) suggested 9% average yield loss from late planting across years. Rain at (or just before) planting can cause these delays, as can institutional factors such as irrigation water availability and tardy credit or contract seeding. Agronomic research or breeding is unlikely to lessen this constraint on yield, but better functioning institutions could. Timeliness of harvesting is not considered a problem because dry weather prevails then.

Even on the less-favoured compacted clay soil of the CENEB experiment station, **water-holding capacity is favourable**, so grain yield is relatively insensitive to irrigation timing, except around flowering (Fischer et al. 1977). Nevertheless, satellite estimations of yields of fields across five seasons (2001–06) suggested that fields that—contrary to recommendation—received a second irrigation more than 75 days after seeding (as is common for a pre-irrigated seed bed), or received fewer than four irrigations (including the pre-seeding one), yielded significantly less and overall appeared to have lowered valley average FY by 0.29 t/ha, or about 5% (Lobell and Ortiz-Monasterio 2008). Irrigation limitations arise because of institutional reasons. Limitations also tend to occur in seasons when reservoir availability is low at the

outset, despite efforts to reduce planted area to match water availability. Switching to dry seeding and germination on the first irrigation (with greater reliance on herbicides for weed control) could save irrigation water and allow a greater area to be planted, but is unlikely to increase yield.

The current average application rate of total nitrogen fertiliser is ~300 kg N/ha, with three-quarters applied before planting, and the remaining one-quarter applied with the first irrigation after planting. Although organic matter contents of Yaqui Valley soils are low, the average application rate should be more than sufficient for wheat yields of at least 8 t/ha (Ortiz-Monasterio 2002). Furthermore, ground survey and remote sensing by Lobell et al. (2005b) in 2001 indicated only a weak association between yield and nitrogen rate across fields (slope 5 kg grain per kilogram of nitrogen applied) and only a few fields significantly short of nitrogen. Repeating the survey in 2003 found no relationships between yield and nitrogen fertiliser (Lobell et al. 2005b).

Ortiz-Monasterio and Raun (2007) showed farmer nitrogen applications in 2002–03, 2003–04 and 2005–06 to be excessive in all of 21 random fields. These authors proposed a strategy that saved ~70 kg N/ha without any loss of yield and delivered a significant lift in profit (based on a nitrogen price of 5 kg grain per kilogram of nitrogen). The strategy was to reduce basal application, with greater supplemental nitrogen as a function of response seen in a high basal nitrogen strip. The proposed strategy has since been confirmed in a detailed modelling study across the Yaqui Valley (Ahrens et al. 2010), which showed that scope exists to double the efficiency of nitrogen fertiliser by avoiding heavy basal applications and tailoring nitrogen application to the residual nitrogen supply of the soil; nitrate and gaseous nitrogen losses were reduced and profits increased, while yield did not change.

Thus it appears that improved nitrogen management tactics could significantly increase nitrogen use efficiency, and notably reduce environmental pollution and greenhouse gas emissions, with little effect on yield (<5% reduction). Surveys suggest excessive nitrogen use is related to risk avoidance, driven partly by credit suppliers (McCullough and Matson 2011). Efforts to promote reduced pre-plant nitrogen, and post plant nitrogen based on crop appearance (through a nitrogen sensor), saved an average of 68 kg N/ha without yield loss on 8,500 ha in 2010–11 (I. Ortiz-Monasterio, pers. comm. 2012).

Early surveys identified weeds as an important limitation (Meisner et al. 1992) but today most farmers use herbicides, and those who plant on beds (currently ~90% of farmers) can also use early mechanical weed control or even hand weeding. Thus recent surveys suggest that **less than 6% of fields have enough in-crop weeds to economically affect yields** (Ortiz-Monasterio and Lobell 2007). Overall it appears that alleviating existing in-crop weed constraints will not lift average FY by very much. Now that summer fallow is the general precursor to wheat, Ortiz-Monasterio and Lobell (2007) used remote sensing to investigate the relationship between summer weeds and wheat yield. The authors found that weedy summer

fallow was associated with 12% lower yield compared with wheat after unweedy fallow. Since only 37% of the fields fell in this category, average Yaqui Valley FY was depressed 4.5% by weedy summer fallow or factors associated with it (e.g. disease carryover). In contrast, soil pathogens have been little studied, although there is some evidence for build-up of the wheat parasitic nematode *Pratylenchus* spp.

Plant stand is generally not considered limiting, with farmers adopting unnecessarily heavy seeding rates (~145 kg/ha), even on raised beds which need less seed (Lobell et al. 2005b). Sometimes there are gaps in the plant stand due to bed erosion or waterlogging in low spots. Occasionally, early lodging can reduce yield and can cause some harvest loss. However, none of these factors appear to be reducing average yield in the Yaqui Valley by more than a few per cent.

The limiting factors discussed above vary in importance from year-to-year and interact with one another. This was clearly shown when regression-tree analysis was applied to field survey data (Lobell et al. 2005b). Although the individual effects of late planting and late watering after planting, and unknown factors associated with summer weeds, are small, when taken together the total effect amounts to ~18% of FY. This explains almost one-half of the FY to PY gap, and the exploitable yield gap would likely close if these constraints were to be overcome—meaning FY would shift very close to attainable yield. Lobell and Ortiz-Monasterio (2008) reach a fairly similar conclusion.

From the above analysis, completely closing the gap to attainable yield would seem quite difficult, especially given that individual constraints interact with seasonal variation, which arises largely without warning. A recent review of the knowledge system for agricultural progress in the Yaqui Valley (McCullough and Matson 2011) revealed most farmers are intricately connected to the various technology providers through strong credit unions. However, the study also indicated that smaller farmers (<10 ha) who often operate land from the now-abandoned collective land-use system (the *ejidos*) are likely to be poorly connected and lagging in innovation. This group probably represents a prime source of the exploitable yield gap in the Yaqui Valley.

Physiological basis of yield progress

The physiology of wheat improvement has been intensively studied at CENEB since 1970. The influence of weather and agronomic management on crop yield is now soundly understood, and there is some confidence in predicting the way forward for increased PY.

Current knowledge is based largely on retrospective studies of improved vs. older varieties, but is supported somewhat by more recent selection studies in modern recombinant populations (R.A. Fischer 2007, 2011; Reynolds et al. 2009). Thus breeding progress in PY started with increase in harvest index (HI) and grain number

(GN) coming from the dwarfing genes, and has continued along this path without further height reduction. Most interesting is the fact that increased stomatal conductance and photosynthetic rate (P_{\max}) appear associated with progress within both the semi-dwarf bread wheats (Fischer et al. 1998) and durum wheats (Fischer 2007). Aisawi (2011) reported that crop growth rate, radiation use efficiency (RUE) and stomatal conductance before flowering all increased with year of release in bread wheats.

Harvest index, at ~ 0.45 , does not seem to have reached the likely limit (see Section 9.2 on physiological components of PY progress), but at the same time there is some evidence that the latest progress in the Yaqui Valley is associated with greater dry matter (DM) and, surprisingly, greater grain weight (GW) (Aisawi 2011). As attention turns to greater DM, whether leading to greater GN or GW (or probably both), considerations of limits to RUE become critical. An alternative way to increase DM is to increase crop growth duration—easy to achieve and not limited in the Yaqui Valley by multiple cropping constraints—however, it is argued that this offers little scope for yield improvement (see Section 9.3 on increasing accumulated intercepted photosynthetically active radiation).

Conclusions for wheat in the Yaqui Valley

The Yaqui Valley is an important bellwether for wheat in WME1 around the world. It is of great concern that—despite a relatively large research and development investment as a result of CIMMYT's presence—PY improvement has slowed to only 0.3% per annum (p.a.), although it has not ceased. Improvements in FY continue in response to new technology, but at 0.5% p.a. the rate of FY increase is not much greater than PY increase. In the hands of the valley's generally capable farmers working with good communications and infrastructure, the yield gap, currently 41% of FY (6.4 t/ha FY vs. 9 t/ha PY), has been closing slowly over the past 30 years.

The estimated yield gap suggests that FY is now not very far below attainable yield, and agrees with there being no single major agronomic constraint identified despite many land-based and recent satellite surveys of Yaqui Valley crops. These have, however, pointed to several small manageable agronomic constraints (late sowing, irrigation delays and summer weeds) that together could explain about one-half of the yield gap. Three other worrying developments over the past 30 years are the almost complete loss of cropping diversity, excessive use of nitrogen fertiliser and the degree to which current yields (but not yield gaps) have been inflated by unusually cool seasons (i.e. T_{\min} is currently running 1.2 °C below the 30-year average, giving a 0.5 t/ha boost to yields). This last-mentioned bonus may not persist.

3.3 WME1—Indo-Gangetic Plain and the Indian state of Punjab

Introduction

From Pakistan, across India, Nepal and Bangladesh, at low altitudes between latitude 33 °N in the north-west and 23 °N in the south-east, a relatively mild, dry winter–spring is followed by a warm to hot summer with monsoonal rains; this area is known as the Indo-Gangetic Plain (IGP) (Map 3.3). Having a flat topography with soils developed on alluvial deposits, conditions in the IGP are ideal for double cropping, typically with irrigated spring wheat in the winter season followed by irrigated or rainfed lowland rice in the summer. This vast so-called rice–wheat cropping system occupies about 13.5 Mha (Ladha et al. 2003b). More than 10 Mha of rice–wheat double crop is also found in eastern China, but this latter area is somewhat distinct and discussed separately in Section 3.7. The populous IGP produces more than 60% of the calorie intake of the nations involved (Timsina and Connor 2001).



Map 3.3 Indo-Gangetic Plain of South Asia and key locations and states of India. International borders are approximate.

Apart from the warmer south-eastern portion, including much of Bangladesh, which belongs to WME5, wheat in the IGP comprises the largest contiguous area of WME1. The north-western IGP first experienced the green revolution in wheat and rice, starting in the mid to late 1960s, and this part of the IGP now contributes substantial surpluses of wheat (and rice) to the rest of India and Pakistan. The IGP has remained the target of large national wheat research programs since the 1960s. Collaboration with CIMMYT and the International Rice Research Institute (IRRI) remains strong, and in the past 20 years this collaboration has included a special focus on natural resource management in the rice–wheat farming system (Harrington and Hobbs 2009). The discussion in the next section considers irrigated wheat in the Indian portion of the IGP, which produces most of India’s wheat. About one-half the wheat planted is within a rice–wheat system.

Indian state of Punjab

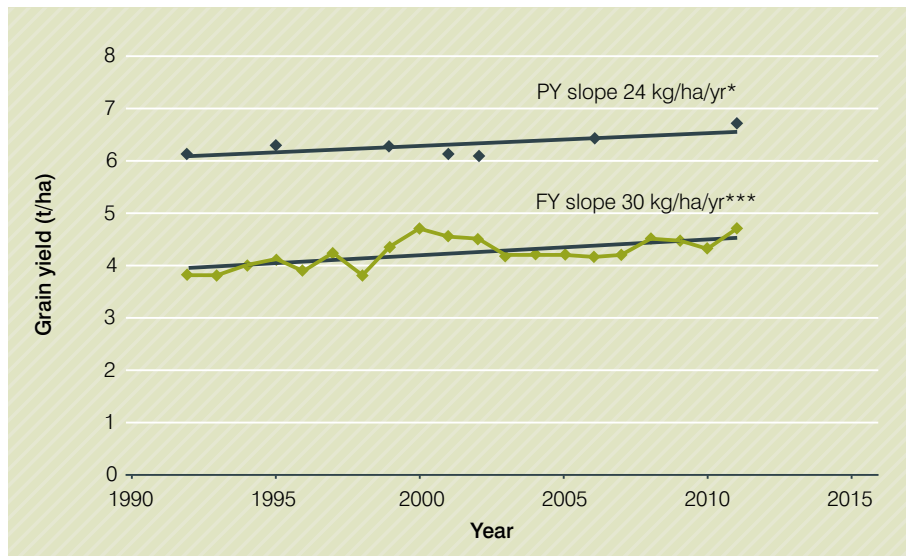
The most advanced agriculture and highest wheat yields of the Indian portion of the IGP occur in the north-west in the state of Punjab and in the adjacent Indian state of Haryana. Punjab has the most favourable wheat climate in India, and in comparison to the average Indian FY of 2.8 t/ha, achieves an average FY of 4.5 t/ha. The climate is similar to the Yaqui Valley, Mexico, although with a more northern latitude (31 °N) and more continental climate, Punjab experiences a little more winter rain (total 100–150 mm) and cloud, and a more rapid rise in spring temperatures. Punjab’s total wheat area is steady at 3.5 Mha. Cropping intensity is close to 200%, with mostly rice–wheat rotation but also some cotton–wheat in the west.

The rice–wheat system is now largely irrigated (>90%) from shallow tube wells, which became important in the latter half of the 20th century. Canal irrigation, established in the 19th century, remains the dominant form of irrigation in the south-west where the cotton–wheat system is more common. Farm size in Punjab is small to moderate (average ~4 ha), with growing consolidation of operational areas. Wheat prices are now close to world parity, although several inputs—particularly nitrogen fertiliser and electricity for tube wells—have been subsidised for many years.

Wheat farm yield, potential yield and yield gap progress in Punjab

FY in Punjab has shown significant growth over the past 20 years. As has occurred in the Yaqui Valley, progress in Punjab has slowed in comparison to the green revolution period—when the FY slope was 90 kg/ha/yr (1965–1990)—but certainly has not ceased. **Since 1990, growth in FY has occurred at 30 kg/ha/yr to reach an estimated FY of 4.5 t/ha for 2011 (Figure 3.2), with relative progress currently 0.7% p.a.** This comes despite a record yield of 4.7 t/ha in 2000 (after very favourable February weather) and a flat period of poorer yields from 2003 to 2007. Reaffirming

the yield progress trend of Punjab, to the south the state of Haryana—with less wheat following rice, and more wheat following cotton or millet—has achieved similar FY progress over the past 20 years (relative progress 0.8% p.a. and current FY 4.25 t/ha).



* $0.05 < P < 0.10$, *** $P < 0.01$

Figure 3.2 Wheat farm yield (FY) plotted against year for the Indian state of Punjab, and potential yield (PY) for the North West Plains Zone (NWPZ) of India, plotted against year of variety release from 1992 to 2011. Source: FY from DACNET (2013), PY for North West Plains Zone varieties in S.S. Singh et al. (2011) and I. Sharma (pers. comm. 2013) for the 2011 release

Average annual weather data for the period January to April in Punjab over the 20-year span 1992–2011 shows very highly significant ($P < 0.01$) increases to both minimum ($+0.105\text{ }^{\circ}\text{C/yr}$) and maximum ($+0.159\text{ }^{\circ}\text{C/yr}$) temperatures.²⁴ This trend is also seen in several other parts of the IGP, but no significant change in R_s has been observed (at least in Punjab). Using the method of correlation of year-to-year differences, it appears that annual yield fluctuations are especially sensitive to change in average minimum temperature during the period February to March (slope $-148\text{ kg/ha/ }^{\circ}\text{C}$, $0.01 < P < 0.05$). This is not surprising given that February–March is the most critical growth period for wheat in Punjab (Ortiz-Monasterio et al. 1994). The slope is less than that for the Yaqui Valley, but this may be due to other weather variables associated with change in minimum temperature.

²⁴ Data from Punjab Agricultural University, Ludhiana, courtesy S. Yadav (pers. comm. 2012)

Applying the above correction to the trend in minimum temperature for the period February–March 1992–2011 (+0.105 °C/yr) suggests that increased minimum temperature has reduced FY progress by 15 kg/ha/yr. **The weather change correction adds 0.3% p.a. to estimated technological progress in Punjab, which becomes 45 kg/ha/yr, or 1.0% p.a. of the 2011 estimated FY.** This weather correction due to warming is somewhat less than estimated by others using simulation modelling (with constant variety and agronomy) for the Ludhiana district. For example, for the 1970–2006 period, Timsina et al. (2008) estimated a PY decline of 41 kg/ha/yr, equivalent to 0.6% p.a. of their final PY. For a shorter period, 1985–99, Pathak et al. (2003) found simulated PY for the Ludhiana district of Punjab to decrease at 20 kg/ha/yr, but this was not statistically significant ($P > 0.05$). Currently February–March minimum temperatures are running ~0.5–1.0 °C above the 20-year average and are certainly reducing yields relative to more average weather.

As for PY progress in the Punjab, Nagarajan (1998) reported for the North West Plains Zone (NWPZ)—an Indian wheat testing zone, of which Punjab is a major portion—that PY progress was 0.9% p.a. across semi-dwarf varieties, starting with the first green revolution semi-dwarf variety in 1965, and ending with the 1995 release of PBW343, which became a very widely grown cultivar in the whole NWPZ for the next 20 years. Recently S.S. Singh et al. (2011) presented measured PY values for outstanding NWPZ variety releases between 1992 and 2006 (Figure 3.2); to these can be added a 2011 release. **Thus PY progress is 24 kg/ha/yr ($0.05 < P < 0.10$) and the slope is 0.4% p.a. of the estimated PY in 2011 (6.5 t/ha).**

Figure 3.2 shows an estimated PY value of 6.5 t/ha in 2006 but this may include other lower yielding parts of the NWPZ; simulation modelling generally produces higher values for Punjab locations. For example, Aggarwal and Kalra (1994), using their own WTGROWS simulation model, estimated PY for the whole of Punjab to be 7–8 t/ha. Other modelling has targeted the Ludhiana district, where current average wheat yield is 10% higher than the Punjab average due to more favourable climate and better management (outweighing the effect of poorer soil). Pathak et al. (2003) used the DSSAT v3.5 model to estimate PY at Ludhiana to average 7.9 t/ha for the 1985–99 period. Later Pathak et al. (2009)—this time using DSSAT v4.1, parameterised for cultivar PBW343—calculated average PY to be 8.4 t/ha for the 2002–06 period. Independently the earlier mentioned Timsina et al. (2008) study (also parameterising for PBW343) estimated PY for Ludhiana for the 1970–2006 period to be only ~6.5 t/ha. As should occur, all the above models estimated PY without water or nitrogen limitation. Reasons for the differences in estimated PY remain unclear and point to the limitations of current simulation models.

For the purposes of this book, **the PY relevant to Punjab is taken to be 7 t/ha in 2011.** This estimate accounts for the above modelling, while recognising that experimental yields >6 t/ha are rare in Ludhiana, and noting that recent yield maximisation experiments in the rice–wheat zone of Haryana, immediately south of Punjab (30 °N), failed to produce wheat yields above 5.5 t/ha (Coventry et al. 2011a). The implication of this PY estimate is that **the yield gap for the Punjab is 56% of FY**; the more confident conclusion is that PY is advancing very slowly.

It is notable that PY in Punjab is ~2 t/ha (or 22%) below that seen in the Yaqui Valley, despite a more northerly latitude (31 °N vs. 27 °N). Correction for climate around the critical flowering period—somewhat more favourable in the Yaqui Valley—does not appear to explain much of this difference (Ortiz-Monasterio et al. 1994). A possible explanation is the likely greater frequency of hot spells ($T_{\max} > 34\text{ °C}$) during grain-filling in Punjab (Lobell et al. 2012a).

On-farm yield constraints for wheat in Punjab

There are many possible causes of the moderately large yield gap in Punjab, and few data on the relative impacts of the various yield constraints. However, the three main constraints appear to be low soil fertility, delayed sowing and irregular water supply. Extensive surveys have also identified these same three principal constraints for the rice–wheat system in adjacent regions of Pakistan (Byerlee et al. 2003).

For many years only 120 kg N/ha was recommended for wheat. This rate is barely adequate for a 5 t/ha crop, especially given commonly light-textured soils that contain extremely low organic carbon (generally <0.5%) and are subject to leaching losses. Soils often also have possible deficiencies of potassium, sulfur and zinc (Ladha et al. 2003a). Statistics show that wheat in Punjab received 240 kg/ha of fertiliser nutrients²⁵ in 2003, and that this amount may be still increasing. Recommendations for the neighbouring state of Haryana have recently risen to 150 kg N/ha, and surveys in the rice–wheat zone (Singh et al. 2010) suggest that farmers are using nitrogen at ~160 kg N/ha (with most adopting more efficient multiple splitting of nitrogen topdressing), as well as phosphorus (P) fertiliser at 58 kg P_2O_5 /ha and zinc sulfate at 8 kg/ha; use of potassium (K), however, was still well below that recommended. On-farm experimentation in the same part of Haryana found no response to supplementation with boron (B), copper (Cu), iron (Fe), sulfur (S), zinc (Zn) or manganese (Mn) (Coventry et al. 2011b). However, 15 t/ha of farmyard manure added to the recommended nitrogen, phosphorus and potassium (NPK) did lift yields by ~0.5 t/ha, possibly because of the extra phosphorus provided.

Many observers point to late sowing as a constraint that often arises because of late harvest of the preceding cotton or rice crops. Both experiment and simulation have pointed to yield loss from delayed sowing—a more severe loss in the IGP than in the Yaqui Valley because of the continental climate. Aggarwal and Kalra (1994) indicated yield loss of ~0.8% per day from planting after 15 November, while Timsina et al. (2008) claim about one-half of this. Ortiz-Monasterio et al. (1994) measured a decrease of ~1% per day after 15 November at Ludhiana. Satellite imagery of Punjab over the 2000–09 period (Lobell et al. 2010) estimated that, depending on year, 20–50% of the wheat crop was planted after the optimal date (15 November) in the cotton-growing district of Punjab. However, across the whole state the imagery and surveys suggest

²⁵ $N + P_2O_5 + K_2O$ since Indian statistics do not separate elements and continue to use phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O)

that the average sowing date for Punjab is optimal at around 10 November (Lobell et al. 2012b), although there is no comment on the proportion that is late sown at the state level. Lobell et al. (2010) also report that sowing date was more likely to be post-optimal in the adjacent states of Haryana and Uttar Pradesh, even if (over the last decade) average sowing date has become 10 days earlier, with likely benefits for yield.

In the low-rainfall winter of the IGP, simulation shows that another variable constraint, poor irrigation water supply, greatly reduces yields (Aggarwal and Kalra, 1994; Timsina et al. 2008). The effect was seen in yield decline with increased distance from the canal in a canal-irrigated district of Punjab (Lobell et al. 2010). Yield is additionally constrained by increasing salinity of tube well water (especially in the south-west) and irregular power supply for tube wells.

Because rice–wheat potential evapotranspiration (ET_p) exceeds rainfall, the watertable is declining at 0.2–1.0 m/yr, notwithstanding that there is some lateral recharge from canals and rivers. It is estimated that by 2025, 30% of the watertables of Punjab will have fallen below 30 m (Humphreys et al. 2010). However, declining water levels in tube wells are probably not yet directly limiting FY.

A 2007–08 survey of the NWPZ concluded that the greatest constraints were weeds (including herbicide-resistant *Phalaris minor*) and insects (including termites), followed by soil fertility and poor plant stands (data supplied by R. Singh Poswal, pers. comm. 2011); curiously, late sowing and poor water supply did not feature. Finally many have pointed to soil compaction—aggravated by the soil puddling for paddy rice—as another problem for the following wheat crops, especially as soil compaction slows traditional land preparation for planting.

Most of the constraints mentioned above are amenable to amelioration (i.e. they are exploitable). It is noteworthy that in Haryana in 2008, the top 15% of farmers (across a sample of more than 1,000) achieved yields of 1.5 t/ha or 36% above the average state FY of 4.16 t/ha; several reached 6 t/ha (R.K. Malik, pers. comm. 2009). Furthermore, in 2007–09 in Punjab, some farmers' fields were close to 7 t/ha (Frontline Demonstrations 2007–09, data supplied by R. Singh Poswal, pers. comm. 2011).

Direct seeding of wheat after rice (and cotton) is an effective new technology that offers great scope for ensuring timely sowing, conservation of water and fuel, and less *Phalaris minor* pressure because this weed thrives with soil disturbance. Adoption of this practice—catalysed by the development and subsidisation of simple minimum-till seed drills—rose rapidly to reach 2.4 Mha in the north-western IGP by 2005–06, mostly in Haryana (Harrington and Hobbs 2009). Such plantings in Haryana in the last week of October have even out-yielded plantings at the recommended optimum date of 15 November by ~10% over the last four seasons (R.K. Malik, pers. comm. 2011).

The next challenge for wheat seeding is direct planting into the rice crop residue, which is no longer collected by farmers and is often burned (leading to serious atmospheric pollution). Seed drills that can handle this residue are becoming available (although at

more expense), but the presence of mulch is unlikely to raise yields of irrigated wheat, although it could save some scarce water by reducing soil evaporation early in the wheat crop cycle.

Wheat across the Indian Indo-Gangetic Plain

The Indian portion of the IGP shown in Map 3.3 contains notable climatic and socioeconomic gradients. Pathak et al. (2003) simulated PY at the optimal planting date at locations along the IGP using the model GENERIC CERES v3.5, calibrated to a 1985 cultivar (HD2329) and holding variety and agronomy constant. PY ranged along this climate gradient from 7.9 t/ha at Ludhiana to 5.2 t/ha at a location in West Bengal, 24-Paragan, steadily decreasing a total of 34% from the cooler north-west to the warmer south-east. Erenstein (2012) reported on the socioeconomic gradient by surveying villages from the north-west to the south-east: rural population density increased from 300 to greater than 1,000/km², population below the poverty line rose from 7% to 50%, farm size decreased from 4 ha to less than 1 ha and the informal annual interest rates rose from 21% to greater than 90%!

Pathak et al. (2003) also studied FY across the whole IGP; although the period studied (1985–99) is not recent, the results still shed some light on the gradient. In eight Indian IGP districts, from Ludhiana district in Punjab (31 °N) to the 24-Paragan district in West Bengal (23 °N), Pathak et al. (2003) found average district FY ranged from 4.3 t/ha in Ludhiana to 2.1 t/ha in 24-Paragan, with an overall average FY of 2.8 t/ha. FY increased significantly with time in most districts (average 50 kg/ha/yr), amounting to 1.5% p.a. relative to the 1999 estimated average FY for the whole region, and suggesting good progress at the farm level. Wheat season solar radiation fell annually on average 0.12 MJ/m²/day. This decline is probably the result of atmospheric pollution, but temperature tended also to decline (–0.04 °C/yr); thus the average simulated net effect of these weather changes on yield was close to zero. These district FY numbers, and those of simulated PY, also from Pathak et al. (2003), suggest a large yield gap, ranging from 83% of FY in Ludhiana in the west,²⁶ to well over 100% in most eastern districts. Earlier simulations of Aggarwal and Kalra (1994) support this conclusion.

Twenty-three long-term rice–wheat experiments, conducted across the IGP—from Ludhiana (Punjab) to Dinajpur (Bangladesh), and finishing around 2000—were summarised by Ladha et al. (2003a) and bear heavily on the question of productivity and sustainability. Recommended NPK fertiliser rates (120 kg N/ha for wheat) and best varieties of the day were used in experiments maintained for 7–23 years. On average wheat yields increased 15 kg/ha/yr, but only four sites showed significant positive slopes, and two showed significantly negative ones. Ladha et al. (2003a) ascribed slow yield progress to generally low soil organic carbon contents, combined with inadequate fertiliser application (especially insufficient potassium, but also nitrogen and zinc in

²⁶ This is larger than the aforementioned calculation of 55% for Punjab today, primarily because this latter figure refers to an earlier period and uses a higher value for PY (7.9 vs. 7 t/ha).

some places); most trials showed, in their final year, linear fertiliser responses up to the maximum NPK rate.

Two other facts from the Ladha et al. (2003a) study stand out. First, the average trial yields were often only marginally better than the surrounding district average FY. Second, the experimental treatment at Ludhiana that received more nitrogen (150 kg N/ha) reached a highly significant rate of yield increase of 201 kg/ha/yr, to give a FY of 6 t/ha in 2000. This is to be compared with other experiments at Ludhiana with only 120 kg N/ha, and for which yield increased at only 55 kg/ha/yr. So although Ladha et al. (2003a) described the yields in these long-term IGP experiments as 'stagnant', the cause might be attributed to poor experimental agronomy rather than anything else.

Concluding with a comprehensive review of the IGP situation, Ladha et al. (2003a) listed and discussed all likely causes of yield gaps. As well as those related to inadequate nutrition mentioned above, these authors added shortage of irrigation water (plus waterlogging in the east), rising salinity, delayed sowing and (especially in the centre to east) poor land levelling, pests and disease, and slow variety turnover. Despite a tendency for decreased winter–spring solar radiation over time, weather change did not feature as a consistent factor in simulated IGP wheat yield trends (noting that these studies finished in 2000). Chauhan et al. (2012) reviewed constraints in the rice–wheat system, coming to similar conclusions as Ladha et al. (2003a), but also discussing many opportunities for relief of constraints.

Since most of the on-farm yield constraints identified for the IGP would appear to be amenable to exploitation, there is a good possibility of substantial yield gap closure, especially in the less-developed but generally wetter central and eastern IGP. This is the region targeted by the new Cereal Systems Initiative for South Asia (CSISA) project, managed by IRRRI and CIMMYT. It is exciting to learn of validated field wheat yields in excess of 7 t/ha in eastern Uttar Pradesh (in the middle of the region) when farmers have been able to eliminate all these constraints (R.K. Malik, pers. comm. 2012). However, yield gap closure will be also constrained by the socioeconomic circumstances of the south-eastern IGP. Erenstein (2012) argues that innovations suited to capital scarcity will be needed, more so than the labour-saving innovations that are increasingly being developed and adopted in the north-west.

Conclusion for wheat in the Indo-Gangetic Plain and Punjab

FY in Punjab is progressing by 0.7% p.a. (or 1.0% p.a. if corrected for warming) to reach around 4.5 t/ha in 2011, and it is not stagnant as popularly reported. In contrast, PY progress appears to be slower (0.4% p.a.), notwithstanding considerable resources devoted to wheat breeding.

PY in 2010 was estimated to be around 7 t/ha, but there is some uncertainty around this number, which would indicate a yield gap of 55%. Simulation modelling, surveys and anecdotal evidence suggest that delayed sowing, inadequate nitrogen and other

fertiliser elements (i.e. K, P, S and Zn), along with interruptions to irrigation water supply, may be the largest constraints on FY in Punjab. Most of these constraints, amounting to at least half of the current yield gap, are exploitable. For example, direct drilling of wheat after rice will facilitate sowing at the optimal time and should lead to some yield gap closing, but this adoption process appears to have stalled in the past 5 years or so (Lobell et al. 2012b). Future negative influences also loom, including continued deterioration of the climate for wheat (due to warming) and overexploitation of the watertable by tube well pumping.

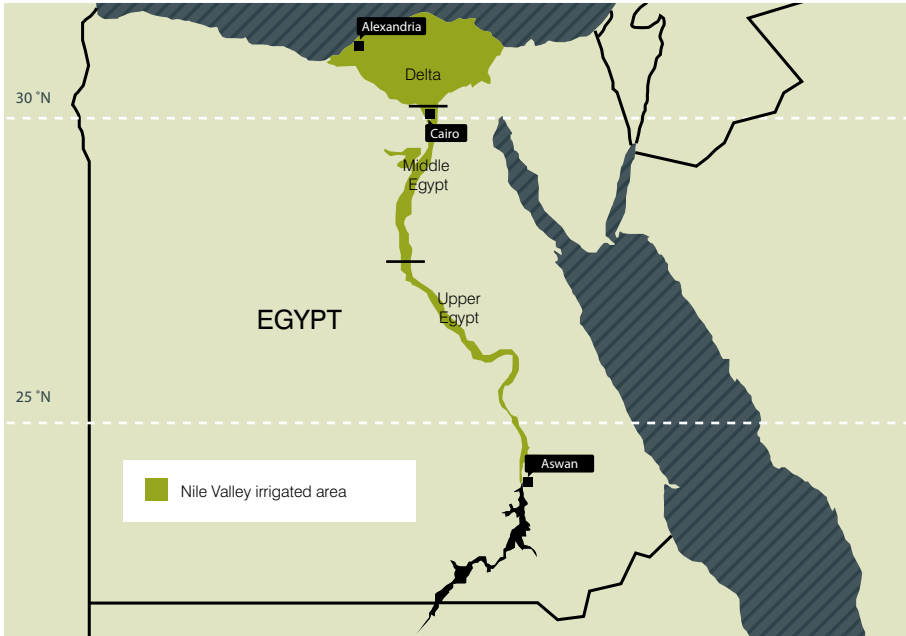
Across the Indian IGP as a whole, many of the cited IGP studies used data series that ended more than a decade ago. The larger yield gaps there may have since begun to close, as the Punjab section above concludes, because FY in the central and eastern states is also progressing slowly. However, it is likely that the yield gap remains greater than in Punjab, and steadily increases towards eastern Indian IGP (Bihar, West Bengal), where additional constraints on yield are more evident (i.e. poor land levelling, pests and diseases and low variety turnover).

3.4 WME1—Egypt

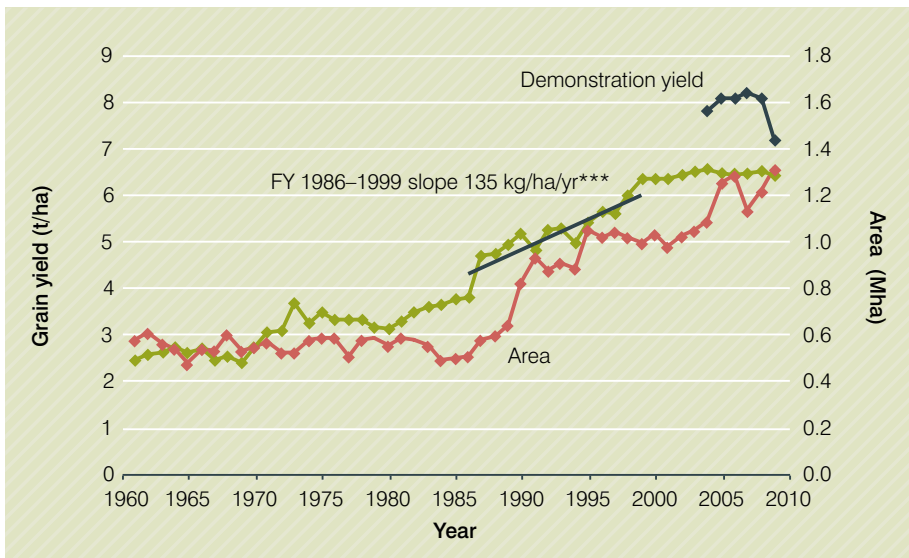
Wheat is grown in Egypt between latitudes 25 °N and 31 °N (Map 3.4). Most of the wheat area (57%) lies in Lower Egypt (the Nile Delta), but there are small areas in Middle Egypt (18%) and Upper Egypt (17%). Although only 1.2 Mha of wheat is grown, several aspects of wheat in Egypt are noteworthy.

With an estimated 2010 FY of 6.5 t/ha (Figure 3.3), Egypt has the highest national wheat yield of the developing world. All wheat is irrigated and the WME1 climate is extremely favourable, with winter temperatures ~2 °C lower than the Yaqui Valley, Mexico, and with mostly cloudless days (although spring temperatures in Egypt rise more rapidly, especially in Upper Egypt). It is also notable that high yields have been achieved on very small farms (average ~0.6 ha) with a high cropping intensity (180%) according to FAO (2005). Further, a diversity of crops is found in the wheat system (e.g. maize, rice, berseem clover, potatoes and vegetables), but double cropping wheat–rice is difficult to achieve.

The most notable additional observation from Egypt is that after years of negative rates of farmer price assistance in order to keep food prices low, policy reforms in the late 1980s dramatically reversed the situation to one of strong positive assistance, which has subsequently gradually declined to price neutrality (Cassing et al. 2007). As a result, starting in 1985, wheat area has doubled to reach the current 1.2 Mha (Figure 3.3, right-hand axis). Moreover, modern varieties were widely planted and yield rose dramatically during the first 12 years following the policy reforms (slope 135 kg/ha/yr between 1987 and 1999, or more than 2% p.a.). Since 1999, growth has slowed notably, probably because of deteriorating wheat profitability (S. Sabry, pers. comm. 2012).



Map 3.4 Egypt showing the irrigated Lower (Nile Delta), Middle and Upper regions. International borders are approximate.



*** $P < 0.01$

Figure 3.3 Change in farm yield (FY), demonstration yield and harvested area of wheat in Egypt plotted against year from 1961 to 2009. Source: FAOSTAT (2013) and M.G. Mosaad, pers. comm. (2011)

Egypt has had an active public wheat breeding program for many years and introduced semi-dwarf varieties soon after the green revolution, but detailed data on recent PY progress are unavailable. However, 2003–09 demonstrations in farmers' fields with the best varieties and management averaged 7.9 t/ha (Figure 3.3), and 8 t/ha appears to be the PY of the latest cultivars, Misir 1 and Misir 2 (Mosaad 2009). This indicates a yield gap of only about 22%.

The future of PY and FY in Egypt presents another important bellwether for the developing world. It will be the outcome of the combined effects of huge political pressure to reduce wheat imports (currently ~8 Mt p.a.), uniformity and predictability of the wheat environment, and substantial local research effort.

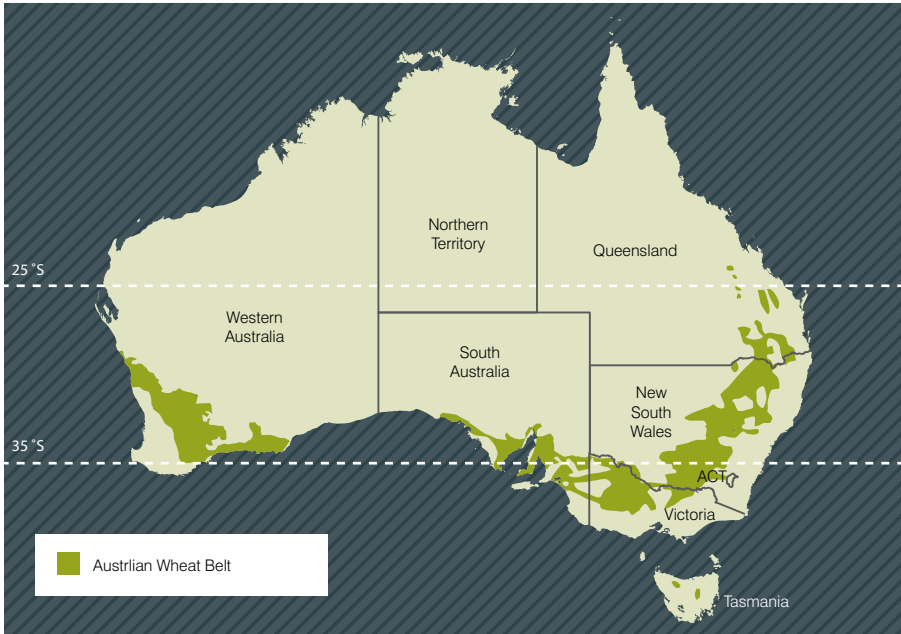
3.5 WME4—Australia, notably Western Australia

Introduction

Australian cropping and cropping research has always been dominated by wheat; 55% of Australian cropland is occupied by the current wheat area of ~14 Mha. The wheat crop is almost entirely contained within rainfed WME4, and largely comprises spring wheat varieties planted in late autumn to early winter. The dry Australian climate ranges from winter rainfall dominant (Mediterranean) in the west, to summer rainfall dominant in the north-east where stored soil moisture plays a key role in augmenting the water supply from in-crop rainfall (Map 3.5).

Parts of the Australian wheat environment are very relevant to WME4 in the developing world. In particular, the western region of the Australian Wheat Belt is relevant to northern Africa and Chile, and the north-east to Argentina. In contrast, however, farms in Australia are usually mixed (typically crops plus livestock and pasture, ideally leguminous); farm size is very large; and substantial public investment in research, development and extension has been as high as 5% of agricultural gross domestic product in the past (currently 3%). From such research, there have been many lessons for semi-arid cropping regions.

Despite recurring droughts and generally low yields, Australia has experienced substantial wheat yield progress, with FY increasing over the 20th century from 0.5 t/ha to ~2.0 t/ha (Figure 3.4), even as wheat area has increased almost sixfold, largely through expansion into drier areas. A great deal is known about this yield progress (summarised in Figure 3.4), and is described in many recent research publications (e.g. Fischer 2009). National statistics are, however, too broad for detailed interpretation, and recently were heavily distorted by the 'Millennium' drought between 1997 and 2009 in south-eastern Australia (Figure 3.4); the noise created in the data by this event is why, in Table 3.1, no significant FY progress is recorded for the past 20 years. Thus, Western Australia, with a Mediterranean climate and less recent drought, was chosen for analysis here. Brief mention is made of relevant results from elsewhere.



Map 3.5 Australian Wheat Belt and states of Australia

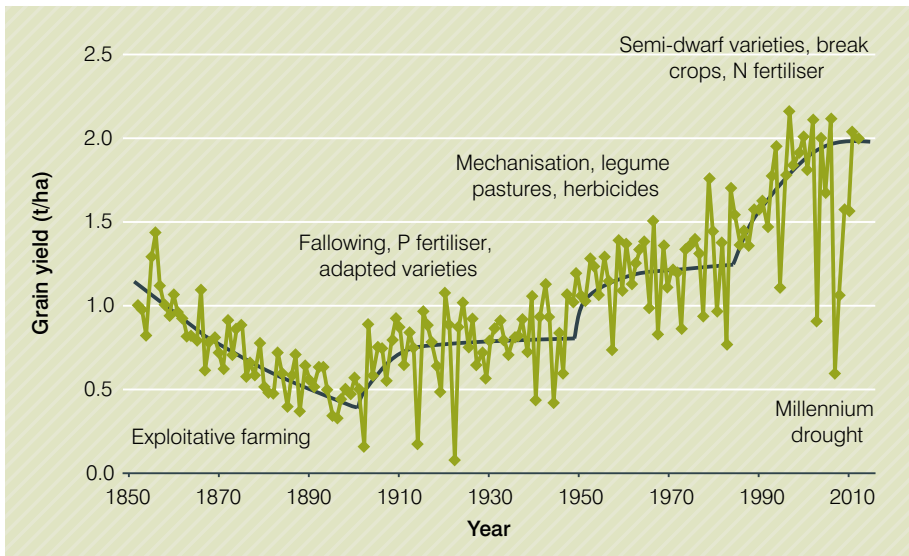


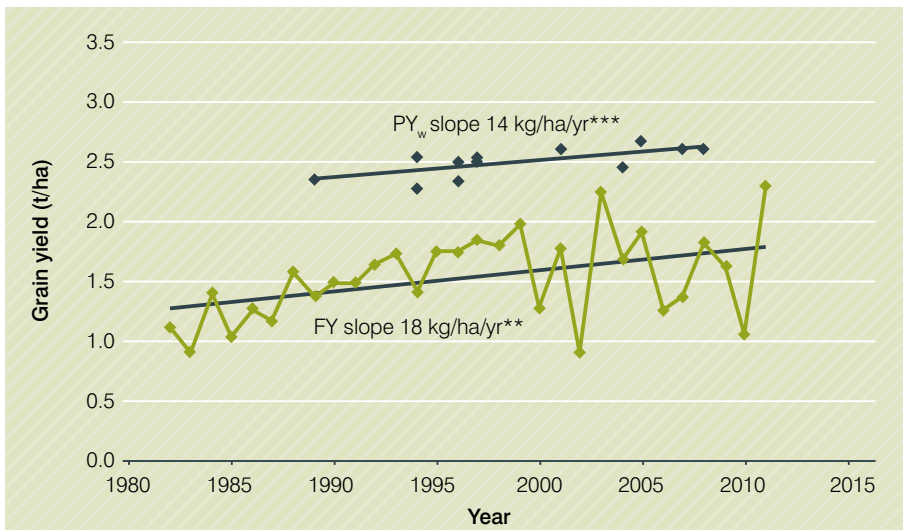
Figure 3.4 Change in average farm yield (FY) of wheat in Australia from 1852 to 2011 and major drivers of change. P = phosphorus, N = nitrogen. Exploitative farming refers to the 19th century when there were no inputs besides seed, labour and animal power and manure (effectively organic farming). Black trendlines are hand-drawn. Source: Adapted from Fischer (2009) and J.F. Angus and J. Kirkegaard, pers. comm. (2011)

Wheat farm yield and water-limited potential yield in Western Australia

Wheat in Western Australia encounters a rainfed Mediterranean environment with low to moderate average annual rainfall (275–500 mm), concentrated in the April to October growing period, but nonetheless very variable. Soils are generally infertile and erodible with light surface textures, and are especially variable. Plant available water-holding capacity (PAWC) is commonly poor for the deep, light soils (50–60 mm) and only moderate where the topsoil is underlain by heavy clay (duplex soils, 70–80 mm). For less common deep loam soils, PAWC may reach 130 mm.

In 1950 wheat area was about 1 Mha and FY only 0.8 t/ha. Since then area has increased at a rate of 3% p.a. until 2000, after which it changed little, with an average area around 5 Mha. Even though area expanded onto generally poorer land, **FY has also risen strongly since 1980 (Figure 3.5), with a rate of progress of 1.0% p.a. of the 2010 estimated FY of 1.8 t/ha**; the rate of progress was more than 2% for the first two decades of this period.

In the last decade, FY in Western Australia has been subject to serious rainfall variability, in particular drought in 2002, 2006, 2007 and 2010 (Figure 3.5). FY can be corrected using growing-season rainfall (GSR) (May–October) over the 30 years shown in Figure 3.5 as a better measure of technological progress—the corrected FY slope becomes 21 kg/ha/yr, equivalent to a rate of progress of 1.2% p.a. of the estimated 2010 FY of 1.8 t/ha.



*** $P < 0.01$, ** $0.01 < P < 0.05$

Figure 3.5 Change in farm yield (FY) plotted against year, and in water-limited potential yield (PY_w) plotted against year of release, for wheat in Western Australia from 1982 to 2011. Source: PY_w from NVT (2009); FY from ABARES (2012)

In fact, growth in average farm total factor productivity (1989–2004)—also corrected for moisture availability—was an impressive 2.5% (Kokic et al. 2006), primarily due to improved technology and management decisions. Farm size has grown steadily so that by 2006–09 each farm operated on average ~2,550 ha, annually cropping ~1,400 ha (60% planted to wheat), and running 3,600 sheep or equivalents in cattle.²⁷ Western Australia is therefore of interest as a technically advanced semi-arid wheat system in which grazing animals play a significant role.

Apart from the recent gradual drying and droughts, a unique feature of the Western Australian wheat environment is that average GSR fell sharply around the mid 1970s to be about 10% less in the following 30 years, relative to the previous 30 years; totals in the wettest months, June and July, in particular have decreased (Ludwig et al. 2009). However, this step change happened before the periods considered here. A second climatic factor—for which there is no easy correction of yield—is the remarkable increase in damaging spring frosts in the last decade or so in the central-southern portion of the Western Australian Wheat Belt (Stephens et al. 2011).

The genetic component of progress since 1980 includes the complete adoption of semi-dwarf varieties. Data from Western Australian trials grown over the relatively dry 2000–07 period and containing key 1990–2008 varieties (all semi-dwarf) appear as the state-wide estimated average PY_w in Figure 3.5. All PY values were adjusted upwards by 5.5% to allow for the lower general yield during the trial period. Water-limited potential yield (PY_w) shows a slope of 14 kg/ha/yr and **an estimated 2008 PY_w value of 2.6 t/ha. Thus the rate of PY_w progress is 0.5% p.a. of the estimated 2008 yield, and the yield gap 0.8 t/ha (45%).**

The above rate of progress of 0.5% p.a. for PY_w agrees well with earlier studies of historic sets of varieties under rainfed conditions in Australia (range 0.4–1.0%, average 0.5%; Fischer 2009), with the higher rates over shorter periods in the 1970s and 1980s when semi-dwarf wheat varieties were released. Relevant to this are also two recent reports from neighbouring South Australia: rate of breeding progress was reported as 0.3% p.a. by Saunders (2008) and 0.5% p.a. by Black et al. (2008). The Saunders (2008) rate is especially interesting since side-by-side comparisons were conducted under very dry conditions (309 mm annual rainfall, 230 mm GSR) yet progress was very highly significant (7.2 kg/ha/yr, $P < 0.01$) with estimated PY_w for the latest (2002) vintage variety being 2.3 t/ha.

Modelling of yield under water limitation can be used as another approach to estimate the current observed level of PY_w for Western Australia. Much work has been done with the APSIM wheat model, extensively validated in this environment (e.g. Asseng et al. 1998), and with simple evapotranspiration (ET) based models (e.g. Stephens et al. 2011). APSIM modelling with a properly representative sample in time and space for

²⁷ Data consolidated from 2011 reports to the Grains Research and Development Corporation (GRDC) prepared by the Australian Bureau of Agricultural and Resource Economics and Science (ABARES), available from <www.abares.gov.au>

Western Australia (e.g. Asseng et al. 2001; Ludwig et al. 2009) points to PY_w at least over 2 t/ha, but greater confidence is thwarted by at least two issues.

First there is a lack of knowledge of the exact proportions of soils of different PAWCs, and PAWC is so critical for rainfed performance. Second there is uncertainty about dealing with droughted crops; all appear in the modelled average PY_w , but in reality, some droughted crops would not have been harvested (being grazed out instead) and thus would not be included in district and regional FY yield statistics, which are based on harvested area (S. Asseng, pers. comm. 2011). ET modelling with a good spatial spread suggests the PY_w is ~ 3 t/ha (Anderson 2010; Stephens et al. 2011). However, for the purposes of this chapter, the variety trial-derived estimate of 2.6 t/ha (as shown in Figure 3.5) is accepted as current PY_w .

Closing the wheat yield gap in Western Australia

Figure 3.5 suggests that there has been considerable yield gap closure over the past 20 years related to improved crop agronomy: the gap was 70% in 1990 and only 45% in 2008. In fact, genetic PY_w progress at $\sim 0.5\%$ p.a. explains less than a half of the FY progress since 1980, estimated above to be $\sim 1.2\%$ p.a. The main agronomic advances contributing to gap closure have been:

- earlier seeding (particularly associated with large-scale mechanisation and a shift to direct seeding)
- improved soil water storage through retention of crop residues
- increased use of nitrogen fertiliser
- better weed control before and in-crop
- break crops (such as lupins and canola) for suppression of wheat root diseases.

Direct seeding (a form of zero-till) has now passed 90% adoption (Llewellyn and D'Emden 2009), nitrogen use is up from 10 kg/ha in 1980 to ~ 45 kg/ha in the past decade (Stephens et al. 2011) and seeding dates have advanced 14 days between 1978 and 1990 (Stephens and Lyons 1998). Seymour et al. (2012) showed benefits from break crops of approximately 0.5 t/ha for wheat following lupin, field pea or canola (compared with wheat following wheat), and 0.3 t/ha for wheat after oats or fallow. Part of the benefit is derived from extra nitrogen after legumes, and part due to improved root disease control (a function boosted by good control of grass weeds in the break crop).

Looking to future FY progress, modelling has clearly confirmed the variability of grain yield at any site as a function of GSR and distribution. Modelling has highlighted the importance of higher PAWC—as affected by soil type, and sometimes other factors like compaction and deep acidity—and of soil surface texture, as it relates to soil evaporative losses. Modelling has also confirmed the critical role of earlier sowing, and of nitrogen supply, especially in wetter seasons.

Modelling by Asseng et al. (2008) has suggested that farm yields are well below PY_w in the good seasons (largely due to lack of nitrogen); this reflects farmer risk aversion towards greater input use (particularly nitrogen fertiliser) in this dry and variable environment and is an obvious area for further yield gap closure. This challenge is illustrated in a second, simpler approach developed by Anderson (2010), and using equation (11) to determine PY_w in Figure 3.5. This equation is based on a relationship between PY_w and GSR first promoted in South Australia by French and Schultz (1984) and which is discussed in detail in Section 2.6.

equation (11) Water-limited potential yield as a simple function of growing-season rainfall

$$PY_w = 20 \times (GSR - (GSR \times 0.30)) \quad (11)$$

where

PY_w is water-limited potential yield given in kilograms per hectare (kg/ha)

GSR is growing-season rainfall given in millimetres (mm), and $GSR \times 0.30$ represents water lost (direct soil evaporation, deep drainage) in Western Australian soils

20 is kilograms per hectare per millimetre of water (kg/ha/mm), estimated to be the best efficiency by which the crop converts transpiration to dry matter and on to grain.

Source: Anderson (2010)

Anderson (2010) estimated PY_w in nine local representative districts in Western Australia (1997–2006), shown plotted against average GSR in Figure 3.6 along with the district FY. The average FY was 2.02 t/ha, and the average yield gap was 1.55 t/ha (77% of FY), a result that is somewhat greater than that estimated in Figure 3.5, even if taken at the mid-point (2001) in that figure..

Figure 3.6 reveals the important finding that absolute and relative yield gaps increase as GSR increases. Yield gap varied from only 0.4 t/ha (30% of FY) in the driest district (average GSR of 141 mm), to as much as 2.0 t/ha (91% of FY) in the wettest district (average GSR 317 mm). This sensitivity to geographic variation in GSR seen in Figure 3.6 may amplify the response to GSR somewhat relative to the above APSIM modelling (which also allows for deep drainage, nitrate leaching, waterlogging and rainfall distribution) but there is no doubt yield gap increases with average GSR. In addition both approaches suggest that at a given site, FY fell relatively further below PY_w in those years with greater GSR. This is a common observation in rainfed cropping: FY is smaller relative to PY_w in wetter years because farmers are very averse to risking higher input levels (e.g. nitrogen, foliar fungicides) that might return nothing (or a loss) if the rains fail. With this attitude, farmers lose the opportunity for greater input responses that occur in wetter years.

Consistent with Figure 3.6, Anderson (2010) points to greater opportunities for closing the yield gap in wetter districts (and wetter years). He discusses possible strategic and

tactical management interventions, emphasising manageable soil constraints such as acidity and compaction in certain soils, weed management, disease and pest control, and crop nutrition. Taken together, the generally additive effects of better management alone could lift FY by 10–15%, which would close the current yield gap by one-quarter to one-third, and probably bring it close to the attainable yield.

Skilful seasonal rainfall forecasts should be added as a means by which risks at a given location can be reduced, thereby encouraging farmers to manage each year according to its potential. Unfortunately, seasonal forecasting skill, based on statistical models, has been barely adequate to justify considering this technology at planting time (Moeller et al. 2008). However, new seasonal forecasts, now based on global circulation models, have reached skill levels in parts of Western Australia that would significantly reduce risk levels surrounding pre-planting nitrogen decisions (Asseng et al. 2012). In addition, tactical mid-season nitrogen fertiliser decisions can be a satisfactory compromise, relying on rain already received and shorter term forecasts.

Precision agriculture—including spatially variable rates for inputs, aided by crop and soil sensors, inter-row seed placement (i.e. between last year’s rows) and controlled traffic—brings another set of agronomic technologies currently receiving attention in Western Australia. However, this seems more likely to deliver cost decreases and resource use efficiencies, rather than yield increases.

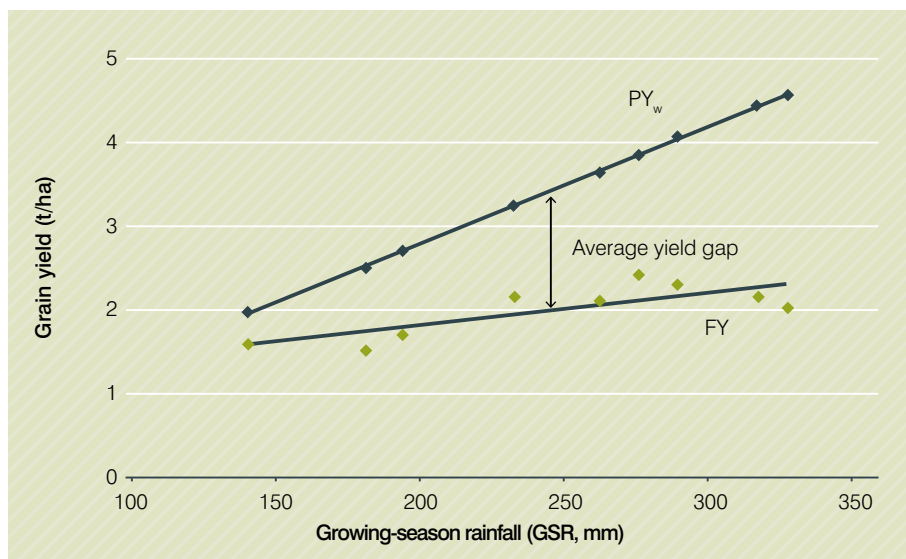


Figure 3.6 Average wheat farm yield (FY) from 1997 to 2006, and water-limited potential yield (PY_w), for nine districts across Western Australia as a function of average growing-season rainfall (GSR) (May–October) of the districts (calculated using equation (11)). Source: Adapted from Anderson (2010)

Physiology and progress in water-limited potential yield in wheat in Australia

Studies of the physiology of genetic yield progress in Western Australia (Perry and D'Antuono 1989; Loss and Siddique 1994) have pointed to the importance of earlier flowering, reduced plant height, increased grain number (GN) and higher harvest index (HI) arising over the past century. There is good evidence for more erect canopies and increased RUE before flowering in more modern varieties (Yunusa et al. 1993). These results are generally confirmed by research in eastern Australia, but comparisons with the most recent varieties are generally lacking. Similar physiological associations with year of release have been reported in Mediterranean Spain for varieties of bread wheat (Acreche et al. 2008) and durum wheat (Royo et al. 2008), but again few modern varieties were included, and there appeared to be little breeding progress after 1975.

Sadras and Lawson (2011) in South Australia did, however, focus on a more restricted 'modern' variety set (releases 1958–2007). Notwithstanding the very favourable season (average yield 4.9 t/ha across three sites), they found that relative progress in PY_w was similar to that shown in Figure 3.5. In this detailed study, PY progress was also associated with increased HI, with greater GN for early vintages, and greater grain weight (GW) for later vintages. There was no change in flowering date and only small reductions in height early in the vintage series. Crop growth rate between stem elongation and anthesis increased with year of release, in parallel with increased RUE (with peak values of 2.7 g/MJ), greener leaves, greater stomatal conductance and more stem water-soluble carbohydrates at anthesis.

Conclusion for wheat in Australia including Western Australia

Western Australia is a particularly marginal version of WME4, both in terms of climate and soil; yet breeders, agronomists and farmers have delivered a remarkable rate of FY progress in the past 30 years (at least 1.2% p.a.). Earlier planting, better control of biotic stresses and better soil fertility have permitted fuller expression of PY of modern semi-dwarf varieties. This is an excellent example of exploitation of the interaction between agronomic management and variety.

PY_w continues to show a modest rate of progress (0.5% p.a.), and there is a reduced but still significant yield gap (about 50% of FY). The yield gap could be closed a little more with fine-tuning of crop and system management, but the period of rapid FY progress may be ending. The biggest impact in the future could come from reducing the statistically small, but greatly feared, risk of economic loss from investing in higher inputs—a dominating feature of marginal rainfed cropping. Steadily improving seasonal forecasts could play a role in reducing risks associated with higher input use.

Wheat cropping systems in eastern Australia (comprising the southern and northern cropping regions) are somewhat more complex than those in Western Australia (the western region). This is partly because of the greater proportion of rainfall outside the

wheat season, and hence greater system options and challenges. Despite differences among the regions, conclusions for progress are likely to be similar. However, Stephens et al. (2011) reported somewhat lower values for water use efficiency (WUE) and for recent WUE progress in the southern and northern wheat regions.

Finally, for all three wheat regions, the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) has regularly used farm survey data to analyse the sources of the significant but declining total factor productivity progress in cropping enterprises (dominated by wheat). Hughes et al. (2011) is the latest and most comprehensive example, and will be referred to in the case studies in Section 12.4.

3.6 WME6—spring wheat at high latitudes

Introduction

WME6 comprises a vast area of high-latitude environments in the Northern Hemisphere where winters are too cold for autumn-sown winter wheat to consistently survive, especially in situations where protective snow cover is not assured. Thus spring wheat is planted in April–May and harvested after mid August. The crop is rainfed and, in most locations, often water-limited. At the southern limits of the WME6 region—where the January mean temperatures reach as high as $-8\text{ }^{\circ}\text{C}$ to $-5\text{ }^{\circ}\text{C}$ —winter wheat is often found alongside spring wheat and, if there is no winter killing, will substantially out-yield spring wheat.²⁸

Major production in WME6 is found in North America and northern Asia, with northern Europe making a smaller contribution. Western Canada and the northern Great Plains states of the USA are the major producing areas in North America (Map 3.6). In northern Asia, major producing areas include half of the Russian Federation wheat area largely in Siberia, as well as northern Kazakhstan (Map 3.7), and Mongolia and north-east China.

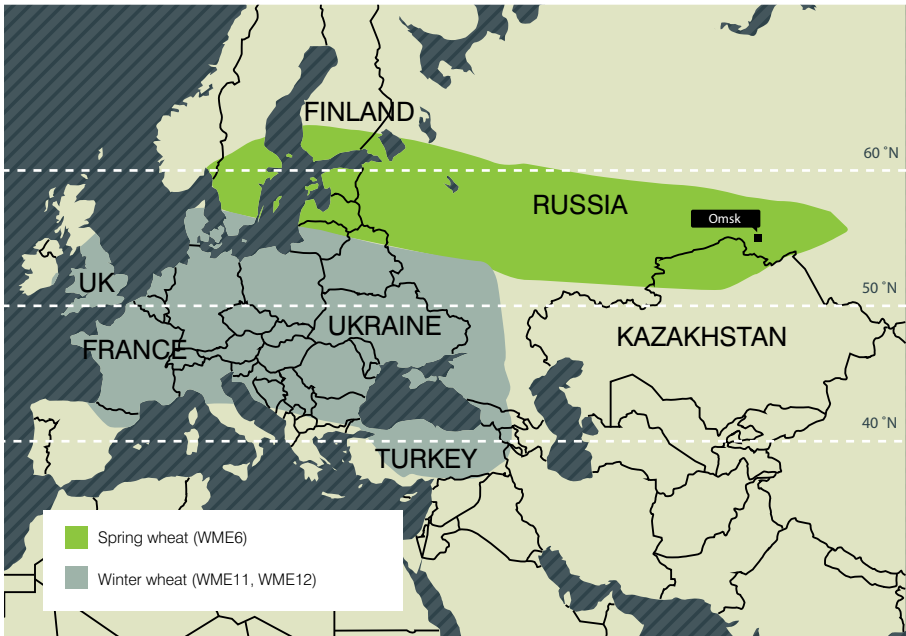
WME6 is of special interest because global warming would likely permit a northern expansion of this mega-environment. Warming and other factors favouring winter wheat—such as greater genetic winter hardiness and better snow trapping with conservation tillage—may at the same time lead to contraction of the WME6 southern boundary.

Trethowan et al. (2006) summarised climatic conditions across the major regions of WME6 in the world and characterised leading wheat varieties from each, but did not discuss yield progress. Fortunately there are some recent detailed studies of progress from North America as well as Finland and Western Siberia.

²⁸ Wheat will be killed by extreme T_{\min} occurrences in the absence of snow cover ($T_{\min} < \text{approximately } 20\text{ }^{\circ}\text{C}$), so average T_{mean} can be taken as only an approximate guide.



Map 3.6 Major spring and winter wheat regions of the USA and Canada. Source: Map developed from USDA CropScape and Monfreda et al. (2008)



Map 3.7 Major spring and winter wheat regions of Europe and north-western Asia. Source: Crop areas hand-drawn after R.A. Fischer (personal observations) and Monfreda et al. (2008)

Wheat in North America—Saskatchewan, Canada

During the 2007–09 seasons, Canadian wheat area comprised 68% spring BW and 23% spring DW. About half of spring BW is found in the driest prairie province, Saskatchewan, which in 2004–08 (latest available data) grew 3.3 Mha of spring BW. Due to rotational diversification, the area of spring BW is now about half what it was 30 years ago. In contrast, canola area has expanded fourfold to reach 2.7 Mha, DW area has increased modestly to 1.7 Mha and broadleaf crops (including pulses, flaxseed and sunflower) now total ~2.3 Mha.

In Saskatchewan crops were traditionally grown on summer fallow (one crop every 2 years) but the proportion of those crops has declined to less than 15%, while the proportion under conservation tillage (stubble retention, chemical weed control during fallow, zero-till seeding, crop every year) has grown to more than 60% (Veeman and Gray 2010). This has happened in the past 20 years or so; thus there has been a true agronomic revolution in Saskatchewan. Although quite variable due to periodic droughts, **spring bread wheat FY has registered significant progress of 19 kg/ha/yr ($0.01 < P < 0.05$) over the past 30 years** (data sourced from STATCAN 2011). **This is equivalent to a gain of 0.8% p.a. relative to the 2010 estimated FY of 2.25 t/ha.**

Using spring BW registration trials (unprotected, mostly on summer fallow) at 13–15 locations across Saskatchewan, DePauw et al. (2007) showed rate of yield increase from breeding (1980–2003) to be 0.74% p.a. of the yield of the control cultivar Katepwa (released 1980). With data given in that paper, **this can be converted to PY_w progress of 25 kg/ha/yr, or 0.6% p.a. relative to the 2003 estimated PY_w of 3.8 t/ha in this water-limited environment.** This is an improvement over only 6.5 kg/ha/yr from trials covering 1947–92 (McCaig and DePauw 1995), equating to 0.2% p.a. relative to a 1992 PY_w of 3.2 t/ha. These two numbers agree with a variety index—calculated from varieties observed to be grown by farmers and their relative PY_w advantage (see Section 2.2)—which showed a 0.3% p.a. rate of progress between 1976 and 2006 (Veeman and Gray 2010). The increase in rate of breeding progress seen in DePauw et al. (2007) is notable given the stringent quality requirements for variety release (such as maintaining high protein content). Among other features, increased progress has been attributed to doubling population sizes in the breeding program.

The above PY_w results suggest that the yield gap for spring BW in Saskatchewan in 2003 was ~75% of FY, with PY_w and FY showing similar relative rates of progress. The gap is somewhat surprising given the widespread inclusion of canola and pulses in the crop rotation, the adoption of conservation tillage and the apparent appropriate use of nitrogen fertiliser (DePauw et al. 2010). The gap estimate could have been biased somewhat due to inflated values of PY_w because of the tendency to grow the trials on summer fallow and to plot edge effects in wet seasons. For example, the breeders' practice of planting plot borders to winter wheat (R. DePauw, pers. comm. 2011) may balance underground moisture competition, but in good seasons is unlikely to compensate for the benefits of extra light intercepted by plot edges.

For spring BW in Saskatchewan, McCaig and DePauw (1995) noted that grains per square metre (GN) increased with year of release, but that time to maturity, plant height, grain weight (GW) and hectolitre weight (weight per hectolitre, an important measure of grain plumpness and predictor of milling yield) had not changed. More recent studies show increases to GW and grain-filling rate (Wang et al. 2002), and nitrogen HI (the proportion of total nitrogen uptake in grains at maturity), with faster and more complete mobilisation of nitrogen to the grain (Wang et al. 2003). Interestingly—given the emphasis placed on deep rooting by an early Saskatchewan wheat breeder, E. A. Hurd—recent studies show no change in soil water extraction to 120 cm depth at maturity (Wang et al. 2007), which was also the case with DW wheat varieties (see next paragraph).

This analysis of spring BW in Saskatchewan is strengthened by a report on spring DW progress (Clarke et al. 2010). These authors showed that over the 1964–2009 period, FY increased at a rate of 16 kg/ha/yr ($P < 0.01$), or 0.7% p.a. of the estimated 2009 FY of 2.2 t/ha. From 6–12 trials annually across the main durum area—unprotected, largely disease-free, all on summer fallow (C. Pozniak, pers. comm. 2011)—rate of breeding progress was strongly linear at 0.7% p.a. of the yield of control cultivar Hercules (released 1969). Quality parameters (protein and pigment concentration, and gluten strength) steadily increased, while disease resistance was maintained. The average PY_w of Hercules was 2.5 t/ha (C. Pozniak, pers. comm. 2011) and the estimated 2009 PY_w was 145.5% of the Hercules PY_w value. **Thus the relative rate of PY_w progress converts to 17 kg/ha/yr, or 0.5% of the estimated 2009 PY_w of 3.6 t/ha, and the yield gap is 65%.** As for BW varieties mentioned above, Veeman and Gray (2010) calculated a variety index for DW varieties grown by farmers, which increased at 0.4% p.a. between 1976 and 2006. Thus the yield gain for DW wheat in Saskatchewan is fairly similar to spring BW, with the same concerns regarding possible inflation of the PY_w estimate.

Given the agronomic revolution in Saskatchewan, it is surprising that FY progress for both bread and durum wheats has not exceeded breeding progress as reflected in PY_w progress. This trend is most likely explained by increased cropping intensity with the decline of summer fallow, a phenomenon that is likely to occur throughout the lower rainfall parts of WME6 with the adoption of conservation tillage.

Wheat in North America—North Dakota, USA

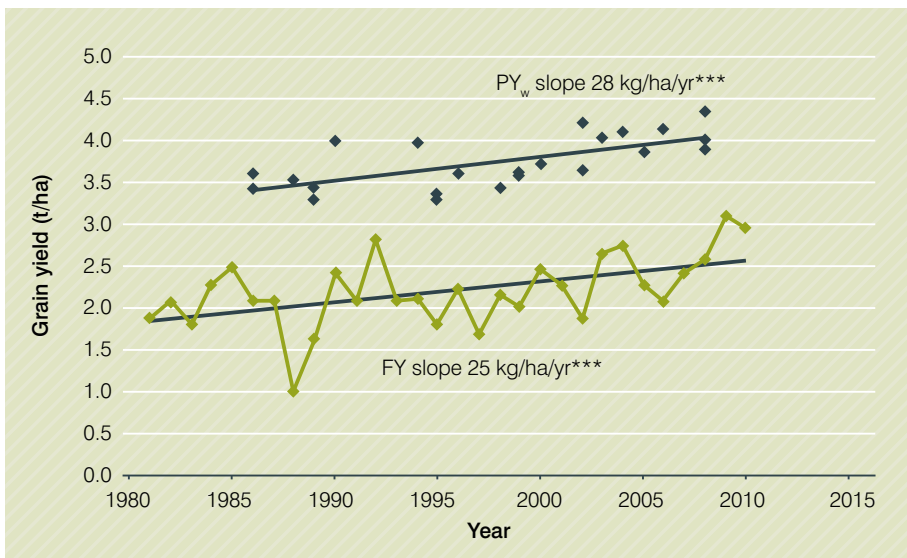
Thirty-one per cent of the harvested wheat area in the USA is in WME6. North Dakota to the immediate south-east of Saskatchewan and in the northern Great Plains is the major spring BW producing state, with a steady annual area of ~2.6 Mha of spring BW. This rainfed crop is grown in rotation with a large diversity of broadleaf crops including canola, sunflower, pulses and flaxseed (total area ~1.3 Mha), plus soybean (1.7 Mha). Only ~0.6 Mha of spring DW and minor amounts of winter wheat are grown. **FY rate of progress for spring BW wheat is 1.0% p.a. of the estimated 2010 FY of 2.5 t/ha (Figure 3.7).**

Underdahl et al. (2008) reported breeding progress across 33 varieties (1968–2008) grown unprotected at five representative sites over two representative years (2004 and

2005). While genetic resistance to leaf rust and *Fusarium* head blight (FHB) improved with time, both were evident in most tests and influenced yield. It is possible to correct progress in PY_w for change in genetic disease resistance by fitting a multiple linear regression with year of release and disease as independents. For varieties released after 1985 there was a good fit for yields ($R^2 = 0.66$), with significant but small coefficients for leaf rust index (Roelfs et al. 1992) and FHB score (Underdahl et al. 2008), and a highly significant coefficient for year of release (28 kg/ha/yr).

Yields (PY_w) corrected for leaf rust and FHB are shown in Figure 3.7. **The estimated 2008 PY_w in Figure 3.7 is 4.0 t/ha, giving a rate of 0.7% p.a. PY_w progress.** Without correction for disease, there was a biased and higher linear slope for year of release (39 kg/ha/yr) because older varieties had become more susceptible to disease. **Assuming that PY_w is representative in space and time, the yield gap in North Dakota therefore is ~1.5 t/ha or 60% of FY (Figure 3.7).** The yield gap in Figure 3.7 appears to be closing only gradually, perhaps for the same reasons as given for Saskatchewan, and despite the fact that springs are becoming warmer and spring wheat planting dates earlier in the North Dakota region (Lanning et al. 2010), something that should favour FY, other things equal.

Underdahl et al. (2008) found that breeding between 1968 and 2008 did not change plant height or days to heading, but did increase GN, GW and hectolitre weight.



*** $P < 0.01$

Figure 3.7 Change in farm yield (FY), plotted against year, and corrected (see text) water-limited potential yield (PY_w), plotted against year of variety release, for spring bread wheat from 1981 to 2010 in North Dakota, USA. Source: NASS (2012) for FY; Underdahl et al. (2008) for PY_w

Wheat in Finland

At very high latitudes (60 °N and 65 °N) and under mostly humid conditions, Finland now grows 0.20 Mha of wheat, 95% of which is spring bread wheat. The area has doubled since Finland joined the European Union (EU) in 1995. FY increased between 1980 and 1996, then dropped away sharply in 1995 (from 4.0 to 2.0 t/ha) as farmers adjusted to the new regime, before recovering to **a long-term trendline showing steady progress of 35 kg/ha/yr (0.01 < P < 0.05) over the past nine years (equating a rate of 1.0% p.a. FY progress), with an estimated FY of 3.7 t/ha in 2008.**

Progress has been analysed by Peltonen-Sainio et al. (2009a) using the Official Variety Trials conducted during 1976–2006 at 28 locations across the country; trials appeared to follow good farmer practice, but were unprotected. A mixed-model statistical technique determined the fixed effect of variety, which was then plotted against year of variety introduction into the trials. Breeding progress was linear throughout (36 kg/ha/yr) but average yield of these trials fell away after 1995 before recovering to be closely parallel to FY, although a few hundred kilograms per hectare above FY (Peltonen-Sainio et al. 2009a).

Peltonen-Sainio et al. (2009a) ascribe levelling-off of yields to the EU agricultural policy and changes in markets (for example, poorer farmer terms of trade as support shifted from grain price support to direct income payments). Nitrogen use has been restricted, so fertiliser rates have declined and practices have become less intensive. **The Peltonen-Sainio et al. (2009a) data suggest that PY (with the best agronomy) was at least 4.8 t/ha in 2006;** PY was somewhat greater in the south than in the north, in proportion to the change in growing-season length (P. Peltonen-Sainio, pers. comm. 2011). From these data, **the rate of PY progress in 1976–2006 was 0.8% p.a. and the 2006 yield gap is ~30% of FY.**

PY increase in Finland in spring bread wheat has been associated with increased GN rather than increased GW (Peltonen-Sainio et al. 2007). Harvest index (HI), currently only 0.40, is seen by Peltonen-Sainio et al. (2009a) to offer scope for further PY increase through breeding. Climate change effects have been minor to date, although warming has permitted earlier spring cereal sowing (by 1–3 days per decade since 1980) (Kaukoranta and Hakala 2008). Future warming is expected to increase wheat yield through earlier planting and a longer growing season, as well as increasing the cultivable area for wheat (Peltonen-Sainio et al. 2009b).

Wheat in Western Siberia, Russian Federation

The Russian Federation grows ~14 Mha of spring wheat (2006–08 average; ROSSTAT 2012), approximately as shown in Map 3.7. The western Siberian region, lying between latitude 54 °N and 56 °N and longitude 60 °E and 90 °E, grows about one-half of the 14 Mha of spring wheat grown in the Russian Federation (Morgounov et al. 2010).

Focusing on the centrally located Omsk district, annual precipitation is low (325 mm) and wheat is generally grown on summer fallow (one crop every two years). FY is quite variable (as might be expected in a low-rainfall region), but during 1980–2011 has nevertheless grown significantly ($0.01 < P < 0.05$) at a rate of 1.1% p.a. relative to the estimated 2011 FY of 1.6 t/ha (data supplied Y. Zelenskiy, CIMMYT, pers. comm. 2012).

At the Siberian Institute of Agriculture (SRIA) at Omsk, vintage trials over seven years (2002–08) compared 47 varieties grown in the region between 1900 and 2000 (Morgounov et al. 2010). Plots were unprotected and received no fertiliser, but the Chernozem soil was very fertile with 6–7% organic matter. Since leaf rust levels and heading date were recorded and had effects on yield, a multiple regression was again made but using grain yield of only the most recent 26 varieties (1976–97) along with the independent variables: leaf rust score, days from seedling emergence to heading and selection year. The regression coefficient for leaf rust was significant (-5.5 kg/ha/\% ; $P = 0.03$), while both that for days to heading (84 kg/ha/d ; $P = 0.008$) and year of release (56 kg/ha/yr ; $P < 0.001$) were very highly significant (overall $R^2 = 0.702$). For an average number of days from emergence to heading (44 days) and zero rust, the predicted PY_w was 4.4 t/ha for a variety selected in 1997. Thus the **rate of increase in PY_w of 56 kg/ha/yr amounts to an impressive 1.3% p.a. of the 1997 variety PY_w** . The yield gap was large, at $\sim 175\%$. There is, however, insufficient information to ensure that the soil and climate at SRIA are representative of the region, and thus to ascribe this gap solely to management.

The strong breeding progress seen at SRIA, Omsk, may explain why varieties from western Siberian performed best across all WME6 environments in the study of Trethowan et al. (2006). The Siberian varieties tend to be tall (average 106 cm, no major dwarfing genes used) and late flowering because of their photoperiod sensitivity. Neither of these traits has been changed consistently by breeding at Omsk and both are probably critical for high-latitude adaptation in spring wheats (Morgounov et al. 2010). Breeding progress was, however, highly significantly associated with both increased GN and GW, the former driving about three-quarters of the PY_w yield increase seen at Omsk.

Immediately south of the western Siberian region are the vast rainfed spring wheat lands of northern Kazakhstan. Under drier conditions than in Western Siberia, currently 12 Mha of spring BW is grown for a FY of about 1.2 t/ha (Petrick et al. 2013). Data on progress are currently unavailable, but Omsk varieties are among those grown in the region. Northern Kazakhstan is adopting conservation tillage rapidly, with very positive results.

Conclusion for spring wheat at high latitudes

Progress in FY (0.7–1.0%) appears quite respectable across the WME6 examples studied, as does PY and PY_w progress (0.6–1.3%); the latter progress is largely from breeding and has been achieved in the face of strong emphasis on grain quality in the North American situations. The adoption of conservation tillage has been a major

agronomic innovation in the past 20 years in North America and Kazakhstan; however, its contribution to PY_w is not clear because it has reduced the proportion of wheat grown after summer fallow, especially in western Canada. Yield gaps range from 30% to 85% of FY, with the exception of a likely larger yield gap in Western Siberia that needs further investigation. Not enough information was available on farm-level constraints anywhere, except that a less yield-positive European Union (EU) policy environment is reported from Finland. WME6 in North America is unique for the generally high degree of rotation of wheat with broadleaf grain crops (canola, pulses, sunflower and flaxseed). Such rotation is also facilitated by conservation tillage, but when compared to wheat, most of these rotation crops have the disadvantage of leaving little residue for snow trapping. The plant phenotype for best performance under spring sowing at high latitude appears to be unique, as exemplified by the most recent tall day-length-sensitive Siberian varieties.

3.7 WME10-dominated wheat in China

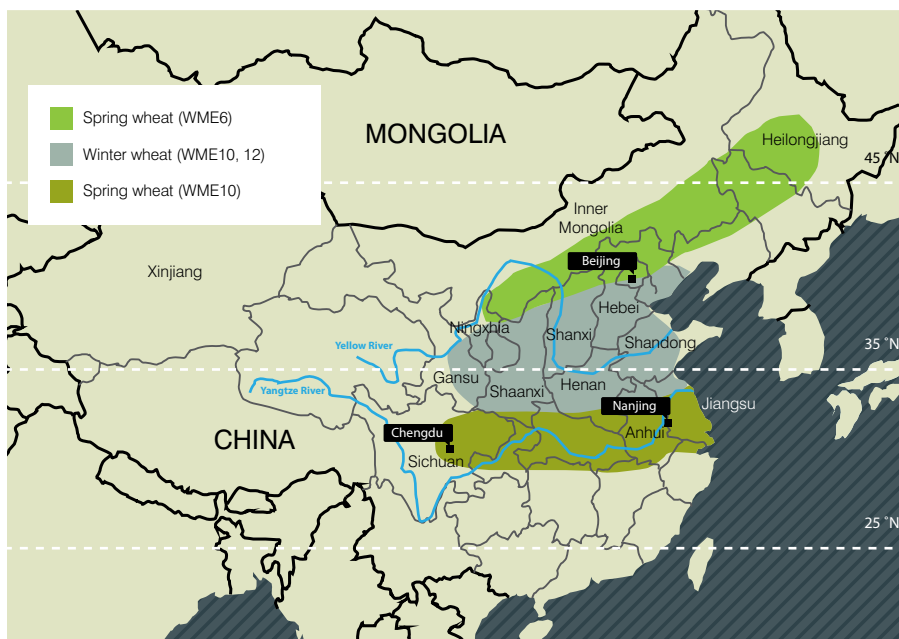
Introduction

China is the world's biggest wheat producer. However, driven by policy aimed to balance supply and demand, and by competition from higher value cropping, wheat area has decreased by ~2% per year since 1990 (Table 3.1), levelling out at almost 24 Mha during 2009–12. As the contraction of wheat area has been greater in the lower yielding north-east than in the major high-yielding wheat provinces of the central north, the overall value for FY progress may be slightly inflated by this effect.

Since 1991, national FY has shown a strong rate of progress (81 kg/ha/yr; $P < 0.01$, or 1.7% of the estimated 2010 FY of 4.7 t/ha). In the past decade, there has also been notable progress in the industrial quality of new varieties (He et al. 2010). Undoubtedly most of the yield gain reflects increased fertiliser use and improved varieties. Both technologies have been encouraged by the economic system of 'household responsibility' introduced in 1979, and have driven yield progress across the country (H. Wang et al. 2009). Further reforms were introduced in 2004 as China sought to stay close to self-sufficiency in wheat (and rice). These later reforms reduced farmers' taxes and instituted modest subsidies for staple grains (J. Huang et al. 2011).

Wheat in China covers several mega-environments—principally WME1, WME6, WME10, and WME12 (Map 3.8)—and there is great diversity in wheat systems, agronomy and varieties (He et al. 2010). The major region is winter and facultative wheats (WME10 and WME12) and this region comprised 59% of the 2007 wheat area. A large proportion of this major region is irrigated (WME10) and located in the North China Plain, which runs north from the Huai River Valley (32 °N) to Beijing (40 °N) and west to the edge of the Loess Plateau. WME10 is divided into the Northern Winter Wheat Zone (Hebei

province, and Beijing and Tianjin municipalities) and the Yellow River and Huai River Valleys Winter and Facultative Wheat Zone (Henan and Shandong, and parts of Jiangsu and Anhui provinces). Irrigation supplements the low to moderate in-crop rainfall in both zones (F. Wang et al. 2009). Wheat is followed by maize (the dominant double-crop system), but also by cotton, peanut and other summer crops. To the west, on the Loess Plateau, the largely rainfed plantings of Shaanxi, Shanxi and Gansu provinces are winter and facultative wheats (WME12).



Map 3.8 Major wheat regions in China—autumn-sown spring wheat (WME1), winter and facultative wheat (WME10, WME12) and spring-sown spring wheat (WME6). Source: Map drawn after data from He et al. (2010) and Monfreda et al (2008). International borders are approximate.

Autumn-sown spring wheat (WME1) represents ~33% of China's wheat area and is grown south of latitude 32 °N, in the middle and lower Yangtse Valley (Jiangsu and Anhui provinces) and Sichuan province in the south-west. In this region, moderate to high in-crop rainfall markedly reduces the need for irrigation. Across WME1, the wheat is double cropped with summer rice, bringing parallels with India's Indo-Gangetic Plain (Section 3.3). Finally, spring-sown spring wheat (WME6) represents 8% of China's wheat area and is found nowadays in the far north (Inner Mongolia and Ningxia provinces) rather than the more humid north-east (Heilongjiang province) where wheat area has declined notably in favour of maize and soybean.

Both WME10 and WME1 regions have recent reports on breeding progress and were the subject of a comprehensive review of agronomic advances (F. Wang et al. 2009). Several unique factors bolster interest in the Chinese wheat system:

- very small farm size (0.5–0.7 ha)
- intensity of cropping systems (~150%) in which wheat is found
- reports of significant warming in the northern wheat season over the past 30 years
- investment in hybrid wheat.

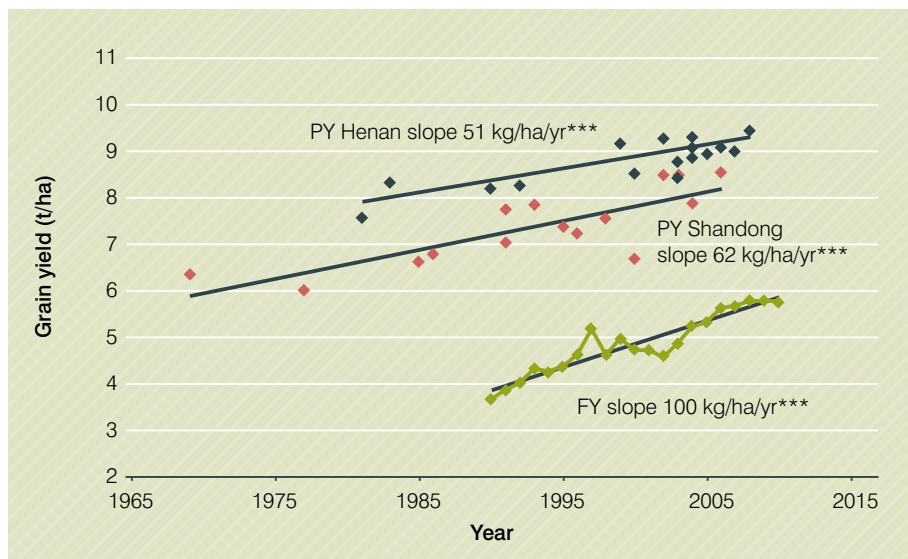
Evidence of warming is provided, for example, by Tao et al. (2012), who studied changes in temperature and wheat phenology across China. Since 1980, heading and maturity dates of adapted varieties have been advancing at least partly because the growing season has become warmer and the growing cycle shorter; so planting dates of autumn-sown wheats have tended to become later. For example, at Zhengzhou in Henan province, the wheat season mean temperature increased by ~0.75 °C per decade, and the advances in heading and maturity were 2.6 and 0.6 days per decade, respectively. These changes are likely to be positive for wheat yield, especially in WME6, WME10 and WME12, where winters are normally very cold. Moreover earlier wheat maturity (and later wheat planting) would have positive implications for performance of summer crops following wheat in the North China Plain.

Progress in WME10—irrigated winter and facultative wheat region

Over the past 20 years, wheat in the two major winter and facultative wheat provinces, Henan and Shandong (together growing a total of almost 9 Mha), shows an impressive **rate of FY increase of 1.7% of the estimated 2010 FY of 5.8 t/ha** (Figure 3.8). The drop in yield seen in 2001–02 can be attributed to policy hiccups, and while Figure 3.8 indicates a slowing in FY progress in the past 5 years; this does not declare an end to yield increase. Policy changes, improved varieties and nitrogen fertiliser (as mentioned above) were important for the wheat yield increase, aided in these two provinces by the spread of tube well irrigation. Rate of yield progress in FY has also been excellent in the adjacent winter wheat growing province of Hebei; FY progress has been 1.5% p.a. of the current 2010 FY of 5.3 t/ha.

The PY progress from winter and facultative wheat breeding—as seen with the protected vintage trials shown in Figure 3.8 and Table 3.4—confirms earlier reports across the same region (Zhou et al. 2007b), but extends to varieties from the last decade and adds physiological measurements. In all cases in Table 3.4, progress was linear with no decline in rate after 1990. The lower PY seen in Table 3.4 in the Hebei study probably fell short of full PY. For example, at a nearby site Zhou et al. (2007b) reported PY values for winter wheat varieties (vintage 2000) around 7 t/ha. Nevertheless, the Hebei study provides useful corollary data.

The PY data from **Henan and Shandong provinces (Figure 3.8, Table 3.4) suggest that the current PY is around 8.8 t/ha; hence, the average relative rate of PY progress is 0.7% p.a. and the yield gap is 50% of FY.** This estimate of PY agrees with the 9.1 t/ha from extensive experiments of Liang et al. (2011) in Hebei, and also H. W. Li et al. (2012) in northern Jiangsu (35 °N). Over 3 years with a recent variety of winter wheat, the latter authors achieved a PY of 7.9 t/ha using high-input farmer practice and 9.7 t/ha with innovative agronomy.



*** $P < 0.01$

Figure 3.8 Farm yield (FY) given as the arithmetic mean of Henan and Shandong provinces of China, plotted against year, and winter and facultative wheat potential yield (PY) plotted against year of variety release, from 1969 to 2010. Source: FY (Z. He, pers. comm. 2011), PY (T. Zheng 2011 for Henan, and Xiao et al. 2012 for Shandong)

Simulations of PY have been made for wheat across the North China Plain using the WOFOST model (Wu et al. 2006). These authors found PY rose from 7.5 t/ha in the far south to 9.5 t/ha in the north, more or less as solar radiation increased and mean temperature fell. This agrees with Figure 3.8 estimates for locations in the central region (34 °N to 36 °N). Liang et al. (2011) simulated PY of winter wheat in Hebei to be 11.5 t/ha. Using a locally validated version of the APSIM model, Chen et al. (2010) estimated the average simulated PY for wheat at latitude 38 °N in the North China Plain to be 7.1 t/ha; this figure is judged to be too low, and will not be considered further.

Table 3.4 Recent reports from China of wheat potential yield (PY) progress through breeding, and associations of PY change with harvest index (HI), final dry matter (DM), grain number (GN), grain weight (GW) and other physiological traits

Province	Vintage range	PY			PY associations ^a					Source ^b
		Slope		Latest variety t/ha	HI	DM	GN	GW	Physiological traits ^d (all positive and $P < 0.05$)	
		kg/ha/yr	% p.a. ^c							
Winter (and facultative) wheat (WME10)										
Hebei	1970–2000	60	1.0	6.1	***	***	***	ns	Heading RWC, P_{max}	1
Henan	1981–2008	51	0.6	9.3	***	**	*	***	Grain-fill P_{max} and g_s	2
Shandong	1969–2006	62	0.8	8.2	***	***	***	ns	Anthesis LAI ^e , grain-fill P_{max}	3
Spring wheat (WME1)										
Jiangsu	1949–2000	14	0.3	4.8	ns	ns	ns	ns		4
Sichuan	1949–2000	41	0.6	6.8	***	**	ns	***	Days to heading ^e	4
Jiangsu	1950–2005	54	0.7	7.5	**	ns	***	***	^e Spikes/m ² , LAI, P_{max} all times	5

a ns = $P > 0.10$; * $0.05 < P < 0.10$, ** $0.01 < P < 0.05$, *** $P < 0.01$

b 1 X. Zhang et al. (2010) under the three-irrigation regime, 2 T. Zheng et al. (2011), 3 Xiao et al. (2012), 4 Zhou et al. (2007a), and Z. Tian et al. (2011) at the highest level of nitrogen application

c Relative to latest variety shown

d RWC = relative water content; P_{max} = maximum photosynthetic activity; g_s = stomatal conductance; LAI = leaf area index

e Negative associations

The analysis from Liang et al. (2011) is more interesting because of the attention given to FY in the irrigated wheat–maize system across many farms at latitude 37 °N in the Hebei Plain for the 2004–05 season. The average FY was 6.6 t/ha; the average for on-farm maximum yield experiments was 9.1 t/ha; and, as mentioned, the average simulated PY was 11.5 t/ha. Taking PY as the average of the last two values leaves a yield gap of 60% of FY. These authors went on to list FY constraints as:

- inappropriate sowing time (70% of farmers)
- poor seedbed preparation due to heavy maize residue and inadequate machinery
- poor irrigation control due to infrastructural failures
- excess nitrogen use (average 300 kg N/ha), bringing more diseases and lodging.

Phosphorus use averaged 67 kg P/ha (adequate) and potassium 21 kg K/ha (inadequate), but rates varied greatly among farms. It was also noted that farms were very small, farmers were poorly informed by a weak extension system and many farmers were attracted to more remunerative urban work. The Liang et al. (2011) survey is probably well representative of irrigated winter wheat in the North China Plain. For example, excess nitrogen use is common throughout China.

It remains to be emphasised that winter and facultative wheat generally consumes large amounts of irrigation water (on average >200 mm and increasing as winter–spring rains decrease with more northerly locations). Where irrigation is drawn from groundwater (a common practice), the watertable is falling by >1 m per year (see Section 11.2 ‘Water use efficiency’). Wu et al. (2006) also simulated rainfed yields, and found that yields of irrigated wheat exceeded rainfed yields by 1 t/ha in the south, and by as much as 5 t/ha in the north, so irrigation water supply is a looming problem.

Considerable physiological knowledge regarding PY progress has appeared recently (as summarised in Table 3.4). Plant height decreased in the 1970s (but not thereafter), settling around an optimum of 80–90 cm under the influence of major dwarfing genes *RhtD1b* or *Rht8c* (or both). Days to flowering remained unchanged, except with varieties from Hebei, which flowered 4 days earlier over the vintage range. Chinese authors comment that the plant type has become sturdier, with more erect and sometimes smaller leaves, but that not even the best winter and facultative varieties in Table 3.4 had harvest index (HI) values greater than 45%. Xiao et al. (2012) and T. Zheng et al. (2011) reported maximum photosynthetic rate (P_{max}) increases during (but not prior to) grain-filling, while X. Zhang et al. (2010) reported similar increases at heading (the only stage measured).

The study of X. Zhang et al. (2010) in Hebei province is also noteworthy for determining complete water balances. It revealed that evapotranspiration (ET) for crops receiving three irrigations (and probably therefore unstressed) increased only 4% across the vintage range (average ET ~450mm) while yield rose 34%, and thus water use efficiency was increased notably by breeding (see also Figure 11.1). X. Zhang et al. (2011) later reported that stomatal conductance around anthesis increased significantly (~30%) among varieties released between 1970 and 2000.

Progress in the southern spring wheat region—WME1

Over the past 20 years in Jiangsu province (2 Mha of wheat), FY advanced at a rate of 39 kg/ha/yr ($0.01 < P < 0.05$), to reach 4.6 t/ha in 2010. Thus the current rate of 0.8% p.a. FY progress is below that of the winter and facultative wheat areas immediately to the north. Further to the south-west and with a warmer climate, Sichuan province (1.3 Mha of wheat) showed no FY progress at all and averaged 3.4 t/ha.

Spring wheat PY in protected vintage trials was also linearly related to year of release (Table 3.4) over a period that, at the outset, included the introduction of major dwarfing genes. However, the first Jiangsu study—although registering significant

yield progress—had generally low yields without clear explanation. **The results for Sichuan were clearer (0.6% p.a. PY progress), as was the second Jiangsu study involving three seasons and three levels of nitrogen (0.7% p.a. PY progress).**

Taking 7.5 t/ha as the current PY in Jiangsu, the yield gap is 65% of FY. A PY of 6.8 t/ha in Sichuan indicates a large yield gap of 100% of FY. Both provinces experience high humidity throughout spring and are subject to heavy disease pressure, in particular from *Fusarium* head blight in Jiangsu, and yellow or stripe rust in Sichuan. Given that a variety derived from a synthetic bread wheat (of CIMMYT origin) was recently reported to deliver both a 20% yield increase and good yellow rust resistance in Sichuan (He et al. 2010), absence of strong yellow rust resistance may explain the lack of FY progress in Sichuan; with no other information on the situation in Sichuan it is not included in the summary analysis (Table 3.6).

Excluding the earlier Jiangsu study (Zhou et al. 2007a), spring wheat PY progress was associated with HI and GW (Table 3.4). Also, PY in Sichuan was associated with earliness. The later Jiangsu study (Z. Tian et al. 2011) at Nanjing in Jiangsu was quite comprehensive, with four to nine varieties from each decade. In that study, spike number decreased with PY progress, but area per flag leaf and leaf area index (LAI) increased, as did P_{\max} , measured from 10 days before anthesis to 35 days after (P_{\max} increased 15% from the 1955 to the 2005 vintage). Zhou et al. (2007a) reported that HI reached 48–50% in the best varieties, while Z. Tian et al. (2011) reported just 40%.

Hybrid wheat in China

Another significant development for the winter wheat areas of China is the ongoing investment to develop a viable hybrid wheat system (He et al. 2010). Taking advantage of thermo-photo sensitive male sterility (otherwise known as a two-line system), which permits seed production in more southern regions,²⁹ together with considerable progress in selecting for improved natural cross-pollination, hybrid seed production is showing some promise. Hybrid varieties are yielding ~10% more than inbred varieties in northern China and planting of hybrid wheat reached 20,000 ha in 2009–10 (C. Zhao, pers. comm. 2012).

Conclusion for wheat in China

Wheat in China has been a great success story over the past 20 years. FY has increased at an unprecedented rate (1.7% p.a.) across more than 24 Mha of very small farms. The revolution began in the early 1980s when farmers were given greater individual plot responsibility and greater marketing opportunities; yield progress was driven by more irrigation, more fertiliser, a continuing stream of modern varieties, and (later) small-scale mechanisation.

²⁹ The gene causes male sterility in cool short days.

Research investment in wheat in China continues to be substantial, but PY progress is now well behind that in FY. This means that the yield gap is closing (as seen in Figure 3.8), but even so, remains surprisingly large (50% and more). The remaining constraints to FY—apart from water shortages in the north, and widespread disease in farmers' fields in the south—are not easy to identify, but appear to relate to generally inadequate crop management from poorly resourced and very small farms.

The substantial investment in modern breeding techniques (including hybrid wheat) needs now to focus also on disease resistance and quality, and be matched by attention to on-farm crop management. A further consideration is that, with scarce arable land, it makes sense for China to shift to higher value land uses and keep wheat production close to (but not more than) consumption. For example, 2007–09 statistics indicate China's net wheat imports were about 1 Mt annually.

3.8 WME11—United Kingdom and other parts of north-western Europe

Introduction

Wheat mega-environment WME11 comprises the humid, rainfed winter wheat areas of northern and central Europe, Ukraine and southern Russian Federation, and eastern USA. This is the largest WME in both area and production (Table 3.2).

The United Kingdom (UK) provides an important guide to progress. The well-documented UK situation combines a competitive private breeding sector, substantial but diminishing public sector research, and skilled farmers who these days operate at world prices. WME11 areas in other north-western European countries are considered briefly in this section—in particular, to illustrate interesting policy developments.

Wheat farm yield, potential yield and yield gap in the UK

Despite the northern latitude (51 °N to 55 °N), the humid maritime climate of the UK (Map 3.7) affords mild winters. The wheat crop is not irrigated but the UK growing-season temperatures and evapotranspiration are both relatively low. This combination of conditions offers one of the most favourable wheat growing environments in the world. Even so, Sylvester-Bradley et al. (2005) cite estimates showing, over a run of years, that low moisture may reduce average national yields by 10–20%, primarily on sandy and/or shallow soils in the drier south-east.

Carver (2010) provides an excellent review of the current wheat industry in the UK. He notes that winter wheat dominates, and occupies the land for 10–11 months each year (planted September–October, flowering early June and harvested August). The UK has among the highest national average wheat FY, now reaching ~8 t/ha over 1.9 Mha (Figure 3.9), although it is interesting to note that Ireland, Belgium and The Netherlands produce slightly higher FY (Table 3.5) but over much smaller areas.

UK wheat area has changed little over the past 20 years (Table 3.5), and FY progress has clearly slowed since the mid 1990s (Mackay et al. 2010). During the past 20 years FY has fluctuated (6.8–8.3 t/ha, at 15% moisture) with three clearly poorer years (Figure 3.9), **yet FY has progressed significantly ($0.01 < P < 0.05$), but only at 0.4% of the estimated 2010 FY of 8.0 t/ha.** Others have pointed to a FY plateau in UK wheat yields (P. Grassini, pers. comm. 2012; Lin and Huybers 2012), detected to commence in 1997 from analyses starting with 1960 yields. However, as this book describes at the outset (Section 2.2 on measuring progress in PY and FY), the focus here is to analyse FY change over the past 20 years in stable humid situations like the UK. A 20-year period is too short to identify a major shift in slope (such as the onset of a 'yield plateau').

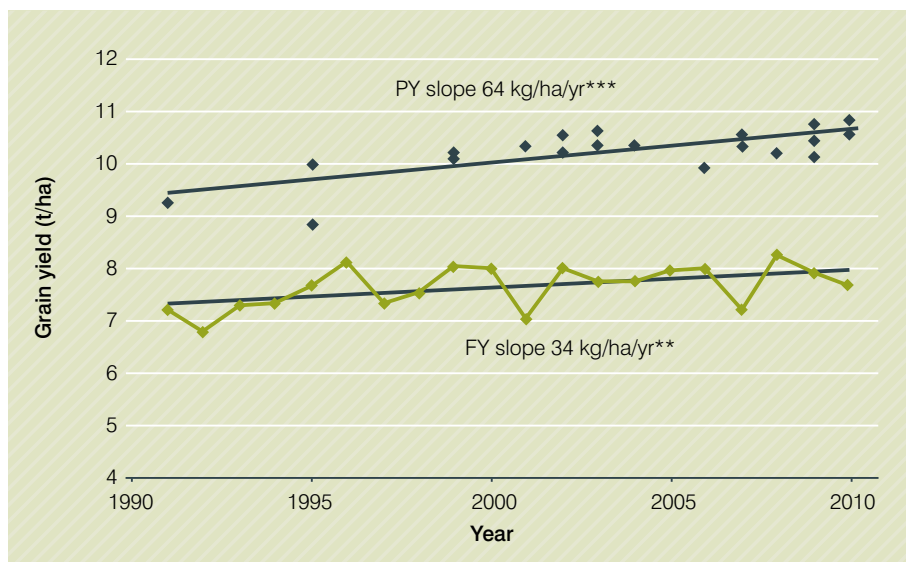
An excellent and extensive system of national trials for the UK (complete with disease and pest control) is conducted by the Home Grown Cereal Authority (HGCA). These trials permit estimation of PY progress and the current PY level. The 2006–10 trials (HGCA 2011), which are dominated by the latest varieties, showed an average control yield of 10.5 t/ha. Figure 3.9 shows a 20-year series constructed from HGCA (2011) for 1991–2011 releases of food classes of BW (milling and soft bread wheats)—**PY is seen to be increasing at 0.6% p.a. of the estimated 2010 PY level (10.7 t/ha).**

The HGCA (2011) data also permit examination of the performance of various classes of variety released since 2000. Milling wheats showed 0.4% p.a. progress for this period, and feed wheats 0.7% p.a.—both significantly ($0.01 < P < 0.05$) positive, but not different from each other. Note that the UK wheat crop is about two-thirds feed varieties, which yield about 3% more than milling varieties of the same vintage.

There have been other recent estimates of PY progress in UK winter wheats. Shearman et al. (2005) reported PY progress of 119 kg/ha/yr (or 1.0% p.a. of the 1995 PY) for 1972–95 releases grown at Sutton Bonington. Mackay et al. (2010) applied appropriate statistics to the huge unbalanced dataset from HGCA trials over the years, and estimated progress in PY (from the fungicide-protected series) for 1982–2007 releases to be 74 kg/ha/yr (or 0.8% p.a. of the 2007 yield). Interestingly, the difference between protected and unprotected yield of a given variety increased on average at ~100 kg/ha/yr of variety age, but 'unprotected' was already 1.8 t/ha lower in the first year of testing.

Finally, more than 40 varieties from 1953 onwards were independently tested under the HGCA protocol at three or four sites per year from 2007 to 2010 (R. Sylvester-Bradley, pers. comm. 2010). Excluding old varieties prone to lodging, this independent

testing revealed that leading milling varieties (1980–2008) progressed at 53 kg/ha/yr (or 0.5% p.a. of the 2008 PY) while leading feed varieties (1977–2007) progressed at 45 kg/ha/yr (or 0.4% of the 2007 PY), with neither showing any tendency for rate decrease in the last decade.



0.01 < P < 0.05, *P < 0.01

Figure 3.9 Wheat farm yield (FY) plotted against year, and potential yield (PY) plotted against year of variety release, in the UK from 1991 to 2010. Source: FAOSTAT (2013) for FY; HGCA (2011) milling plus soft winter wheat varieties (released 1991–2011, grown 2006–10) for PY

In summary, the estimate of 0.6% p.a. current PY progress in the UK, as shown in Figure 3.9, is close to the average of these other UK studies, but a little below Danish, French and Dutch data, presented below. With FY estimated to be 8.0 t/ha in 2010 and PY 10.7t/ha (Figure 3.9) **the current yield gap in the UK is 2.7 t/ha or 34% of FY**, and the relative slopes suggest that yield gap may be increasing slightly. New varieties are adopted rapidly in the UK, so the yield gap is likely due to crop management.

The aforementioned Mackay et al. (2010) study using HGCA trial results also calculated year effects, which in this case reflect changes in trial agronomy, but may also include any effect from an increase in CO₂ or other shifts caused by weather. Independent modelling (Jaggard et al. 2007) suggests that 1976–2004 wheat yields showed no significant trends due to climate alone. Therefore year effects seen in Mackay et al. (2010) are largely agronomic. In fact, until 1981 the apparent PY gains from agronomy were as important as gains from new varieties. It is notable, however, that gains from agronomy were close to zero for 1981–2007.

Limited yield gains from changed agronomy arising since 1981 may also have been the case in farmer fields. Certainly grain farmers' terms of trade have deteriorated since then as EU policies moved away from price support. Nitrogen use has not increased since 1981, and currently averages 174 kg N/ha for feed wheats and 204 kg N/ha for milling wheats (Carver 2010). Crops are now sown earlier, however, with more than 50% of crop planted before 30 September (Carver 2010), bringing yield advantages (provided excess early growth is avoided). Other agronomic indicators—tillage, rotation, biocide and growth regulator usage—have not changed notably.

Approximately 70% of the current 30 or so winter wheat HGCA trial sites each year follow non-cereal or oat crops. In the 2011 HGCA trials, wheat following non-cereal crops yielded 17% more than wheat following cereals other than oats, and fungicide protection across all trials prevented a 15% loss in yield. This does not imply, however, that the yield gap is due to losses from pests and disease. In fact, UK farmer fields are usually well protected by chemical applications. Carver (2010) reports that UK farmers now average about seven biocide applications, and at least one growth regulator application per crop. The high number of passes through the growing crop necessitates the use of the 'tramlines' that are so evident in UK crops.

The yield gap is more likely to be caused by a host of small losses driven by economic decisions to use lower input levels, and poorer timing and rotations than those adopted in the HGCA trials. In addition there is the ongoing challenge of biocide resistance (e.g. in mildew, *Septoria* sp. and grass weeds) and the growing challenge of environmental regulations on nitrogen use (Carver 2010). Even so, with such a relatively small gap between FY and PY in the UK, FY may already be close to attainable yield. This leaves little scope for the UK to close the yield gap, and implies that future FY increase is more dependent on PY increase, which in turn now largely depends on breeding.

Physiology of yield progress in the UK

Shearman et al. (2005) offer the most recent thorough study of the physiology of yield progress in UK winter wheat. This study was dominated by seven semi-dwarf varieties released since 1980, which is fortunate, given that all new varieties now carry one or other of these major dwarfing genes. Grain yield progress was clearly associated with more grains per square metre (GN), more spikes per square metre, increasing harvest index (HI) across older varieties and greater final DM with later varieties. Grain yield progress was not associated with grain weight (GW).

The Shearman et al. (2005) findings confirm several earlier studies in north-western Europe (although none of the earlier studies recorded progress in final DM). Shearman et al. (2005) also found RUE to increase in the critical pre-anthesis period (Growth Stage 31–61; peak RUE was ~2.6 g/MJ) with year of release—flag leaves became smaller, thicker and more erect with newer varieties. At anthesis, total DM (g/m²) tended to increase with year of release, while the weight of stem water-soluble carbohydrates then clearly increased at a rate about equal to 20 mg per extra grain (average GW was 53 mg) and approached 4 t/ha in the latest varieties.

Sylvester-Bradley and Kindred (2009) examined nitrogen use efficiency (NUE), which they defined as grain yield per unit of nitrogen supply (soil plus fertiliser application,³⁰ reported as kg/kg N). The study compared old varieties (1977–87; $n = 10$) with new varieties (1991–2007; $n = 15$) in experiments across the UK—all of which were managed according to HGCA protocols—and produced 129 variety nitrogen response curves. Results indicated that, at any given nitrogen level (e.g. 200 kg N/ha), new winter wheat varieties out-yielded old varieties (9.47 t/ha vs. 8.34 t/ha) and delivered higher NUE (26.5 kg/kg N vs. 23.4 kg/kg N). The findings of Sylvester-Bradley and Kindred (2009), showing higher NUE in new varieties, are probably due to small gains (at a given nitrogen level) in both components of NUE—nitrogen capture (uptake) efficiency and nitrogen use efficiency (see also Section 11.3 'Nutrient use efficiency').

Wheat in other parts of north-western Europe and the impact of policy

Table 3.5 shows relevant wheat FY data from countries in north-western Europe, dominated by winter wheat grown under reasonably similar humid conditions as in the UK. The UK is included in Table 3.5 for purposes of comparison, but note that the 20-year period in Table 3.5 refers to 1990–2009 (not to 1991–2010 used above and in Figure 3.9).

The UK is seen to occupy an intermediate position in terms of FY rate of progress and current FY. Belgium is the outstanding performer for FY progress (Table 3.5). With the advantage of better rainfall and more sunshine than the UK, Ireland is the highest yielding country (but limited to a very small area of feed wheat).

A national perception of lack of recent FY progress with wheat in Denmark has been subject to detailed scrutiny by Petersen et al. (2010) who calculated progress of only 18 kg/ha/yr (~0.2% p.a. of 2006 FY) for their 1990–2006 study period. Note that such studies provide guidance only, because—as the slightly longer period (1990–2009) in Table 3.5 shows—Denmark now appears to be progressing at a rate of 0.4% p.a. of the estimated 2009 FY of 7.5 t/ha.

Petersen et al. (2010) concluded that breeding progress continued unabated over the 1990–2006 study period at about 1.0% p.a. to reach a current PY of ~9.5 t/ha in 2006. This estimate of breeding progress is higher than the rate estimated for the UK (0.6% p.a.), but matches that for France (see below, this section). To their estimate of 1% p.a. breeding progress, Petersen et al. (2010) added estimates of the expected yield effects of CO₂ rise (0.2% p.a.) and better fungicides based on strobilurin introduced early in the study period (0.4% p.a.) to arrive at a value of 1.6% p.a. for expected FY progress. Yet observed FY progress was only 0.2% p.a.

³⁰ Note that NUE is used elsewhere in this book (e.g. Section 11.3) and is always defined as yield per unit fertiliser nitrogen (kg/kg N).

Table 3.5 Wheat harvested area, area change and farm yield (FY) progress in countries of north-western Europe from 1990 to 2009

Country ^a	Area		FY progress		Estimated FY in 2009 (t/ha)	Slope as per cent of estimated 2009 FY (% p.a.)
	2007–09 (Mha)	Change from 1990 to 2009 (%)	Slope of progress (kg/ha/yr)	Standard error of slope (kg/ha/yr)		
Ireland	0.09	+11	93	**38	9.1	0.6
Belgium	0.21	0	120	***20	9.0	1.3
Netherlands	0.15	+15	29	ns 22	8.6	0.3
UK	1.91	-6	43	***14	8.0	0.5
Germany	3.14	+26	66	***17	7.8	0.8
Denmark	0.69	+27	29	*16	7.5	0.4
France ^b	5.29	+3	26	ns 16	^b 7.1	0.4
Switzerland	0.09	-7	-6	ns 15	5.9	-0.1

ns $P > 0.10$, * $0.05 < P < 0.10$, ** $0.01 < P < 0.05$, *** $P < 0.01$

a Countries ranked by estimated FY

b Bread and durum wheat together; latter is 8% of total area. For bread wheat yield add about 3% to national average FY.

Source: FAOSTAT (2013)

Peterson et al. (2010) explained the difference by minor negative effects at the farm level due to slight April–July warming over the study period (+1 °C), an increase in wheat monoculture with greater wheat cropping (rising from 20% to 60%) and reduced nitrogen fertilisation (and suboptimal substitution by manure slurry) under new environment regulations. Even after this, they reckoned there was still an unexplained lag of up to 0.4% p.a. in FY progress. They concluded that reduced cereal prices and an associated reduction in management intensity (input levels and/or decision-making) may explain this final gap. It should be noted that if current PY is 9.5 t/ha and FY is 7.5 t/ha, the yield gap in 2006 was respectably low at 27%. The above-listed yield-depressing factors are not expected to further impact yield increase, and thus future yields should better reflect breeding progress.

Brisson et al. (2010) recently thoroughly analysed 1950–2008 French BW yields and revealed strong statistical evidence for a plateau or stagnation in FY commencing in 1997. This is a similar result to Table 3.5, which points to statistically insignificant progress in French FY (0.4% p.a.; $P = 0.13$) in the past 20 years. However, Brisson et al. (2010) found breeding progress (measured in fungicide-treated trials in the dominant bread wheat areas of northern France) to be **115 kg/ha/yr** ($P < 0.01$), **equivalent to 1.1% p.a. of the estimated 2008 PY of ~10.8 t/ha** (a PY similar to the UK but a greater rate of PY progress). Thus, in contrast to FY, breeding progress in France has been linear for at least 30 years, with no sign of stagnation since 1997.

With most trials in the northern France, the above PY is best compared to FY in the three representative northern departments chosen by Brisson et al. (2010): growing around 0.4 Mha of winter wheat, FY increased in the past 20 years at 26 kg/ha/yr (0.3% p.a., $P = 0.12$) to reach 8.6 t/ha in 2008. **Thus the PY to FY yield gap is 2.2 t/ha (or 26% of the 8.6 t/ha FY)**, and has widened lately with PY progress clearly exceeding FY progress. These authors concluded that the widening gap arose because FY increase is being slowed by:

- higher temperatures during grain-filling
- increased drought during stem elongation
- replacement of two-thirds of the proportion of legumes prior to wheat with canola (currently ~30% of wheat follows wheat, 30% follows canola and only 10% follows legumes)³¹
- reduced nitrogen fertilisation (to a slight extent).

Note that policy and economics could be playing a role in the last two listed changes.

A very recent analysis of winter wheat FY and yield trials between 1978 and 2008 in a favoured part of The Netherlands (marine clay soils) found FY and PY (due to variety only) to both be progressing linearly and very highly significant at about 90 kg/ha/yr, reaching 9.5 and 11.3 t/ha in 2008 (Rijk et al. 2013). Thus relative progress was 1.0 and 0.8% p.a., respectively, of the 2008 yields, and the yield gap 20%. In contrast to the Mackay et al. (2010) analysis of the UK yield trials, the Netherlands study of trials also found significant year progress (i.e. effects of agronomy plus weather change) at about 0.4% p.a. This implies the total apparent PY progress ($0.8 + 0.4 = 1.2\%$ p.a.) is somewhat greater than FY progress (1.0% p.a.), as in France. Rijk et al. (2013) attribute this fact to larger farms (poorer timeliness), soil compaction (from preceding root crop harvests and spring manure applications) and lower wheat prices associated with European policy reforms.

Switzerland is a noteworthy exception in Table 3.5. Wheat yields have been stagnant over the 20-year period, despite the fact that the producer price there is more than twice that of the other countries (average US\$400/t for 2000–08, compared with US\$145–160/t elsewhere). Finger (2010) clearly attributes this to the introduction of environmentally friendly policies in 1992, whereby farmers could choose to 'extensify' wheat production by eliminating agrochemicals (except fertiliser, which is reduced) in return for an annual payment of currently ~US\$400/ha. About 50% of Swiss wheat is under the extensified scheme with an average yield of 5.0 t/ha, compared to 6.6 t/ha for intensive wheat (R. Finger, pers. comm. 2011); thus extensification carries a 24% yield penalty.

³¹ Wheat after canola outperforms wheat after wheat (as happens everywhere), but apparently wheat after legume is even higher yielding.

Conclusion for wheat in the UK and north-western Europe

The UK and north-western Europe regions have strong, highly competitive private wheat breeding sectors, and breeders appear to still be making 0.6–1.0% p.a. PY progress. Farmers are adopting the latest technology and the yield gap is generally small. Agronomic innovations for yield increase may, however, have been exhausted, with FY increase closely paralleling PY increase. There have even been some yield losses on the agronomic front as crop rotations have deteriorated, prices have become less attractive and agrochemical inputs have been reduced in response to environment policy.

FY increase in the future is likely to be even more dependent on breeding progress. In some regions, slight warming may also be reducing FY progress. Lin and Huybers (2012) analysed wheat FY trends over a longer period (1960–2010) and pointed to recent yield plateaus in several European nations, which they ascribed largely to policies favouring environment over yield increase.

3.9 WME12—Great Plains of the USA and other regions

Introduction

With a current harvested area of 8 Mha, the Great Plains of the United States of America (USA) form the largest contiguous area of low-rainfall winter wheat cropland (WME12) in the world (Map 3.6). Other major WME12 regions include the US Pacific North-west states (Washington, Oregon and Idaho; 1.3 Mha), Montana in the USA (0.9 Mha) and Anatolia in Turkey (5 Mha).

The Great Plains have dominated US wheat production for a century. Harvested area fluctuates annually across years—from 70% to 90% of planted area. Substantial as it is, this crop loss does not seem to be changing with time, and it is associated with full grazing by cattle, late spring freezes, winter kill, drought, severe disease and hail.

Five core states (in order of wheat area: Kansas, Oklahoma, Texas, Colorado and Nebraska) produce almost exclusively high-quality hard red winter wheat. A thorough analysis by Feyerherm et al. (1988) of the 30 years preceding 1984 (in Kansas, Oklahoma and Nebraska) showed strong FY progress of 30 kg/ha/yr (or 1.3% p.a. of the 1984 FY), which was attributed to breeding (61%), more applied nitrogen (27%) and improved management factors such as pesticides and tillage.

Harvested area has steadily declined since 1984 by a total of 37% as maize and soybean areas have expanded in the wetter portions. Rate of FY progress has also fallen since 1984, between 1985 and 2010 averaging only 13 kg/ha/yr or 0.5% of the estimated 2010 FY of 2.5 t/ha. Given the seasonal variability in the dataset, this rate of increase is not significant at $P = 0.11$. Hu et al. (2005) showed that spring in the Great Plains region has warmed slightly over the past 50 years (average slope of $+0.13$ °C per decade), but precipitation has not changed. For the winter wheat cultivar Kharkof, used as a control (check) in many trials, the heading date now occurs significantly earlier (having moved forward at an average of 1.6 days per decade).

Further insight into yield progress across the region comes from the Southern and Northern Regional Performance Nurseries, comprising 50 sites across the Great Plains. Each year, these nurseries contain about 30–50 largely different advanced winter wheat entries, and one recurrent control cultivar, Kharkof (released in 1905). Graybosch and Peterson (2010) analysed the nurseries separately, but as the data are quite variable, the average across the two nurseries has been calculated here. Between 1984 and 2008, the yield of Kharkof increased at a rate of 14 kg/ha/yr ($0.05 < P < 0.10$), presumably due to management and possibly climate change. The average of the average yield of the top five entries in each nursery, which here is assumed to measure PY_w , increased at a rate of 36 kg/ha/yr ($P < 0.01$) to reach 4.4 t/ha in 2008. The increase was notably greater in the Northern Nursery, which did not include Texas, Oklahoma or Colorado. This increase was due to breeding and management, plus possible effects of climate change. Breeding progress for PY_w can be estimated by the difference in yield slope for the check cultivar and that for the top five entries; the difference is 22 kg/ha/yr, which is highly significant ($0.01 < P < 0.05$) but equates to breeding progress of only 0.5% of the 2008 PY_w .

Graybosch and Peterson (2010) attribute slow breeding progress to the cost of maintaining both desirable hard wheat quality and resistance to pests and diseases—especially yellow rust, which lately has become more prevalent. An incorrect interpretation, promoted in *Crop Society of America News* (November 2010), implied that breeding progress ceased after 1984; it is proposed here that progress is still significant, despite an increase in data variability over time. It is possible that the above progress estimate is inflated by increasing disease susceptibility of the recurrent control cultivar (Kharkov), but the 1905 release date for Kharkov makes this effect unlikely.

Battenfield et al. (2013) conducted a vintage trial, with and without fungicide, over two years at 11 locations in the southern Great Plains (Texas, Oklahoma and Kansas). Looking at only semi-dwarf 1971–2008 varieties, breeding progress was highly significant ($0.01 < P < 0.05$) for both treatments: with fungicide (10.3 kg/ha/yr) and without fungicide (11.5 kg/ha/yr). The former slope suggests breeding progress was 0.3% p.a. of the estimated 2008 PY_w of 3.1 t/ha; absence of fungicide lowered yield on average 0.4 t/ha or 14%.

Further discussion of this vast region will focus on Kansas, the most central and largest wheat-producing state.

Wheat yield progress in Kansas, USA

The state of Kansas—with the exception of the wettest south-east corner—grows winter wheat under a relatively dry continental climate, with 400–800 mm summer-dominant annual precipitation. During 2008–10, Kansas harvested 3.5 Mha of wheat—20% less than 25 years ago. FY is variable, and yield is lowered by major climatic events: drought, late spring freeze damage and grain-filling heat. Nevertheless, **FY registered a significant upwards slope of 20 kg/ha/yr since 1985 (Figure 3.10), equivalent to 0.7% p.a. of the estimated 2010 FY of 2.8 t/ha.**

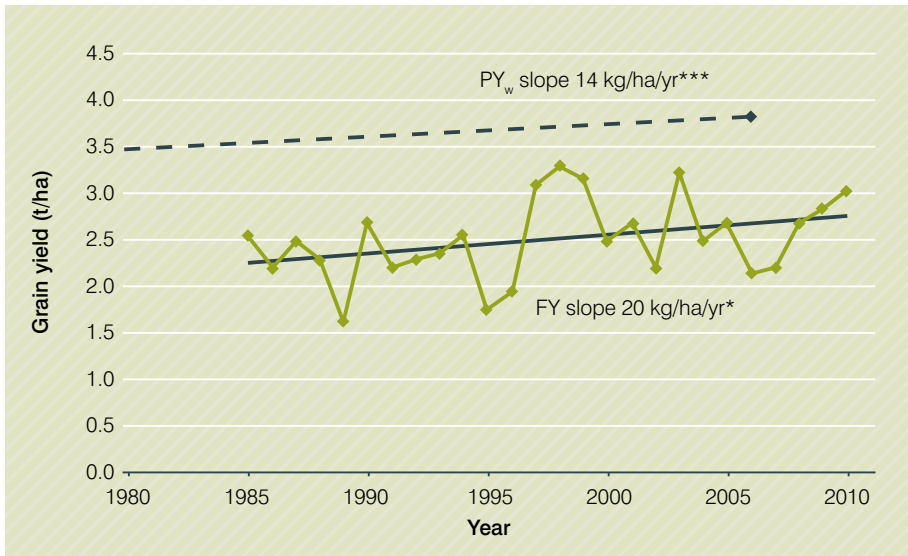
Vintage trials with fungicide in Kansas (Donmez et al. 2001) and nearby Oklahoma (Khalil et al. 2002), and an unprotected vintage trial in adjacent Nebraska (Fufa et al. 2005), gave annual rates of PY_w progress of 0.8%, 0.6% and 0.7%, respectively. None of these studies showed any signs that progress is slowing with time. It should be noted, however, that the most recent varieties in these studies were released in 1997 or 2000.

Nalley et al. (2006, 2008) present a more recent and thorough analysis of varieties released in Kansas, with data from annual Kansas Performance Tests of the Kansas Agricultural Experiment Station (KAES)³² comprising more than 20 popular winter wheat varieties that are grown each year at over 20 sites across the state. For the 1977–2005 tests, Nalley et al. (2006) calculated average yield ratios relative to the recurrent control cultivar, Scout 66, and regressed the ratios against year of release. Taking the 17 hard red winter wheat varieties released by KAES between 1977 and 2002 indicates that PY_w progress was ~40 kg/ha/yr or 1% p.a. of the 2002 PY_w level.

The estimate of progress in Nalley et al. (2006) is, however, likely to be an overestimate, as a later paper (Nalley et al. 2008) reveals. Nalley et al. (2008) added 2006 data and re-analysed the 1977–2006 results with an ordinary least-squares multiple regression model that included year of trial and year of variety release. The regression dealt directly with the unbalanced data and included correction for significant multiplicative heteroskedasticity (variability of error variance). **The resultant coefficient for year of release (pooled across all types of wheat varieties), and hence PY_w progress, was highly significant, but much lower (14 kg/ha/yr; $P < 0.01$; Figure 3.10).**

To obtain an estimate of the current PY_w —not given in Nalley et al. (2008)—yield is averaged across the 13 dryland sites of the Kansas Performance Tests for the six cultivars released around 2005, measured in the relatively normal years of 2008 and 2009. **Thus, the estimated PY_w for Kansas is determined to be 3.8 t/ha in 2005, and the rate of PY_w progress only 0.4% p.a. of this yield level.** The relative rate of progress is similar to that estimated by Battenfield et al. (2013) for the southern Great Plains in a study that shared some of the varieties included in Nalley et al. (2008).

32 See K-State Research and Extension at <www.ksre.ksu.edu>.



*0.05 < P < 0.10, ***P < 0.01

Figure 3.10 Wheat farm yield (FY) in Kansas, USA, from 1985 to 2010, plotted against year, and estimated water-limited potential yield (PY_w) changes (dashed line; see text) plotted against year of release. Source: FY from NASS (2012); PY_w changes estimated from Nalley et al. (2008)

The Nalley et al. (2008) regression is shown in Figure 3.10 as a dashed line. The reason the earlier yield ratio approach, using the same control cultivar Scout 66, gave higher apparent progress is likely explained because the trials had no protection from diseases, and Scout 66 may have become more susceptible over the study period. An interesting result from the Nalley et al. (2008) analysis was the absence of a significant effect of year (1977–2006). This suggests there has been no progress in trial management and/or wheat agronomy, a similar situation to that noted in the analysis of UK trial yields, referred to in Section 3.8 on WME11.

There is surprisingly little recent published research on the physiology of wheat yield progress in Kansas or neighbouring states. Changes in plant height and flowering date have ceased in the past 20 years. While recent progress appears largely related to increased grain number (GN) (e.g. Donmez et al. 2001; Fufa et al. 2005), most physiology has concentrated on tolerance to heat during grain-filling, obviously perceived as a major constraint in the region (e.g. Yang et al. 2002; Hays et al. 2007).

Wheat yield gap and constraints in Kansas, USA

The current PY_w for winter wheat in Kansas has been estimated above to be 3.8 t/ha. Given that FY is estimated at 2.8 t/ha (Figure 3.10), **the yield gap is only 36%**

of FY, and relatively stable. The yield gap is surprisingly low for such a variable rainfed environment, particularly one beset with many changes and manageable constraints (see below). Note that the above analysis would have underestimated the yield gap if the performance tests had not, as assumed here, accounted for such changes and had not eliminated such constraints in their measured PY_w .

Although irrigated wheat yields out-yielded rainfed wheat in Kansas (4.5 t/ha vs. 2.0 t/ha in 2007), only 6% of wheat in Kansas is irrigated (USDA 2007) so it seems unlikely that any change in the proportion of wheat irrigated would significantly influence the FY trend. More important developments could be the 20% decline in wheat area over the study period and the decreasing proportion of wheat grown on summer fallow. Both wheat and sorghum have decreased in area (0.8 and 0.4 Mha, respectively) at the expense of an increase in maize area of 1 Mha (to reach 1.5 Mha) and soybean area of 0.6 Mha (to reach 1.2 Mha). These more profitable (predominantly transgenic) crops have displaced wheat from the better soils and wetter areas of eastern and central Kansas.

Summer fallow is used to build valuable soil water reserves in the subhumid climate and will generally deliver higher yields. Summer fallow treatments were applied in 37% of the 2008–09 Kansas Performance Tests, but summer fallow area in the state has decreased by 14% between 2002 and 2007 to reach 1.3 Mha—about 37% of the current planted wheat area. Reduced reliance on summer fallow is the result of conservation tillage practices—which have brought marked improvement in soil moisture storage during the fallow period, and thus the possibility of greater cropping intensity (Lyon et al. 2004). However, this development has likely reduced wheat yields compared to wheat after summer fallow.

Inputs for winter wheat in Kansas are tracked by census. This has shown that fertiliser application has been steady over the past 20 years. In 2006, nitrogen was applied at 64 kg N/ha to 88% of the planted area, and phosphorus at 15 kg P/ha on 66% of planted area; a very small proportion received potassium, sulfur or zinc (USDA 2007). In a system with little legume pasture or other crops in the sequence with wheat, this level of applied nitrogen is barely sufficient to balance that removed in the grain. Soil acidification has also become a problem in parts of the central and southern Great Plains, leading to wheat yield responses to lime (Zhang et al. 2004). Therefore fertility decline and acidity increase could also be significant constraints.

Herbicides and pesticides are generally used when needed, although there appear to be no recent records. The increased incidence of stripe rust in the Great Plains has been a new development, as is the increased occurrence of virus diseases linked to wheat curl mite—wheat streak mosaic virus and High Plains virus—which is possibly associated with zero-till (R. Sears, pers. comm. 2010). Meanwhile, leaf rust can still be severe in some years.

This broad view of little progress in the management side of wheat cropping concurs with the apparent lack of progress in trial agronomy in the annual Kansas Performance Tests reported above (Nalley et al. 2008). However, also slowing FY progress may be a drier environment in Kansas and unattractive wheat prices (at least until 2008).

Conclusion for wheat in Kansas and the Great Plains of the USA

Wheat area has declined notably in this renowned wheat-cropping region of the USA. FY is very variable, but shows moderate progress (0.5–0.7% p.a.). There is no evidence that rate of FY progress has slowed in the past 30 years or so, but it may be slower than it was prior to that period. Equally there is low to moderate PY_w progress from breeding (0.3–0.5% p.a.) but no evidence of a breeding yield plateau.

In Kansas, there is a moderately small (35%) but stable yield gap. On the one hand, wheat is suffering competition from more profitable maize and soybean on the better soils and in wetter portions of the state. On the other hand, wheat is beset with difficulties; soils may have deteriorated, and breeders must contend with new pests and diseases. Conservation tillage offers significant stored moisture gains that should benefit overall system productivity, but not necessarily wheat yields. The cropping system lacks non-cereal alternatives, and (in Kansas) there is little evidence that recent agronomic improvements have contributed to progress in wheat yield.

3.10 Summary of yield progress in wheat

Current farm yields, potential yields and yield gaps in world wheat

Key data collected on wheat are summarised in Table 3.6. Western Siberia and Sichuan province, China, were excluded because of incomplete data on FY constraints. Egypt was excluded because of doubts about PY values. Some WMEs are missing because they were not sampled. FY values shown in Table 3.6 should be sound because they derive largely from national or regional statistics, but the average FY (unweighted for area) in Table 3.6 is higher than the current global average (~3.0 t/ha; Table 3.1) indicating that the case studies were biased towards higher yielding regions. PY values contain some doubts regarding the representativeness of the data collected.

The resultant yield gaps in Table 3.6, however, show a surprisingly narrow range (26–69%) around an average of 48% of FY. Other data collected here suggest that some regions have yield gaps that are (at least) more than 100% (e.g. Western Siberia). Lobell et al. (2009) reported yield gaps for irrigated wheat in South Asia and north-west Mexico averaging 46% ($n = 9$; range 5–150%) calculated as per the method used here.

Table 3.6 Summary of global wheat farm yields (FY), potential yields (PY) or water-limited potential yields (PY_w) and yield gaps in 2009 or 2010, and current respective rates of change measured over the past 20–30 years

WME	Region ^a	Estimated yield (t/ha) and yield gap (%)			Rate of change (% p.a.) ^d		
		FY	PY	Yield gap	FY ^e	PY ^e	Yield gap ^f
1	Yaqui Valley, Mexico	6.4	9.0	41	^g 0.9	0.3	-0.6
1	Punjab, India	4.5	7.0	56	^g 0.7	0.4	-0.3
1	Jiangsu, China	4.6	7.5	63	0.8	0.7	-0.1
4	Western Australia ^b	1.8	2.6	44	^g 1.0	0.5	-0.5
6	Saskatchewan, ^b Canada	2.3	3.8	69	0.8	0.6	-0.2
6	Saskatchewan, ^{b,c} Canada	2.2	3.6	64	0.7	0.5	-0.2
6	North Dakota, ^b USA	2.5	4.0	60	1.0	0.7	-0.3
6	Finland	3.7	4.8	30	1.0	0.8	-0.2
10	Shandong and Henan, China	5.8	8.8	52	1.7	0.7	-1.0
11	United Kingdom	8.0	10.7	34	0.4	0.6	+0.2
11	Northern France	8.6	10.8	26	0.3	1.1	+0.8
12	Kansas, ^b USA	2.8	3.8	36	0.7	0.4	-0.3
Average (n = 12)		4.43	^h na	48	0.83	0.61	-0.23

- a Organised by key WME
- b Rainfed cropping regions commonly experiencing water shortage so PY_w was estimated
- c Durum wheat
- d All rates of FY progress and gap closing contain the direct effect of CO₂ rise (~0.2% p.a., see Section 2.4 on confounding factors).
- e All FY and PY slopes are statistically significant at *P* < 0.10 or better, except for the FY slope for northern France (*P* = 0.13)
- f Calculated as FY rate of change less PY rate of change
- g FY rates of change include small but significant weather trends (see text) for which no correction is applied here; two were unfavourable and one favourable for FY
- h not applicable

Source: Estimates taken from preceding sections of Chapter 3, excluding those that were incomplete or lacked reasonable certainty.

Yield gaps did not differ among WME regions with plentiful water or limited water. In modern economies with favourable physical environments (i.e. the UK, France and Finland) and perhaps surprisingly one with a risky environment (Kansas, USA), the gap was close to the likely minimum to be expected (30% of FY), suggesting that FY was close to attainable yield. Improved farm practices for further closing yield gaps were identified in most other situations, but nowhere was there evidence for a single obvious agronomic constraint.

The most common exploitable constraints seemed to be late sowing in the Yaqui Valley (Mexico) and Punjab (India), and poor irrigation water supply (Yaqui Valley, Punjab and the North China Plain). Inadequate nitrogen was a special problem in risk-averse rainfed Western Australia and undoubtedly in other rainfed systems also. Most wheat cropping systems were cereal dominant and lacked diversity; only in Australia, northern North America and possibly western Europe were there significant proportions (say >25% of wheat area) of broadleaf crops and pasture leys in the system. Very low soil organic matter may be a special problem in Punjab and the rest of the Indo-Gangetic Plain, and is reversible only in the long term.

Overall prospects for yield gap closure must therefore be seen as relatively limited compared with some other crops (see Chapters 4–7 on rice, maize, soybean and other crops). Following these chapters, Chapter 8 then discusses general prospects for yield gap closing.

Rates of change of yields and yield gaps in world wheat

Despite choosing somewhat favoured regions, the **average rate of 0.83% p.a. FY progress for wheat** (Table 3.6) is reasonably close to the world average of 1.0% p.a. (Table 3.1). One reason for the small discrepancy is that it was not possible to develop a case study in the Russian Federation, a major wheat-producing nation, where FY increase has been rapid (1.6% p.a.) and yields are low (Table 3.1). The rate of progress in FY in Table 3.6 shows no relationship to FY level, probably because diminishing returns at higher yield levels are balanced by difficulties in achieving progress where yields are low and annual variability high. Only the FY slope for northern France was not significant at $P < 0.05$, but nonetheless was significant at $P = 0.11$.

With a special effort made to avoid situations where estimates of breeding progress may be inflated by loss of disease resistance in older varieties, the resultant **average progress in PY is only 0.61% p.a.** (Table 3.6). It is noteworthy that PY increase was about the same in spring wheats (0.58% p.a., $n = 8$) as in winter wheats (0.70%, $n = 4$). Also, it was no less in rainfed situations—in other words, progress in PY_w has been about the same as that for PY (in relative terms).

An independent estimate of global PY progress in spring wheats ought to be available from CIMMYT's regular analyses of the performance of its advanced breeding lines in yield trials, sent annually to a vast global network of sites. Thus Sharma et al. (2012) reported on the average yield of the five best-yielding bread wheat lines in trials between 1995 and 2009. This five-line average yield exceeded the yield of the recurrent control cultivar (the relatively high-yielding Attila) by an amount that annually increased at the following rates (given as a per cent of the average yield for Attila in each situation):

- 0.6% p.a. for the combined WME1–2 and WME4–5
- 0.5% p.a. for WME1

- 0.6% p.a. for WME2
- 1.1% p.a. for Egypt
- 0.8% p.a. for India
- 0.5% p.a. for Pakistan.

Notwithstanding doubts that frustratingly have not been discussed (e.g. change in disease susceptibility of the recurrent cultivar), the Sharma et al. (2012) numbers appear to corroborate the estimates in this chapter for PY progress in spring wheats (0.54% p.a.).

In a separate ongoing international yield trial targeting spring BW in semi-arid conditions (presumably WME4), from 1994 to 2010, Manes et al. (2012) showed that the average yield of the top 10% of entries each year, assumed here to measure PY_w , increased at rates of 1.0% p.a. relative to the recurrent check cultivar Dharwar Dry. Adjusting for the low (and constant) yield of the control cultivar, this figure becomes 0.7% p.a. of the average 2010 PY_w of the advanced lines. Splitting each year's trials into low (average = 2.25 t/ha) and high (average = 5.1 t/ha) yield groups revealed PY_w progress at 0.4% p.a. and 0.9% p.a., respectively, on this latter basis. Manes et al. (2012) implied that trial crops were little impacted by disease, but did not provide disease data. These estimates are comparable to those for PY_w progress in Table 3.6.

While rates of increase in FY and PY in Table 3.6 are in most cases lower in the study period chosen than in the period immediately before it, **the FY and PY slopes were still strongly linear**, and all significantly greater than zero (except for FY in northern France). Thus, there was no obvious slowdown within the 20- to 30-year period to the present. Relative slopes are obviously declining as the denominator from which they are calculated increases, but this effect is small. There may be other factors involved, especially in PY progress, which are discussed in Chapter 9 'Increasing yield potential'. FY progress of course depends partly on this, and on what is happening to the yield gap.

In the dataset presented in Table 3.6, there was a strong tendency for yield gaps to persist, with only **very small rates of yield gap closure** (and it must be recalled that the way yield gap closing is calculated here includes the small effect of CO_2 increase on wheat FY). Excluding the Yaqui Valley (Mexico) where the cooling trend contained in FY progress exaggerates the gap closing in Table 3.6, the yield gap appears to be closing notably only in Western Australia (gap change -0.5% p.a.) and in Shandong and Henan provinces of North China Plain (gap change -1.0% p.a.). In both cases of closing, adoption of improved agronomy was clearly involved. In Saskatchewan (Canada) and North Dakota and Kansas (USA), the benefits of conservation tillage for wheat yield were probably countered by decreased summer fallowing and greater cropping intensity, so gap closing was small. In Europe, environmental policy may be starting to have negative effects on FY; Table 3.6 shows increasing FY gaps for the UK and France (as well as very small yield gaps of ~30%). Meanwhile in China and Egypt, positive pricing policy changes have helped FY increase.

Estimated wheat yield and yield change by wheat mega-environment

A more balanced view of the global wheat situation is given in Table 3.7, which presents a summary for each WME, a global aggregation of yields (weighted for relative WME areas) and relative of rates of progress (weighted for WME production). The order of the columns in Table 3.7 differs from the presentation in Table 3.6 to highlight that PY and yield gap together contribute to FY.

Limitations in Table 3.7 arising from inadequate data coverage among the case studies—and lack of data from the three smallest WMEs, which are lumped with others—have been supplemented by the present authors' expert knowledge. All values have been estimated so as to give global averages for yield gap and rates of PY progress to match those in Table 3.6, because these were considered the most broadly applicable and reliable numbers (notwithstanding uncertainties surrounding the PY value for each WME). World average FY and FY progress match the observed statistics (Table 3.1).

Notwithstanding these uncertainties, Table 3.7 is a useful starting point that can be improved as further data come to hand. Weighting estimated yield gaps for the area in each WME indicates that the biggest global production losses (due to exploitable gap with the minimal gap set at 30% of FY) are occurring in the humid WME1–3 (totalling to 54% of the global loss), followed by the drier, rainfed WME4–5 (14%) and WME6 (13%); all these are dominated by spring wheats. Using similar estimations, losses (again due to exploitable yield gap) are small (<10%) in the other WMEs, which are all facultative and winter wheat areas.

If the progress estimated in Table 3.7 is globally correct, world average FY increase is derived about two-thirds from PY progress and one-third from yield gap closing, but this varies across the major WMEs. It is estimated that no gap closing is taking place in WME11 (high rainfall, winter wheat), but good gap closing is occurring in WME4 (rainfed, low-latitude spring wheat) and WME10 (irrigated winter wheat).

The disaggregation shown in Table 3.7 could be disputed, but there is no dispute about 1.0% p.a. current global rate of FY progress for wheat, and little dispute about the global rate of 0.6% p.a. PY progress, for which individual estimations are remarkably consistent.

Table 3.7 Estimates of 2008–10 farm yield (FY), yield gap and potential yield (PY) and rates of change over the past 20 years across wheat mega-environments (WMEs)

WME	Weighting factor (fraction of total)		Estimated values for 2008–10			Estimated rate of change relative to 2008–10 values (% p.a.)		
	Area	Production	FY (t/ha)	Yield gap (%)	PY (t/ha)	FY	Yield gap	PY
1 + 2 + 3	0.23	0.23	3.0	83	5.5	1.0	−0.4	0.6
4 + 5	0.17	0.08	1.5	67	2.5	1.2	−0.9	0.3
6	0.20	0.13	2.0	50	3.0	1.2	−0.2	1.0
10	0.06	0.09	4.5	44	6.5	1.6	−1.1	0.5
11	0.23	0.38	5.0	30	6.5	0.7	0.0	0.7
12	0.11	0.09	2.3	30	3.0	0.8	−0.3	0.5
World average	1.00	1.00	^a 3.0	^b 50	^a 4.5	^b 1.0	^b −0.4	^b 0.6

- a Weighted by area of WME
- b Weighted by production of WME

Source: Area fractions from Table 3.2; other parameters calculated and estimated by the authors (see text). Estimates apply to 2008–10 when average world wheat area was 222 Mha and production was 674 Mt.

Physiological patterns for potential yield increase in world wheat

Further PY progress should benefit from understanding **the physiological basis of recent PY progress**. Consistent patterns emerged over the past 20–30 years for wheat PY, a period when progress derived from dwarfing and earliness had largely become exhausted. Thus PY progress continued to be associated with harvest index (HI) increase in most cases, but dry matter (DM) increase was a new feature appearing among recent entries in studies in Mexico, Australia, China and the UK. Highest HI values were close to 0.50 in the UK and China, but generally lower elsewhere.

Grain number (GN) increase accompanied almost all PY progress, but for Mexico, Australia and WME6 in North America, GW increases were also seen in recent variety releases. It was not noted whether the GN increase depended on spikes per square metre or grains per spike, because this is a minor issue in wheat (Fischer 2007). Another review (Rudd 2009) recorded no consistent pattern, although often both components were involved. The most interesting observation is that in two cases (Australia and the UK), PY (and GN) increase was associated with greater crop growth

rate and RUE between stem elongation and flowering. This matches increases in stomatal conductance and in maximum photosynthesis (P_{max}) seen during this period in Mexico and Australia, and in two studies in China.

Flag leaves have become generally smaller, more erect and sometimes greener in modern varieties in the high-yielding WMEs of Mexico, the UK and China. Finally, studies in Australia, China and the UK found that stored water-soluble carbohydrates at anthesis increased with higher PY. The implications of these emerging patterns are discussed in Chapter 9 'Increasing yield potential'.



Rice

4



Key points

- World rice production in 2010 approached 700 Mt. Harvested area is currently increasing at a rate of 0.4% per annum (p.a.), and global average yield (or farm yield, FY) at close to 4.3 t/ha is increasing at a current rate of 1% p.a.
- For each of the major rice mega-environments (RMEs), 13 detailed case studies presented in this chapter have explored farm yield (FY), potential yield (PY) and yield gap over the past 20–30 years. Eleven of these case studies contributed to the values quoted in the key points below.
- The current rate of rice FY increase was significant ($P < 0.10$ or better) in all situations, rates of progress ranging between 0.2% p.a. and 2.2% p.a. (relative to FY around 2010).
- The current rates of rice PY increase—and those for its water-limited equivalent (PY_w)—were also all significant ($P < 0.10$ or better), at a global average rate of 0.8% p.a. Rates ranged between 0.3% p.a. and 1.3% p.a. (relative to PY around 2010). Results show that hybrid rice for tropical areas can boost PY by 10–20%, but adoption is still low (<5%).
- The sample average rice yield gap was 76% of FY. The range was wide (25–150%) and, on average, lower gaps were observed for irrigated RMEs compared with rainfed ones (57% vs. 123%, respectively).
- Rice yield gaps appear to be closing slowly; the sample average rate of change is –0.4% p.a. (range –1.5% p.a. to +0.6% p.a.). The strongest gap closing is observed in Brazil’s irrigated and rainfed RMEs. In Japan, policy and quality considerations have constrained FY progress, as has occurred in some other Asian nations (e.g. China).
- The results emphasise the importance of raising PY as the primary means for future rice FY increase. This is particularly the situation for irrigated RMEs, which produce 79% of the world’s rice. In contrast, there is considerable scope for rainfed RMEs to close yield gaps by adopting well-known agronomic interventions.
- Apart from increased number of filled spikelets per square metre, no clear physiological mechanisms have been identified for yield progress in tropical rice. However, research in Japan has associated the greater filled spikelet number and yield achieved by new feed varieties of rice with:
 - greater nitrogen uptake before heading
 - higher radiation use efficiency (RUE)
 - increased leaf photosynthesis (P_{max}) and stomatal conductance around heading
 - increased stem-stored carbohydrates at anthesis.

Rice



4.1 Rice countries and mega-environments

4

The world produced on average 692 Mt of paddy or rough rice (*Oryza sativa*) in 2008–10 (FAOSTAT 2013). The largest producers, shown in Table 4.1, included China with 28% of world production, India (21%) and Indonesia (9%).

Table 4.1 Annual rice production, harvested area and yield in 2008–10 for major producing countries, and annual rates of change from 1991 to 2010

Country or region	Average 2008–10			Rate of change ^c (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^b (t/ha)	Area	Yield
World ^a	691.6	160.2	4.32	0.4	1.0
China	195.7	29.8	6.56	−0.6	0.6
India	142.6	43.4	3.28	ns 0.1	1.1
Indonesia	63.7	12.8	4.97	0.8	0.7
Bangladesh	48.3	11.4	4.24	0.6	2.3
Vietnam	39.2	7.4	5.27	0.7	2.2
Thailand	33.1	11.3	2.93	1.1	1.6
Myanmar	32.6	8.0	4.05	2.2	1.7
South America	24.4	5.1	4.78	−1.0	2.5
Sub-Saharan Africa	18.9	9.3	2.03	1.9	0.9

a Listed countries are major producing regions, not all world production

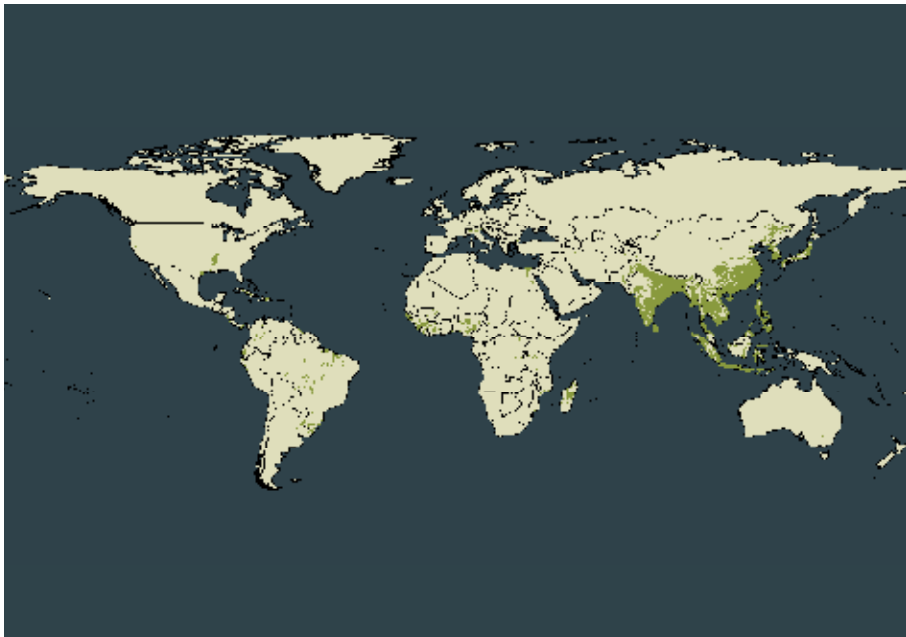
b All weights are paddy rice; what FAOSTAT calls 'yield' the book calls 'farm yield' (FY); see Chapter 2 about definitions.

c Relative to 2008–10 average; all rates of change are significant at $P < 0.01$ except India area increase, which is non-significant ($P > 0.10$).

Source: FAOSTAT (2013)

Rice is predominantly a food crop, but (unlike wheat) only 7% of rice production is traded internationally. Most rice is traded as milled rice, the weight of which is about two-thirds (67%) that of paddy rice. Dominant exporters (values shown as annual average paddy rice equivalents for the 2000s) are Thailand (8.4 Mt), Vietnam (4.4 Mt), India (4.2 Mt), the USA (3.3 Mt) and Pakistan (2.8 Mt) (Dorosh and Wailes 2010). Dominant importers are Sub-Saharan Africa (8 Mt), West Asia (6 Mt) and the Philippines (3 Mt). Mohanty (2013b) points to recent rises in India's exports (10 Mt in 2012) and China's imports (2.5 Mt in 2012).

Rice is grown largely in the tropics and subtropics, with only a small proportion of rice area (3%) in developed countries (Map 4.1). Also, unlike wheat, rice area has increased over the past 30 years by 10% to reach about 160 Mha, and this area is still increasing at a rate of 0.4% p.a. of the 2008–10 area (Table 4.1). There have been notable increases in rice area in Indonesia, Myanmar, Vietnam and Sub-Saharan Africa, countered somewhat by decreases in rice area in China and South America (Table 4.1). Sub-Saharan Africa, in particular western Africa, a large rice-importing region, is now seeing quite a lift in production.



Map 4.1 Global distribution of rice area circa 2000. Source: Harvest Choice project, International Food Policy Research Institute; data from You et al. (2009a)

Because rice lands are classified primarily on field hydromorphology, several rice environments can exist over short distances in non-flat topographies. This makes accurate compilation of rice mega-environments (RMEs) difficult. Table 4.2 describes the rice mega-environments, largely following 30-year-old terminology from the International Rice Research Institute (IRRI) (Khush 1984). However, the relative rice areas shown in Table 4.2 have been derived from more recent data—Dawe et al. (2010) and IRRI Rice World Statistics (2012)—because there has been a notable shift in Asia towards irrigated rice, and away from the upland and tidal rice reported in the early IRRI assessments.

The earlier IRRI classification of irrigated rice (Khush 1984) was dominated by the presence or absence of low temperature stress during seedling or pollen formation stages. More recent thinking from Dawe et al. (2010) departs from the former classification by aggregating irrigated double- and triple-crop systems. Thus Table 4.2 has four irrigated rice categories determined approximately by latitude, prevailing winter temperatures and the overall cropping system. RME4, although small (2.0 Mha), is a unique temperate variant of irrigated rice grown in dry high-solar radiation environments. Finally the tidal rice category of Khush (1984) has been absorbed into other categories. The numbering system (RME1–7) is suggested for the purposes of this book.

Irrigated rice dominates rice area (57%), although Dawe et al. (2010) state this number as 62%. Irrigated rice dominates global production (estimated to be 70% or more, see the section 'Estimated rice yield and yield change by rice mega-environment') and RME1 is the dominant irrigated rice mega-environment (Table 4.2). RME1 covers:

- all rice crops in the double and triple rice crop systems of the humid tropics (e.g. Java)
- wet and (higher yielding) dry season crops in the seasonally wet tropics (e.g. Central Plain of Thailand, Mekong Delta and Central Luzon in the Philippines)
- double crop rice (sometimes following winter crops) in southern China.

Thus 40 Mha of rice comes from fields that are double or triple cropped to rice each year (Table 4.2); however, a very recent compilation from IRRI suggests this number may have now increased to around 50 Mha, including about 6 Mha of triple cropped rice (A. Dobermann, pers. comm. 2013).

The second irrigated mega-environment (RME2) is characterised by sole summer rice where winters are too cold for rice but warm enough for a non-rice crop (e.g. rice–wheat systems). Areas with even cooler winters can support only sole rice cropping (RME3 and RME4) where the rice crop growth duration is clearly limited by low temperature. Most rice outside the tropics can experience low temperature stress, either at the seedling stage or at pollen formation, but if this can be avoided, cooler temperatures result in higher potential yield (PY; see Chapter 2 on definitions), especially under high solar radiation levels encountered in RME4.

Rainfed lowlands (RME5) comprise the next most important mega-environment, and although fields are generally banded to retain rainwater, RME5 rice can be subject to drought and uncontrollable submergence. Despite this challenge, Dawe et al. (2010) estimated that 8 Mha of RME5 is favourable enough for double rice crops (equivalent to 16 Mha crop area). Generally unbanded, rainfed upland fields (RME6) can be termed ‘aerobic’ and are more often droughted and less often waterlogged. The last mega-environment (RME7) is characterised by continuous or frequent deep water of greater than 50 cm (but commonly > 100 cm).

The contrasting soil water and thermal regimes of RMEs have, over the millennia of rice improvement, led to a greater specific varietal adaption—including the differentiation of Indica (warm area) and Japonica (cool area) subspecies—than is seen in the case of wheat. Modern semi-dwarf Indica and Japonica varieties have spread rapidly in the irrigated RMEs and slowly into rainfed lowlands, but hardly at all into the final two (very stressful) mega-environments (RME6 and RME7).

Table 4.2 Rice mega-environments (RMEs), relative areas and major producing regions

RME	Description		Proportion total area (%) ^a	Major regions
	Hydro-morphology	Climate		
1	Irrigated	Warm to hot—tropics (rice all seasons) and subtropics (double crop summer rice)	25	Indonesia, Sri Lanka, Vietnam, the Philippines, south-eastern India, southern China, Bangladesh
2	Irrigated	Warm—tropics (higher altitudes) and subtropics (sole rice after winter crop)	16	South Asia hills, Indo-Gangetic Plain, central China
3	Irrigated	Temperate—(summer rice after winter fallow, warm and humid)	15	Japan, Korean peninsula, north-eastern China, southern Brazil, southern USA
4	Irrigated	Temperate—(summer rice after winter fallow, hot and dry)	1	Egypt, Iran, Italy, Spain, California (USA), Peru, south-eastern Australia
5	Rainfed lowland	Tropics	31	Cambodia, North-East Thailand, eastern India, Indonesia, Myanmar, Nigeria
6	Rainfed upland	Tropics	9	South Asia, South-East Asia, Brazilian Cerrado, western Africa
7	Deepwater	Tropics	3	River deltas of South Asia and South-East Asia, Mali

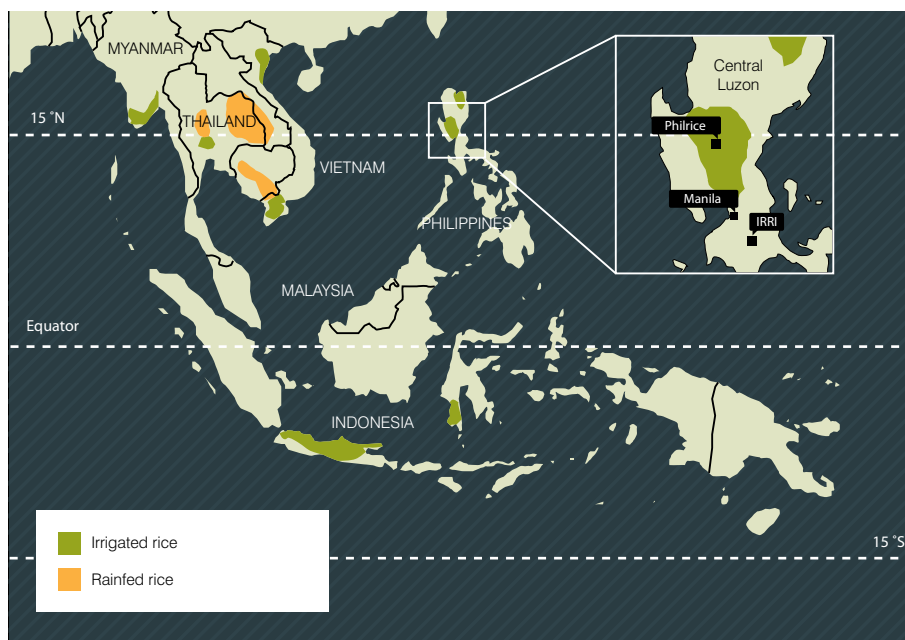
a Percentage of world area; percentages apply to global rice area around 2008–10 (160 Mha). Source: Based on Khush (1984) and World Rice Statistics (IRRI 2012), with adjustments within irrigated rice from Dawe et al. (2010); RME4 was estimated by the authors.

4.2 RME1—Central Luzon in the Philippines, and other rice bowls of South-East Asia

This chapter initially focuses on the Central Luzon region in the Philippines (Map 4.2), noting that rice yield progress for the Philippines—a major rice producer—will be discussed later in conjunction with other nations of South-East Asia.

Rice farm yield progress in Central Luzon

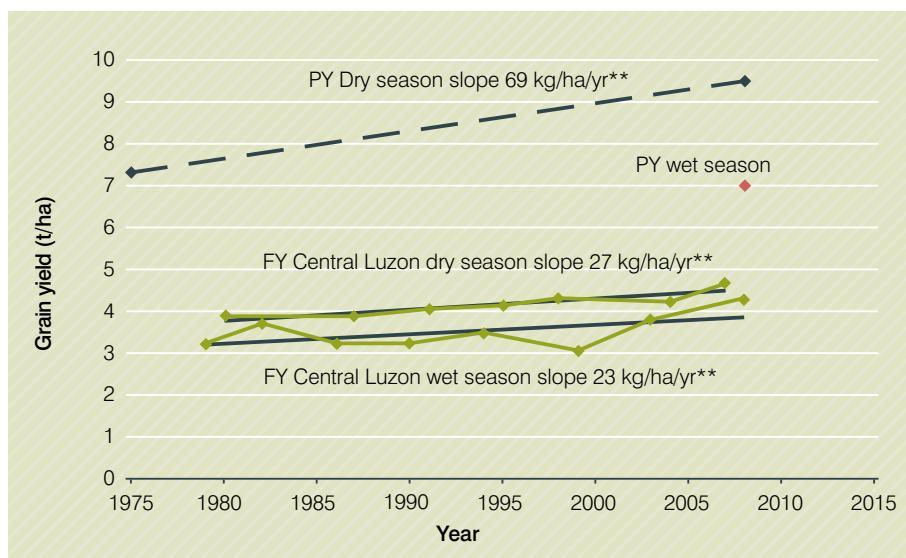
Central Luzon is a large plain north of Manila that produces about one-third of the Philippines's rice. Wet and dry season production of Indica varieties largely under irrigation (RME1) comprises a rice area of 1.2 Mha (Map 4.2). RME1 in Central Luzon is of special interest because it is close to two key rice research institutes: IRRI at Los Baños in the south, and the Philippines Rice Research Institute (PhilRice) in the centre of the region, which nowadays releases the varieties for Central Luzon. Farms in the region are small (average 1.5 ha), and presumably benefit from the substantial local rice research and development efforts.



Map 4.2 Major concentrations of irrigated and rainfed rice in South-East Asia, with inset for Central Luzon, the Philippines, showing locations of PhilRice and the International Rice Research Institute (IRRI). Source: Derived from rice distribution maps from IRRI

IRRI conducts detailed farm surveys (so-called 'loop surveys') across the Central Luzon region every 4 or so years. They have maintained this since 1966, when only traditional varieties were grown, fertiliser use was almost nil and cropping intensity was only 110% for an average yield of 2.5 t/ha.

Figure 4.1 shows farm yield (FY; see Chapter 2 on definitions) for survey farms over the 30 years up to 2008, when only modern varieties were grown (Estudillo and Otsuka 2006; and more recent data from IRRI, unpublished data). **FY rate of progress is slow but steady at 0.6% p.a. for both wet and dry-season rice.** Currently FY is at 3.9 t/ha (wet season) and 4.6 t/ha (dry season). Recent progress in this region has been lower than the national average of 1.6% p.a. (see section on other South-East Asian examples of RME1, below), presumably because Central Luzon had already made the rapid yield gains that accompanied initial modernisation under the green revolution (Section 1.1 'The problem').



ns = not significant, **0.01 < P < 0.05

Figure 4.1 Rice farm yield (FY) in Central Luzon, the Philippines, in the dry and wet seasons and plotted against year, and potential yield (PY) at the International Rice Research Institute (IRRI) plotted against year of release for 1975 to 2008. Source: FY from (Estudillo and Otsuka 2006) and later International Rice Research Institute (IRRI) surveys, corrected to 14% moisture; PY from Peng et al. (2000)

Potential yield progress at IRRI

Even using IRRI's extensive research data, it is difficult to assess PY and its progress for IRRI, let alone Central Luzon. Earlier attempts (Fischer and Edmeades 2010) are now considered inadequate.

The first tropical semi-dwarf rice cultivar, IR8, was released in 1966 with a clear potential yield (established at the IRRI Los Baños farm) of about 6.5 t/ha (wet season) and 9 t/ha (dry season). Other reports claim that, early after release, experimental plots of IR8 even yielded up to 10 t/ha (Peng et al. 2000, 2010). At the end of the 1990s, Peng et al. (2000) tested in the dry season—with intensive disease and insect protection—successful varieties released during 1966–95. They showed that PY for contemporary IRRI inbred releases from the 1990s also reached 9–10 t/ha (1996 at IRRI and PhilRice; 1998 at IRRI). In the same trials, however, the yields of varieties declined progressively with time since release. Thus PY for the oldest cultivar, IR8, was only 7 t/ha at IRRI (6 t/ha at PhilRice), 25% lower than the most recently released variety. In this study the **increase in PY with year of release from 1966–97 was highly significant at 69 kg/ha/yr or 0.7% p.a.** relative to the PY of 9.5 t/ha for 1995 breeding lines, but this was coupled with the enigma of yield decline in older varieties.

The above estimate, obtained by side-by-side comparisons (vintage trials) at IRRI, is a valid measure of breeding progress, particularly given that Peng et al. (2010) confirmed that the genetic composition of the older varieties remained unchanged. Peng et al. (2010) also confirmed that the dry-season PY of IR8 had fallen to about 7 t/ha, while the latest releases have a PY around 9 t/ha, the same as IR8 when first released. This strongly suggests that the dry-season rice environment at IRRI has deteriorated since the 1960s (at least as measured by older varieties). Unfortunately, because of the difficulty in protecting older varieties in the wet season, there is no similarly sound measure of PY breeding progress for the wet season. However, PY of the current best inbreds (~7 t/ha) suggests a similar conclusion for wet season breeding progress.

The environmental changes to which breeders are unwittingly adapting the newest releases appear to be abiotic and could be edaphic, atmospheric and/or climatic. Edaphic stresses seem unlikely given the attention to these questions at IRRI (e.g. Dobermann et al. 2000), but examples of atmospheric stresses may include increasing air pollution (including ozone)—although to some extent these should have been countered by the benefits of increased carbon dioxide (CO₂). On the climatic front, reliable records show that dry-season minimum temperature (T_{\min}) has steadily increased since 1979 by 0.052 °C/yr, but maximum temperature (T_{\max}) and solar radiation have not changed significantly up to 2003.

Greater dry season T_{\min} could reduce the duration of critical growth phases, and reduce radiation use efficiency (RUE) through increased respiration (see Section 2.6 for further explanation of these key processes). Independent analyses point to a strong negative empirical relationship between dry-season yields and seasonal T_{\min} at IRRI over 1992–2003, amounting to a 10% yield decline for each 1 °C rise in T_{\min} (Peng et al.

2004; see also Section 10.3 on direct measurements and modelling). This translates into a strong effect on PY (and FY) of about -0.5% p.a., and offers one likely reason why **PY has gone backwards when measured across time for a given variety**. Atmospheric pollution is another way in which the environment may have deteriorated, but more studies are required to confirm this.

Deterioration in the rice climate at the IRRI farm appears to be continuing. Simulation with the rice model 'ORYZA2000' for cultivar IR72 suggests that PY has declined by about 0.8 t/ha between the decades 1990–2000 and 2001–2011, not only in the dry season, but now also in the wet season (A. Dobermann and G. Centeno, pers. comm. 2012). Modelled PY values in the past decade were about 9.5 t/ha (dry season) and 7.5 t/ha (wet season). Further rises in T_{\min} were recorded, and also decreases in solar radiation.

For the above reasons it is not easy to establish a current value of PY, but for the purposes of this discussion, the experimental and modelling data are combined in Figure 4.1 to show a **2008 PY at IRRI of 9.5 t/ha (dry season) and 7 t/ha (wet season)**. **The rate of PY progress in the dry season for Figure 4.1 is assumed to be 69 kg/ha/yr or 0.7% p.a.**, as determined by Peng et al. (2000); it is not possible to confidently report wet-season progress.

There has been some criticism of the conventional breeding strategy for yield at IRRI (External Program Management Review 2009). Thus the breeding strategy could impact on rate of PY progress as another, quite different factor. On the other hand, breeding at IRRI has made steady and valuable progress in other areas. Cultivars since IR8, the 1966 release, demonstrate more durable pest and disease resistance, better rice quality and reduced crop growth duration. For example, crop growth duration was reduced by 15 days between IR8 (130 days) and the 1988 release, IR72 (115 days) (S. Peng, pers. comm. 2010). This has meant that yield per day—an important measure in multiple cropping systems—has notably increased. Finally the advent of hybrid tropical rice at IRRI since 2000, as discussed later, has boosted PY in this environment.

Rice yield gap in Central Luzon

Figure 4.1 shows that the yield gap in Central Luzon, calculated using the PY at IRRI, is moderate in the wet season (80% of FY) and large in the dry season (107% of FY). Several facts suggest that the real gap could be even larger. First, the rice climate in Central Luzon may be slightly more favourable (and thus PY higher) than at IRRI, as judged by the solar radiation and cooler nights at PhilRice situated within Central Luzon (also there is no evidence that the PhilRice climate has changed significantly in the past 20 years). Second, the general district average FY in Central Luzon appears to be about 13% below that of the farmers surveyed in Figure 4.1 (Tiongco and Dawe 2002).

The 2007–08 IRRI surveys established that rice-cropping intensity is now 150% in Central Luzon. Although this means rice area has increased on surveyed farms, this should not have affected yield gap. The proportion of rice irrigated has remained steady over the past 30 years ($\sim 65\%$ wet season; 100% dry season), while fertiliser use of elemental

nitrogen, phosphorus and potassium (NPK) rose from about 70 kg/ha per crop in the early 1980s to 150 kg/ha more recently.

The large yield gap cannot be due to growing of older disease-susceptible varieties; surveys point to regular variety turnover in Central Luzon, with an average weighted variety age of 10 years (Launio et al. 2008). Up to the mid 1980s (at least), more recent varieties generally out-yielded older ones in farmers' fields (Estudillo and Otsuka 2006). In a detailed analysis of 1966–99 IRRI survey data, Estudillo and Otsuka (2006) found steady gains in total factor productivity in the system, related to adoption of successive modern varieties and better practices of integrated pest management, irrigation and planting (direct seeding). Finally, there was no evidence that these productivity gains were unsustainable.

In a later study of the same survey data up to 2008, Laborte et al. (2012) used the model ORYZA2000 with Central Luzon weather for 1985–2000 to calculate rice PY for the wet season (8.7 t/ha) and dry season (9.6 t/ha). Using the estimated FY values for 2008 (shown in Figure 4.1), these simulated PY values indicated yield gaps of 123% (wet season) and 109% (dry season). Laborte et al. (2012) also calculated average yield of the top decile of surveyed farmers to reveal that in the 1990s, top decile farmers yielded 65% (wet season) and 57% (dry season) above the average FY for all farmers. Using the 1995 survey data, Laborte et al. (2012) noted that higher yield was associated with greater application of nitrogen fertiliser (although the effect was small) and more labour per hectare, but was not associated with farm size or higher farmer schooling levels. Laborte et al. (2012) also reported on changes in yield distributions with time (see Box 8.1 on FY distribution and estimating yield gap).

IRRI has conducted other surveys in Luzon, focusing on the provinces of Nueva Ecija (near PhilRice) and Laguna (near IRRI). Byerlee et al. (2000) refers to these surveys to claim that the top one-third of farmers achieved the experiment station PY in the wet season. Indeed, more recent surveys confirm that the top one-third of farmers are approaching 6 t/ha; however, the average FY of all farmers is considerably lower. In 2008, Nueva Ecija averaged 4.5 t/ha FY, with only a weak upward trend in the past 30 years, while Laguna averaged 4.4 t/ha FY with a 0.4% p.a. rate of progress. These more recent provincial surveys point to yield gaps of 33% and 36% in the wet season in Nueva Ecija and Laguna, respectively. These are lower than the Central Luzon wet-season survey (80% yield gap), possibly because these small regions are favoured by proximity to IRRI (Nueva Ecija) and PhilRice (Laguna) and by infrastructure. Dawe et al. (2006) argued from other survey data that farmers were not using enough nitrogen fertiliser in either Laguna or Nueva Ecija, and suggested that adoption of optimal rates of nitrogen would raise yields by 1 t/ha, equivalent to about 20–25% in the dry season. However, on-farm evaluation (2001–04) of site-specific nutrient management in Nueva Ecija showed only small increases (5–13%) in FY over farmer practice (Gregory et al. 2010), suggesting only small nutritional constraints. Unreliable irrigation supply has been identified by several studies as a constraint to FY, while others point to lodging, disease (sheath blight) and weeds. To date, the relative importance of these constraints does not appear to have been adequately quantified.

In conclusion, there are moderate to large yield gaps in Central Luzon, where yields among farmers ranged widely, even 40 years after the green revolution. Also there is no consistent explanation for these yield gaps, despite substantial attention given to rice production in the region. However, gaps may be smaller in the two provinces adjacent to the rice research centres.

Physiology of progress in potential yield, ideotype breeding and tropical hybrids

For the discussions of the physiology of rice improvement that follow in this chapter, it is useful to note that although grain yield in rice can be expressed as grain number/m² (GN) multiplied by grain weight (GW), this relationship is less revealing than it is for wheat. With rice, GW is remarkably stable in the face of environmental influences. Conditions during early grain-filling affect GN much more than GW through changes in the proportion of partially filled spikelets, which are not considered to be grain-bearing at maturity (Yoshida 1981). Rice spikelets bear only one floret and then one grain, the maximum size, and hence weight, of which is limited by the rigidity of the surrounding hull. Note that generally in rice physiology, GW refers to the weight of the filled spikelet, the true grain plus that of the hull—in other words, the weight of a rough rice grain. The hull constitutes about 20% of the rough rice grain weight at maturity.

The aforementioned side-by-side comparisons of historical varieties at IRRI, which indicated the apparent PY progress in tropical rice varieties discussed above (69 kg/ha/yr), were also the subject of physiological measurements (Peng et al. 2000). It appears that increasing harvest index (HI) was important from 1966 to 1980 as varieties were bred to be shorter and earlier maturing. By shortening the wasteful vegetative period, substantial improvement in yield per day was achieved. Since 1980, however, greater dry matter (DM) and slightly later crop maturity (longer crop growth duration) seem to be associated with the highest yielding varieties. Changes in GN and GW were not consistent across varieties, although the poor yield of IR8 was linked to generally lower proportion of filled spikelets, lower GN and lower HI.

From the early 1990s IRRI breeders have made a concerted effort to boost rice PY by design (**ideotype breeding**), breeding first for the New Plant Type (NPT) and more recently for a second generation of NPT products (NPT2). NPT refers to material selected to have fewer tillers, large erect leaves and large, low panicles.

Table 4.3 shows that NPT2 varieties—which had performed better than the original NPTs—were no better than the best inbred varieties of the same vintage coming from the conventional inbred breeding (W. Yang et al. 2007). This is a disappointing outcome for physiological plant breeding, especially since the development of IR8 itself came from successful ideotype breeding. However, as a consolation to the NPT proponents, the plant type concept has been picked up in China where the NPT ideotype appears to be an important factor in the design of the very high yielding Chinese ‘super’ rice varieties and hybrids in current use (Peng et al. 2008; see Section 4.3 ‘Rice in China’).

Table 4.3 Rice potential yield (PY), total dry matter (DM), harvest index (HI) and growth duration for cultivar IR72 (released 1988), recent inbred varieties, second generation new plant type varieties (NPT2), and hybrids, grown with disease and pest protection at the International Rice Research Institute (IRRI), the Philippines

Trait ^a	Inbreds			Hybrids
	IR72	Other inbreds	NPT2	
	<i>n</i> = 1	<i>n</i> = 3 (or 4)	<i>n</i> = 5	<i>n</i> = 5 (or 4)
Wet season (average 2003 and 2004; W. Yang et al. 2007)				
PY (t/ha) ^b	5.60 AB	6.00 A	5.40 B	5.98 A
DM (g/m ²)	1,339	1,413	1,409	1,317
HI	0.36	0.38	0.37	0.41
Growth duration (days)	113	122	121	113
Dry season (average 2003 and 2004; W. Yang et al. 2007)				
PY (t/ha) ^b	8.29 B	8.73 B	8.38 B	9.55 A
DM (g/m ²)	1,726	1,722	1,691	1,792
HI	0.45	0.46	0.44	0.49
Growth duration (days)	117	117	118	116
Wet season (2004; Bueno and Lafarge 2009)				
PY (t/ha) ^b	5.22 B	5.26 B	na	6.00 A
DM (g/m ²)	1,686	1,753	na	1,906
HI	0.41	0.43	na	0.45
Growth duration (days)	113	112	na	113
Dry season (2007; Bueno and Lafarge 2009)				
PY (t/ha) ^b	9.73 B	8.76 B	na	10.65 A
DM (g/m ²)	2,113	1,899	na	2,139
HI	0.52	0.47	na	0.54
Growth duration (days)	114	115	na	115

- a Biomass and harvest index came from subsamples of hills taken at physiological maturity. Grain yield was determined separately over several square metres. This may explain why yield is consistently lower than the product of biomass and harvest index.
- b Paddy rice measured at 14% moisture; yields followed by the same letters in the same row are not significantly different at $P < 0.05$.
- na = not available

Chinese success with hybrid rice has been followed by success at IRRI with tropical hybrids (Indica × Indica). The best Philippine F₁ tropical hybrids yielded 11–14% more than the best inbreds in the dry season at IRRI, although results of W. Yang et al. (2007) indicated little advantage in the wet season (Table 4.3). In another study, Bueno and

Lafarge (2009) carefully matched hybrids and inbreds for phenology and showed yield advantage of 18% (dry season) and 14% (wet season) for all hybrids compared with all inbreds (Table 4.3). Currently, tropical hybrids occupy about 5% of the Philippine rice area, and yield on average 17% more than inbreds (Janaiah and Xie 2010).

In the hybrid studies at IRRI (Table 4.3), hybrids were superior—except in the wet season of the W. Yang et al. (2007) study—by virtue of both greater DM and greater HI. W. Yang et al. (2007) revealed that hybrids had more spikelets per square metre in the dry season, but this was countered by a lower proportion of filled spikelets; extra yield tended to come from greater GW. Bueno and Lafarge (2009) (Table 4.3) took care to compare hybrids and inbreds of similar days to flowering, revealing that hybrids had on average a 16% yield advantage over inbreds and IR72. The hybrids also had more spikelets per square metre, a slightly lower proportion of filled spikelets, 30% greater GN, 6% lighter GW and a higher crop growth rate during every developmental interval. Lafarge and Bueno (2009) attributed higher HI in hybrids to higher DM partitioning to panicles before flowering, and greater DM remobilisation from culms during grain-filling. Later work by Bueno et al. (2010) confirmed the advantages of hybrid rice relative to the inbred cultivar, IR72, and suggested that both greater specific leaf area and an earlier cessation of tillering might also be involved.

IRRI studies of leaf-level physiology (e.g. maximum photosynthesis and/or stomatal conductance) among historic inbreds (1966–85) did not reveal consistent trends across time (Hubbart et al. 2007). However, the relevance of these studies may be limited by the focus on spaced plants in a growth cabinet.

Mitchell et al. (1998) estimated a PY of 10 t/ha in a detailed analysis of yield determination based on average dry season radiation at IRRI (18 MJ/m²/day), expected radiation interception by a 4-month duration rice crop, a typical radiation use efficiency (RUE) of 2.2 g/MJ and HI of 0.5. The Mitchell et al. (1998) PY result agrees with that calculated earlier by Yoshida (1981) from an effective grain-filling period of 25 days with high RUE assumption. Neither approach necessarily defines the theoretical limit—an issue that is addressed in Section 9.5 on potential yield. However, these longstanding estimates may at last have been fulfilled by the new tropical hybrids.

South-East Asia—the Philippines, Indonesia and Vietnam

The Philippines and Indonesia are rice-importing nations striving for self-sufficiency. By comparison, Vietnam is a rice exporter. All three countries grow rice mostly in RME1, with regions of double and triple cropping of rice, but in addition have significant areas of RME5 (rainfed lowland), some of which is also double cropped rice. All three countries have shown impressive progress in national rice production, both in harvested area and FY (first four columns of Table 4.4), with little sign of abatement in the FY progress, especially in Vietnam. Brennan and Malabayabas (2011) shed some light on the role of breeding in this progress.

Brennan and Malabayabas (2011) collected variety yield data from national trials and farmer variety adoption statistics to construct a variety yield improvement index at the farm level (1986–2009); the method was the same as that of Silvey (1981) mentioned in Section 2.2. Their data are shown in the last three columns of Table 4.4. Although hybrids reach 5–10% of area in these countries (F. Xie, pers. comm. 2012) no data were available on their performance and their area is still too small to greatly affect FY.

Table 4.4 Rice harvested area and area change, farm yield (FY) and rate of progress, and yield index progress for the Philippines, Indonesia, and northern and southern Vietnam for the past 20 years

Country or region	Area		FY		Variety trial results		Rate of yield index progress ^b (% p.a.)
	Average 2008–10 (Mha)	Growth rate (% p.a.)	Estimated FY 2010 (t/ha)	Rate of progress (% p.a.)	Estimated yield in final trial year (t/ha)	Rate of yield increase ^a (% p.a.)	
Philippines	4.5	1.3	3.7	1.6	5.6	0.7	0.5
Indonesia	12.8	0.8	5.0	0.7 ^c	6.5	1.3	0.9 ^c
Northern Vietnam ^d	7.4	0.7	5.3	2.2	na	na	na
Southern Vietnam ^e	4.6	0	5.2	1.9	4.8	1.0	1.0

a Relative rates of increase are calculated (as elsewhere in this book) as linear slopes relative to the yield of the most recent release; all rates $P < 0.05$ or better.

b Yield index weighted for varieties grown by farmers; increase relative to yield index in 2010

c Indonesia's FY showed a sharp decline in 1998 then an accelerated growth; the average 20-year growth of 0.7% p.a. is shown. There was also a clear acceleration in the yield index around 2000, increasing very slowly from 1991 to 2000, and rapidly thereafter (1.9% p.a.); the average rate over the 20 years was 0.9% as shown.

d Variety data are not available for northern Vietnam.

e Comprising the Mekong Delta, the south-east and the south coast.

na = not available

Source: First four columns taken from FAOSTAT (May 2012), except for southern Vietnam, which is taken from the World Rice Statistics of IRRI (2012); final three columns from Brennan and Malabayabas (2011)

The variety data in Table 4.4 reveal several important points. First there is apparently good breeding progress in each country (0.7–1.3% p.a.). Brennan and Malabayabas (2011) calculated that IRRI germplasm had a major influence on varieties released in all countries, and hence on the progress shown in Table 4.4. This outcome is in contrast to the aforementioned situation at IRRI where PY progress (0.7% p.a.) appears to be more limited. The explanation could be complex, but may lie partly in subtle changes in the field environment at IRRI; also, the trials by national breeders were not really PY trials, but had some level of disease and pest infestation (resistance to which is a strong feature of IRRI germplasm).

Second, Table 4.4 shows that breeding progress at the variety level was reasonably well reflected in progress in the variety yield index, as measured by the varieties farmers chose to grow. Table 4.4 also shows that in trials the best varieties exceed FY by 51% (Philippines) and 30% (Indonesia), but were 8% below FY in southern Vietnam. Due to lack of information on variety trial management, it is probably wise to conclude that yields from southern Vietnam do not represent PY. Even the values of trial yield in the final year shown in Table 4.4 for the Philippines and Indonesia are probably underestimates of PY, as is the suggested yield gap.

Mataia et al. (2011), looking at rice farmer surveys across the whole of the Philippines between 1996 and 2006, confirmed the importance of improved varieties for FY increase, adding that an increase in irrigation was also a significant factor.

Laborte et al. (2012)—mentioned earlier in the context of Central Luzon—also examined FY and yield gaps in 1990s surveys of the intensive irrigated rice systems of West Java (Indonesia), Can Tho (Mekong Delta, southern Vietnam) and Suphan Buri province (in the RME1 region of central Thailand). Across these locations, and wet and dry seasons, average FY was 5.0 t/ha. Yields from top decile farms averaged 6.6 t/ha—equating to a yield advantage of 33% (relative to the sample average FY)—while the simulated PY was 8.0 t/ha, or 62% higher than average FY. In contrast, the aforementioned yield gap for Central Luzon (123% wet season and 109% dry season, according to Laborte et al. 2012) seems to suggest larger yield gaps for that particular Philippine region than for other intensive South-East Asian systems.

Laborte et al. (2012) found no relationship in any situation between FY and nitrogen fertiliser, labour input per hectare, farm size or farmer schooling, and they found no explanation for the larger gaps in Central Luzon. It is notable that farm size is intermediate (1.5 ha) in Central Luzon, with smaller farms in West Java (1.2 ha) and Can Tho (0.8 ha), and larger ones in Suphan Buri (2.1 ha). Connected to this, the greatest contrast from the surveys is not between average and high-yielding farmers, but between countries in their respective labour productivities in rice production. Labour productivity is three to six times higher in Suphan Buri, undoubtedly due to mechanisation in that richer location.

Summary for rice in Central Luzon and South-East Asia

The South-East Asian countries of intensive tropical rice cropping (RME1) have shown impressive yield progress in the past 20 years, even as rice areas have increased. Breeding and variety replacement have formed a major component in this progress, but yield gaps remain moderate to large, especially in the Philippines.

Despite extensive surveys, in particular in Central Luzon near IRRI, yield constraints are unclear and probably multiple. In comparing the best 1960s yields to the best current yields, PY breeding progress at IRRI with inbred varieties appears to be zero. However,

this worrying interpretation is complicated by the rise in unknown environmental constraints, against which there has been PY breeding progress. Moreover, breeding gains in many other aspects of the rice crop are apparent, and good breeding increases are evident at the national level in the Philippines, Indonesia and Vietnam.

Despite much research, there appears to be no clear physiological pathway to increased PY at IRRI, apart from increases in DM, HI and GN; it is also notable that PY has increased even as crop growth duration has been shortened. After initial success with the first tropical semi-dwarf variety, IR8, further attempts at ideotype breeding (e.g. NPT) have been disappointing. However, the advent of Indica rice hybrids has boosted PY by 10–15% at IRRI, and is likely to lift FY similarly in the whole region provided efficient seed systems can be developed (Spielman et al. 2012).

4.3 RME2 and RME3—China

RME2 and RME3 lie within China, the world's largest rice producer.

Introduction

Rice area in China has been gradually decreasing, but it seems to have settled at close to 30 Mha since 2004. Yield progress was substantial between 1960 and 1990 (160% increase), given:

- development of semi-dwarf varieties (starting in the late 1950s)
- increased irrigation, mechanisation and inputs
- introduction of Indica hybrids (beginning in the late 1970s)
- major positive policy changes in the beginning of 1979.

However, over the past 20 years, FY progress has slowed to a rate of only 0.6% p.a. of the estimated 2010 FY of 6.5 t/ha (Figure 4.2). Since rice is grown over such a large area—93% under full or supplemental irrigation—there is remarkably little year-to-year change in national yield. The pattern of deviations from linearity (seen in Figure 4.2) probably reflects policy changes.³³

For example, the record yield year of 1998 was followed by declining yields until 2003, as the large stocks in 1998 prompted reductions in price support and other subsidies—a policy that was reversed from 2003 onwards (H. Wang et al. 2009). Considering that the observed 2011 rice yield came in at 6.7 t/ha (FAOSTAT 2013),

³³ There is evidence of slight warming of the rice season across China over the past 20 years or so, but there is no evidence that it has affected rice yields consistently (T. Zhang, pers. comm. 2011).

yield appears to have grown steadily in the past 8 years under a relatively stable policy regime. It should be noted that, similarly with wheat, China seeks to control rice production so as not to exceed consumption. Rice consumption in China is now stable, or gradually falling, as per capita consumption declines with per capita income increase (Timmer 2010), although this notion has recently been challenged.

A recent, detailed description of rice ecologies in China is given by Tang et al. (2010). Those authors also discuss rice-breeding progress, but their boundaries do not always correspond to the RMEs defined here. Rice is grown from latitude 18 °N to 53 °N, covering RME1, RME2 and RME3 moving north from the south-eastern China lowlands (Map 4.3). RME1 dominates (>50% of all rice) although the proportion planted to rice double-cropping has declined lately. Currently about 6 Mha of RME1 is planted to double rice, equivalent to 12 Mha (~40%) of the total China rice area. Yield per crop of double rice is about 20% lower than that of single rice.



Map 4.3 Rice mega-environments (RMEs) in China and major rice growing provinces. Source: Derived from maps of the International Rice Research Institute (IRRI). International borders are approximate.

The boundary between RME1 and RME2 is at ~ 31 °N (the latitude of Nanjing in the southern portion of Jiangsu province). North of this boundary, double rice becomes unsuitable and rice–wheat or rice–canola systems predominate. North of the Yellow River little rice is grown except for the north-east RME3 region (latitude 40 °N to 53 °N),

which grows single rice (no winter crop). Note that an exception to the simple latitudinal split between RME1 and RME2 is found in the south-western plateau region (Map 4.3). This significant rice region (15% of China area, according to Tang et al. 2010) is below 32 °N but higher in altitude—i.e. more than about 1000 m above sea level (masl)—and grows mostly single rice of largely Japonica type.

The Indica variety of rice predominates in RME1 and Japonica rice elsewhere; overall China plants about 75% Indica rice by area (Tang et al. 2010). By 1990, planting of Indica hybrids had increased rapidly to comprise around 15 Mha of the Chinese rice area, and this area has remained fairly stable since then, despite efforts to develop hybrids for cooler environments currently dominated by Japonica rice (only 7% of Japonica rice are hybrids; Z-K. Li et al. 2012). The yield advantage of Indica hybrids is around 10–20% over Indica inbreds, so the adoption of hybrid rice had a major impact on yield in China before 1990, but less so since then. Following Indica hybrids, ‘super’ rice—and then ‘super’ hybrid rice—became national projects in the late 1990s (Peng et al. 2009; Tang et al. 2010).

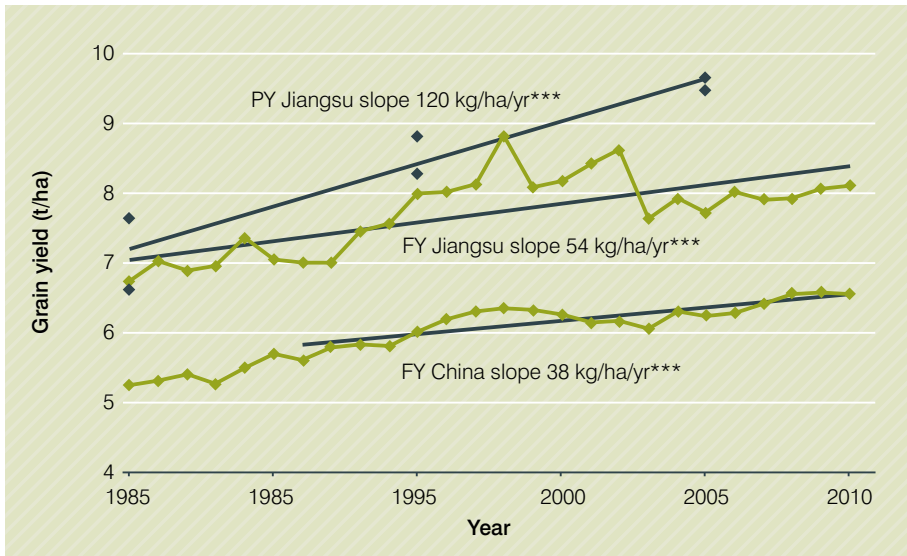
‘Super rice’ is based on a new morphological plant ideotype (including moderate tillering, heavy drooping panicles, and long, erect, thick and narrow upper three leaves)—a concept influenced by the NPT thinking from IRRI. Since the projects began, many ‘super’ rice inbreds (mostly Japonica) and hybrids (Indica, but with some intermediate types) have been released, and the best are achieving 12 t/ha under high-input agronomy (Tang et al. 2010; M. Huang et al. 2011). Currently about 20% of China’s rice area is planted to the ‘super’ inbreds and hybrids (S. Peng, pers. comm. 2012), so the influence on overall FY is still modest.

China has approved the widespread testing of genetically engineered rice—incorporating the *Bacillus thuringiensis* (*Bt*) insect resistance gene—in farmers’ fields, but has yet to authorise wide-scale release. In any case, the effect on yield appears small, although labour and pesticide costs are reduced (Huang et al. 2008).

Yield progress of rice in China including Jiangsu province

The province of Jiangsu (RME2), on the east coast between latitudes 31 °N and 34 °N, grows 2.2 Mha of single rice following mostly wheat, with about 60% transplanted in mid-June, with the rest direct-seeded a week or so earlier. Although the north-eastern province of Jilin (RME3) achieves the highest FY in China, Jiangsu achieves the second highest, with FY close to 8.0 t/ha.

Progress in FY over the past 25 years in Jiangsu has been quite erratic (Figure 4.2). **The rate of progress for FY is 0.7% p.a. of the estimated 2010 FY taken to be 8 t/ha;** FY increase has clearly resumed since the sharp policy-induced decline between 1998 and 2003.



*** $P < 0.01$

Figure 4.2 Change in rice farm yield (FY) plotted against year for China as a whole, and for Jiangsu province, and potential yield (PY) plotted against year of release at Yangzhou, Jiangsu, for 1985 to 2010. Source: FY from IIRRI (2012); PY from H. Zhang et al. (2010)

The erratic nature of FY in Jiangsu is also seen in other major single rice provinces (e.g. Heilongjiang and Sichuan), and in the double-rice province, Jiangxi, which lies several hundred kilometres south-west of Jiangsu. All four provinces showed peak yields in the 1999–2004 period, followed by lows 1–2 years later, and then progress again, but without exact correspondence in the timing of the peaks and troughs between provinces. Again this probably reflects rice policy changes to favour other crops. In contrast, the top rice-growing province (by area) of Hunan, with 4.1 Mha of mostly double rice, shows steady progress at 34 kg/ha/yr, or a rate of 0.5% p.a. of the estimated 2010 FY of 6.3 t/ha.

One recent study of PY progress in Jiangsu (H. Zhang et al. 2010) showed a strong linear PY increase since the mid 1950s, with no sign of slowing in the past two decades (see Figure 4.2). **PY progress at 120 kg/ha/yr is 1.2% p.a. of the 2005 PY (9.6 t/ha)**. There are no other estimates of PY progress, but recent reports of PY for modern ‘super’ hybrids in the lower Yangtse region—grown as single crops (June transplant) and excluding results that provided only a range of yields—averaged 11.0 t/ha (Peng et al. 2008; Y. Zhang et al. 2009), while J. Yang et al. (2007) reported 11.5 t/ha for Japonica inbreds. Finally, H.W. Li et al. (2012) measured 9.6 t/ha with high input farmer practice, but 12.6 t/ha with innovative agronomy, including alternate wetting and drying and early rationing of nitrogen fertiliser. Simulation with the ORYZA2000

model also suggests PY of about 11 t/ha for June transplanted rice in Jiangsu (J. van Wart, pers. comm. 2011).

Taking 11 t/ha as the current PY to compare against the Jiangsu FY of 8.0 t/ha, gives a **yield gap of 38%**. Simulating PY with OYZA2000 across all the major rice systems in China, and weighting appropriately, van Wart et al. (2013b) estimated that the national China rice yield gap is on average only 22% of FY; this seems low compared with the estimate here for Jiangsu, and may reflect an underestimation of PY due to the vintage of varieties used in the modelling.

Peng et al. (2009) and Tang et al. (2010) have discussed constraints to rice FY in China. Apart from the increasing demand for high-quality rice varieties (which are often lower yielding Japonica varieties), most constraints relate to poor irrigation infrastructure, and inadequate and oversimplified crop management. One reflection of the latter is overuse of pesticides and fertiliser (e.g. average rates of 300 kg N/ha in Jiangsu). This overuse not only reduces resource use efficiency (Chapter 11), but sometimes also reduces yield, as excess nitrogen leads to greater susceptibility to lodging and disease, and to slow soil acidification. Other manifestations of oversimplified management are excessive spacing in transplanting, broadcasting of seedlings and single (rather than split) nitrogen doses.

J. Yang et al. (2007) confirm the above management deficiencies in Jiangsu, adding the importance of seedling strength, mid-season draining and alternate wetting/drying irrigation during grain-filling for highest yields. Curiously, modelling suggests that yield is very sensitive to timing of planting (van Wart et al. 2013b), but this does not appear to be a constraint to FY—probably because planting date is a critical event on the Chinese crop calendar and rarely missed. Nevertheless, oversimplified management is a common observation, and is related to poor knowledge, weak agricultural extension and labour shortages.

The root cause of the yield gap—perhaps more evident in the booming Chinese economy than elsewhere in the developing world—would seem to be the failure of incomes on (typically tiny) rice farms to match the growing incomes from urban labour. This is leading to out-migration from farming into the more lucrative urban economy. One part of the solution is a move to mechanical transplanting (Zheng 2010); another must be the consolidation of land management so that good managers can be retained and rewarded. The alternative is a steady drift towards the inefficient subsidy-dependent rice systems of Japan and the Republic of Korea.

Physiology of 'super' rice and hybrid 'super' rice

Peng et al. (2008) noted that the best hybrid 'super' rices in eastern China out-yielded older hybrid control varieties by 10–20%, apparently due to higher DM and maximum photosynthetic rate (P_{max}) around heading, higher specific leaf weight and higher leaf chlorophyll. In addition, the three leaves of 'super' rice hybrids are very erect

(like the NPT varieties from IRRI), but are long and reach well above the panicle (unlike modern wheat). Although panicles are larger, spikelet filling percentage in the 'super' hybrids may be less than desired. Y. Zhang et al. (2009) confirmed the superior yield and DM of hybrid 'super' rices in Hunan, but explained this largely through increased duration of canopy light interception rather than increased RUE. M. Huang et al. (2011)—also experimenting in Hunan—reported 11% higher yields with 'super' hybrids compared to common hybrids and 'super' inbreds, which they attributed to larger panicle size.

Comparing the best Japonica inbreds in Jiangsu, H. Zhang et al. (2010) noted greater yield of more recent varieties was associated with both greater DM and HI. Leaf area index (LAI) and root weight were also greater, leaves were more erect and P_{\max} and root oxidative activity were greater both at panicle initiation and heading. Needless to say, spikelet filling percentage was lower in the latest varieties, and physiologists now target this trait at the hormonal and molecular levels (e.g. Yang and Zhang 2010) as the key to even higher yield. HI never exceeded 0.5 in either the Hunan or Jiangsu province studies, but did reach 0.52 under the innovative agronomy of H.W. Li et al. (2012), who also noted increased DM production around heading, increased P_{\max} and greater root exudation of cytokinins with this treatment.

Consistently very high yields (16.5–19.3 t/ha) have been reported for hybrid 'super' rice varieties transplanted in April and grown with optimal management in the village of Taoyuan in the southern province of Yunnan (latitude 26 °N and 1170 masl, south-western plateau region) (Katsura et al. 2008; Li et al. 2009). There is little doubt that the very favourable climate at Taoyuan (lengthening days from earlier transplantation, higher daily solar radiation and lower T_{\min}) relative to other parts of China (and Japan) provides the principal reason for greater PY there. Thus the high Taoyuan yields arise from both increased crop growth duration and crop growth rate, and hence greatly increased DM production. Yields at Taoyuan have also been compared with those at IRRI, Los Baños, in the Philippines (Ying et al. 1998). The IRRI dry season climate (January transplant) is not so different from that for May transplantation in Yunnan, but duration of daylight is much shorter (11.5 hours vs. 13 hours). Being a short-day plant, crop growth duration and DM production were greater in Yunnan, and yield was 47% higher for Yunnan than that for IRRI.

Conclusion for rice in China

Rice yield in China grew rapidly in the 1970s and 1980s, and in the past 20 years FY has progressed steadily (at a rate of 0.6% p.a. relative to the 2010 FY of 6.5 t/ha) on a gradually declining area. In this way the major policy goal of self-sufficiency appears to be relatively secure, especially as per capita rice consumption is falling.

Measures of PY progress have proved difficult to obtain, but PY appears to be high, at least partly due to targeting of the 'super' rice phenotype over the past 15 years. It is clear that China is investing strongly in the latest technologies in breeding for higher

PY, greater stress resistance and better quality (Tang et al. 2010). As a result, China probably now leads the world in pursuit of these rice traits.

The yield gap is about 40% of FY, and could close somewhat with more skilled agronomic management of inputs that would also allow fertiliser use efficiency to increase markedly through better management of lower rates. However, structural problems (especially tiny farm size) persist and—because of poor labour skills and little incentive to mechanise—may pose a special constraint to agronomic improvement. The recent breeding progress that raised PY for ‘super’ hybrids through increased DM (and sometimes increased P_{max}) parallels observations on progress in Japan (Section 4.5), and reported increases in root mass and root activity are also noteworthy.

4

4.4 Irrigated rice in the Indo-Gangetic Plain (IGP) region of India

Introduction

India has the largest rice area in the world (43 Mha) but yield is relatively low (3.3 t/ha).³⁴ Low rice yield in India is partly related to the high percentage of rainfed rice, especially in eastern India. Irrigated rice dominates across the Indo-Gangetic Plain (IGP, see Map 3.3) from the state of Punjab in the north, to the state of West Bengal in the east, and in the central state of Andhra Pradesh linking to the southern state of Tamil Nadu (Map 4.4).

According to the International Rice Research Institute (IRRI) World Rice Statistics 2004–06, India’s rice area comprises:

- 53% irrigated (RME1 and RME2)
- 32% rainfed lowland (RME5)
- 12% rainfed upland (RME6)
- 3% deepwater rice (RME7).

Rice area is steady, but the irrigated proportion increased linearly from 1960 to a peak in 2000, followed by a small decrease. Thus only some of India’s **moderate FY progress of 35 kg/ha/yr since 1990**—equivalent to 1.1% p.a. relative to an average 2008–10 FY of 3.3 t/ha (Table 4.1)—is likely due to an increase in the percentage of rice area irrigated.

³⁴ Note, however, that yields appear even lower in Indian statistical documents, which usually report rice yield as ‘milled rice’; this equates to only 67% of the paddy yield used throughout this book.



Map 4.4 Major irrigated and rainfed rice regions of India. Source: Derived from maps of the International Rice Research Institute (IRRI); note some areas overlap because RME is determined by hydromorphology, which changes over short distances.

Unfortunately yields are not readily available for the separate RMEs in India. The area-weighted average FY for the four states with more than 90% irrigation (Andhra Pradesh, Punjab, Tamil Nadu and Haryana) in 2007–09 was 5.0 t/ha (IRRI 2012), providing one estimate of yield across all irrigated rice in India (i.e. RME1 + RME2). Another estimate is from Janaiah and Xie (2010) who report 2005–07 average yields across India as 4.9 t/ha (irrigated), 3.4 t/ha (largely irrigated) and 2.2 t/ha (rainfed), with yields increasing at around 1% p.a. in each class. Irrigated rice (RME2) in the IGP of India—in particular, the state of Punjab—is discussed in detail below, while India’s rainfed rice (RME5 and RME6) is reported in Section 4.8.

India currently grows about 2 Mha (~5% of national rice area) of **hybrid rice** (F. Xie, pers. comm. 2012). Janaiah and Xie (2010) reported the area planted to hybrids is now expanding rapidly in the irrigated eastern part of India (including the eastern IGP); seed yields have reached 2.5 t/ha, which is very profitable for seed producers and allows seed to be sold for affordable prices. Third-generation hybrids (non-basmati types, but with better quality and yield than previous generations) are out-yielding inbreds by about 30% in farmers’ fields, and delivering 20% more profit. However, in a recent review, Spielman et al. (2012) point to various scientific, technical and policy

challenges to be overcome if hybrid rice is to drive the yield revolution in South Asia, for which it seems to have potential. Needless to say, until now the effect of hybrid rice on the Indian rice yields has been minimal.

Irrigated rice in the Indian IGP and state of Punjab

The IGP is predominantly located in India, but parts spread into Pakistan (to the west) and Nepal and Bangladesh (to the east, see Map 3.3). There are approximately 18 Mha of rice in the Indian IGP, including some rainfed rice and some winter rice (*Boro*) in the east, but rice is largely farmed in a system of rice–wheat double cropping. Thus in terms of the cropping system, RME2 equates to the wheat mega-environment WME1. Ladha et al. (2003b) report 13.5 Mha of rice–wheat double cropping in the Indian IGP.

Pathak et al. (2003) studied rice yields at eight irrigated rice–wheat districts across the Indian IGP. District rice FY (1985–99) averaged 3.45 t/ha; significant time trends in FY over this period were negative (one district) and positive (two districts), with an average trend of FY increase of only 8 kg/ha/yr (or 0.2% p.a. of the 1999 FY). During the 1985–99 rice crop seasons, four of the eight IGP sites experienced significant solar radiation decline (possibly due to aerosol pollution) and small, non-consistent changes in temperature. Using the 'CERES Rice v3.5' model with these weather data, Pathak et al. (2003) simulated yield trends to be expected from weather change alone ranging from –120 kg/ha/yr to +50 kg/ha/yr. The average trend was –40 kg/ha/yr, or –0.4% of the average simulated yield of 9.4 t/ha. To correct for the deterioration in weather, it is valid to add this 0.4% average trend to the district FY yield change above to obtain a corrected estimate of 0.6% for FY technical progress. Climate deterioration thus goes some way to explaining the slow observed increase in rice FY in the districts.

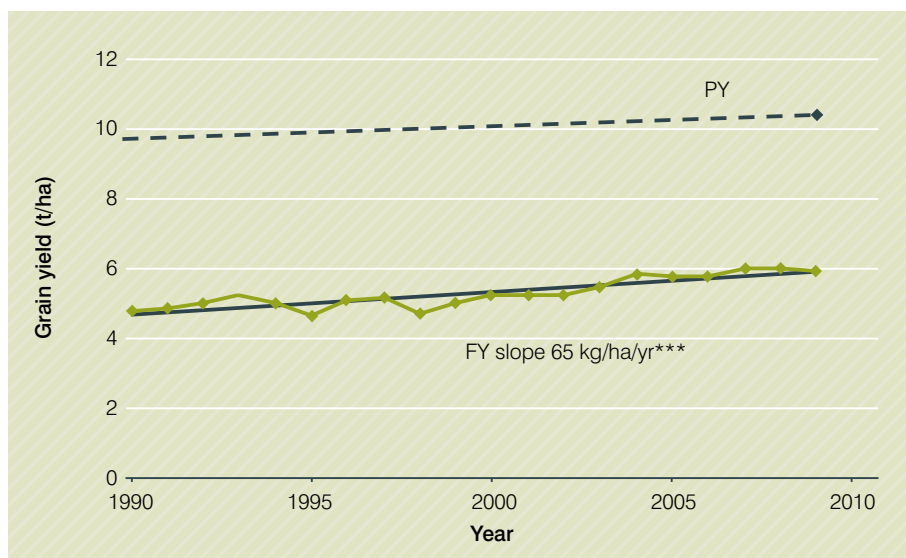
Long-term rice–wheat experiments across the IGP for 7–14 years to 2000—the same period as that covered by Pathak et al. (2003), above—could help clarify the situation. In these experiments, rice yield declined by 41 kg/ha/yr, equating to –0.9% p.a. relative to the average experimental yield of 4.8 t/ha (Ladha et al. 2003b; Tirol-Padre and Ladha 2006). The correction for weather change calculated by Pathak et al. (2003) can also be added to the yield trend from the long-term experiments, but a yield decline (–0.5% p.a.) still results. Unfortunately, it seems clear from this result (and generally poor yield in these experiments) that there were unknown yield constraints relating to nutrition and/or management of the experiments, as discussed by Regmi and Ladha (2005). Another limit to these otherwise comprehensive IGP studies mentioned above is that results are compromised by the time lapse since their completion, because more recent FY progress at the state level looks more promising (IRRI 2012).

Punjab, in the western IGP, grows about 2.6 Mha of rice (99% irrigated) and has the highest state average yield in India. FY for Punjab increased significantly over the past 20 years (1990–2009), **giving a FY of 6 t/ha in 2009 and a rate of progress of 1.1% p.a. relative to 2009 FY** (Figure 4.3).

Other Indian IGP states dominated by irrigated rice after wheat also show FY progress over this recent 20-year period, amounting to a more positive picture than that presented by Pathak et al. (2003):

- Haryana—100% irrigated; current FY 4.4 t/ha; rate of FY progress 0.6% p.a.
- Uttar Pradesh—66% irrigated; current FY 3.1 t/ha; rate of FY progress 0.6% p.a.
- Bihar—42% irrigated; current FY 2.2 t/ha; rate of FY progress 1.0% p.a.
- West Bengal—42% irrigated; current FY 4.0 t/ha; rate of FY progress 1.5% p.a.

Note that the comparatively higher yield in the warmest and most eastern state of West Bengal, India's largest rice producing state, probably arises from the presence of a significant proportion of higher yielding *Boro* rice grown under irrigation and the occurrence of high radiation in the dry winter season.



*** $P < 0.01$

Figure 4.3 Rice farm yield (FY) plotted against year, and potential yield (PY) plotted against year of release, in the Indian state of Punjab, for 1990 to 2009. Source: FY from the IRRI (2012); PY value estimated for 2009 from multiple yield trials, as was PY change

There appear to be no vintage trials or mixed-model regression analyses measuring PY progress in Punjab. Although a great diversity of varieties is released by the Indian Directorate of Rice Research (DRR) and others, the published PY values on release from DRR are quite variable (even for irrigated crops), and are more

influenced by grain quality considerations than year of release. One possibility is to look across the yields of the best non-basmati varieties released each year for the irrigated environment in the region. Data from the DRR (M. Gautam, pers. comm. 2012) show that, over the past 30 years, these yields have increased at about 0.6% p.a. of the PY in 2009. Allowing for the likely influence of changes in environment (e.g. changed agronomic practices, and/or increased CO₂) over the same period, it is estimated that PY progress has been around 0.3% p.a., while noting the need for some direct measurements.

Punjab and Haryana grow a significant proportion of lower yielding, high-quality basmati rice varieties. Thus the **current PY of rice in Punjab** is hard to determine. It is possible that PY may be as high as the simulated results of Pathak et al. (2003), which are given as 10.7 t/ha for Punjab (in the district of Ludhiana), 9.3 t/ha for Uttar Pradesh and 7.7 t/ha for West Bengal. In fact, these estimates of PY, obtained by suspending all water and nitrogen stress in the model, have been confirmed by a later version of the CERES Rice v4.1 model (Pathak et al. 2009), which performs well over many environments for transplanted rice (Timsina and Humphreys 2006).

The latitude and rice climate in Punjab appear to be quite similar to those of, for example, Jiangsu province in China, where the measured PY of rice is around 11 t/ha (see Section 4.3). In fact, simulation suggests that because the district of Ludhiana (in Punjab) experiences higher solar radiation, PY for Ludhiana should be higher than Jiangsu (Timsina et al. 2011).

On the other hand, across seven published reports in the past 5 years, the average of the highest current measured experimental yields in Punjab was only 7.1 t/ha for the best non-basmati variety, transplanted in June, and managed with high nitrogen or site-specific nutrients. All these yields came from the Ludhiana district for which average yield is currently 1 t/ha above the Punjab average. It is curious that data from the DRR variety releases suggest that the PY of the best non-basmati varieties released around 2010 was much higher, at about 11 t/ha.

One possible explanation for the cited low measured yields in field experiments in Punjab referred to above may be that even the best nutrient management is not overcoming limitations posed by degraded soils. For example, Punjab soil organic carbon levels are usually less than 1% (w/w), and often less than 0.5%, in contrast to Jiangsu in China where levels are commonly greater than 1%.

The conclusion is **that rice PY in Punjab is on a par with the simulated PY of about 10.5 t/ha**. This PY value is shown a single point in Figure 4.3; PY change over the previous 20 years is shown at the estimated 0.3% p.a. in the absence of vintage trial data. The PY value points to a **yield gap of 75%** of current FY in Punjab, but the persistence of lower yielding tall basmati varieties in farmer plantings may be a factor in this.

Yield gaps and constraints for irrigated rice across the Indian IGP

The simulation studies of Pathak et al. (2003, 2009), coupled with current decreases in FY moving southwards and eastwards from Punjab along the IGP, leave little doubt that the yield gap is even greater in the Indian IGP east of Punjab. Yield gap likely exceeds 100% in Haryana, and may be greater than 150% further east.

IRRI (2008) estimated that FY of irrigated rice in South Asia was constrained by identifiable limiting factors amounting to 37% of FY, including nutrients (10%), diseases (7%), weeds (7%), water shortage (5%) and rats (4%). This expert opinion differs from the above gap estimates in magnitude, but may be useful for ordering constraints.

Recently, more has been published on **agronomic constraints and opportunities** in the rice–wheat system of the IGP (Ladha et al. 2009; Chauhan et al. 2012). New agronomic technologies for rice include:

- laser levelling of fields
- raised-bed cropping in some soils
- direct seeding and mechanical transplanting of rice in puddled fields (or preferably, non-cultivated fields)
- new weed control strategies (especially for non-puddled plantings)
- site-specific nutrient management for nitrogen fertilisation
- better attention to nutrient balance
- alternate wetting and drying irrigation.

These innovations are likely to reduce cost and conserve resources, as much as they enhance yield; labour saving at planting is a particularly strong driver of innovation. Moreover if a concerted effort is made to bring these innovations—along with modern varieties—to farmers, FY could undoubtedly be lifted, especially in the central and eastern IGP.

IRRI (2008) estimated that investment in research, development and extension targeting the above FY constraints would increase irrigated rice FY in South Asia over the next 15 years by 0.7% p.a. (relative to current FY), essentially through yield gap closing. IRRI is now engaged with other agents in the Cereal Systems Initiative for South Asia (CSISA) project to do exactly this at several ‘hubs’ in the IGP. CSISA reported a 14 t/ha farmer field FY from a modern hybrid rice variety in Uttar Pradesh in 2011 (R.K. Malik, pers. comm. 2012). If this yield can be repeated, the results will be an exciting endorsement for the role of improved agronomy and hybrid rice.

It appears that researchers have given less attention to **longer term issues in cropping systems**. For example, the rice–wheat system lacks diversity. In the central and eastern IGP, where the comparative advantage of rice in the summer is overwhelming, there are few viable broadleaf winter crops as alternatives to wheat. Similarly in the west,

where rice is a heavy user of scarce irrigation water, and groundwater levels are falling (Humphreys et al. 2010), alternative summer crops like maize or soybeans are not grown. Also, where good farm agronomy is already practised in the west, low levels of soil organic carbon can be better overcome with crop rotation, increased (and better balanced) crop nutrition and crop residue return combined with reduced and zero-till systems. This, and research on the neglected area of soil pathology, should deliver new agronomic technologies that will essentially raise measured PY directly and through positive interactions with ongoing genetic improvement.

Conclusion for irrigated rice in the Indian IGP

Rice FY appears to be progressing at about 1% p.a. relative to current FY across Indian rice systems, with some evidence that reductions in solar radiation may be a brake on this progress in the IGP. PY levels and progress measurements are not clear for rice in RME2 of the Indian IGP, but breeding progress appears to be slow. However, PY values may not be so critical, since simulation of PY for non-basmati varieties suggests that the yield gap is large to very large, increasing from about 75% of FY in Punjab to more than 150% in the central and eastern parts of the Indian IGP.

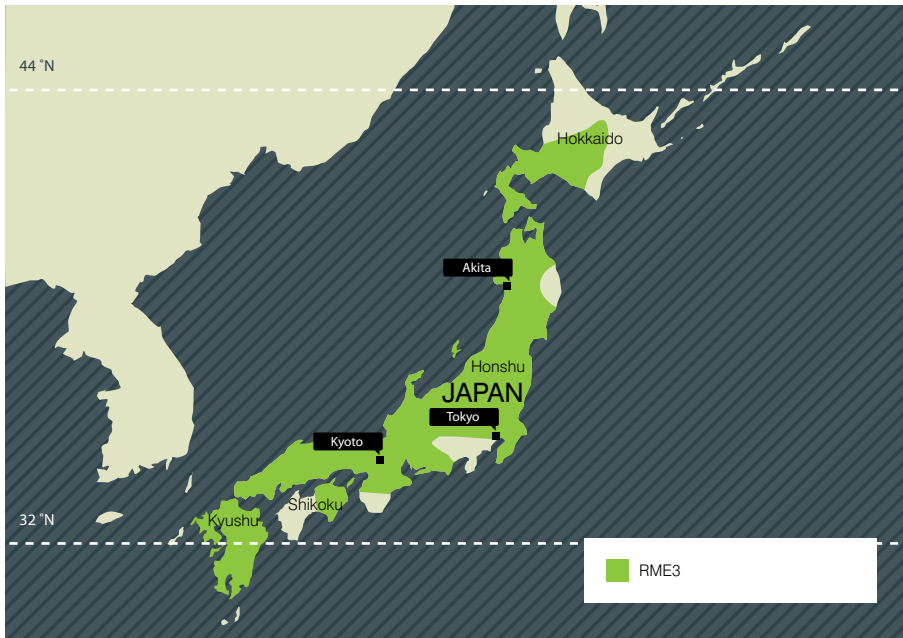
Crop nutrition, diseases, weeds and water supply appear to be the major constraints causing the large yield gap. Agronomic solutions are mostly available, but low cropping diversity in the dominant rice–wheat system may be an added constraint in the long term. Also there is evidence that soil organic carbon in much of the north-western parts of the Indian IGP is now so low as to limit response to inputs and require special ameliorative interventions.

The arrival during the 2000s of adapted hybrids with reasonable grain quality should provide a clear boost for PY and FY. Currently representing only about 5% of total Indian rice area, adapted hybrids may offer a revolution if efficient seed-production systems can be developed.

4.5 RME3—Japan, the first modern rice nation

Introduction

Japan has a long and rich history of research in rice breeding, agronomy, physiology and genetics. It is representative of higher latitude RME3, with a single rice crop grown under the summer monsoon after winter fallow. Irrigated rice is grown in lowlands throughout the islands of Kyushu, Shikoku and Honshu, with a little grown in Hokkaido (Map 4.5). Cultivars of Japonica predominate the national rice crop, but Indica cultivars have become more common during the past 20 years.



Map 4.5 Rice growing regions throughout Japan, representative of rice mega-environment RME3 (irrigated rice in a humid temperate climate)

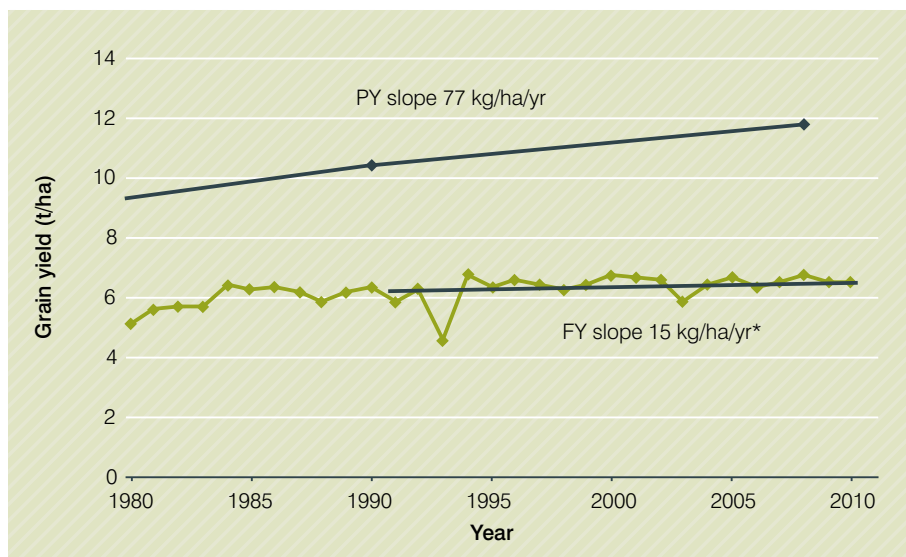
Since 1980, rice area in Japan has been observed to decline by around 1.7% annually to reach 1.6 Mha in 2010. The decline reflects less-favourable policies for rice (although rice remains highly protected), as Japan holds production close to the gradually declining level of national rice consumption.

Japan experienced its green revolution in rice in the 1950s to 1970s (Horie et al. 2005a), resulting in rapid yield increase from new varieties, fertiliser and improved crop management through mechanisation and other modern techniques. National FY increased by about 50% in the 30 years to 1980, reaching close to 6 t/ha.³⁵ In the 1950s and 1960s, before farmer contests were discontinued, winning yields averaged about 11 t/ha and peaked at more than 13 t/ha (Yoshida 1981; Horie et al. 2005a). These winning yields were more than double the national yield at the time, and highlight what can be achieved with skillful management and (presumably) unusually favourable weather conditions.

³⁵ Note that rice yields in Japan are often recorded as brown rice yields (after hull removal), which when multiplied by 1.25 gives equivalent paddy or rough rice yields (as used throughout this book).

Current farm yield and potential yield progress for rice in Japan

FY in Japan is difficult to quantify because of some poor years (especially in cool 1993), but since 1980 (excluding 1993) FY has progressed at only 0.4% of the estimated 2010 FY of 6.6 t/ha (Figure 4.4). The rate of FY progress has slowed even more since 1991, such that to 2010 (excluding 1993) it has improved by only **15 kg/ha/yr (or 0.2% of the estimated current FY)**, but is nevertheless statistically significant ($0.05 < P < 0.10$).



* $0.05 < P < 0.1$

Figure 4.4 Progress in rice farm yield (FY), plotted against year, and potential yield (PY), plotted against year of release, in Japan from 1980 to 2010. Source: FY from FAOSTAT (2013); PY various sources. FY regression 1991–2010 excludes 1993 (anomaly of very cool year). PY line begins with rice cultivar, Nipponbare (released in 1963; PY = 7.7 t/ha), which cannot be shown, but the slope refers to change between 1990 and 2008 varieties.

Rice yield in Japan is limited by one major factor: the overriding attention to production of better food-quality rice, which requires reduced nitrogen fertilisation levels and constrains breeding progress for yield (Okuno 2005; T. Horie, pers. comm. 2009). It is therefore not surprising that the high-quality Koshihikari is still the most popular cultivar grown in Japan today, despite its being released in 1956.

However, in order to use excess paddy lands no longer needed for food rice, Japan commenced a program in 1981 to produce 'super-high yielding varieties' for purposes other than direct human consumption (Mae 2011). Thus an increase in rice potential

yield (PY) in Japan occurred in 1990, with release of the Indica-derived cultivar Takanari. This cultivar has been widely assessed in central and western regions of Honshu, giving an average yield of 10.4 t/ha, which is 36% more than the landmark 1963 cultivar Nipponbare (San-oh et al. 2004; Takai et al. 2006; Katsura et al. 2007; Taylaran et al. 2009; H. Yoshida, pers. comm. 2009). Thus PY advance between 1963 and 1990 was 100 kg/ha/yr, an advance also measured with crop protection clearly specified (e.g. Takai et al. 2006; Katsura et al. 2007). Although Takanari is a conventional cultivar (inbred), at Kyoto it yielded as well as one of the best current Chinese 'super' hybrids (Katsura et al. 2007).

Needless to say, Takanari is not a food-quality rice, and more recently breeders have produced other very high yielding feed-type and forage-type cultivars, such as Bekoaoba in 2005 (Nagata et al. 2007) and Momiroman in 2008 (Yoshinaga et al. 2009). Momiroman with a PY of 11.8 t/ha (14% above Takanari; H. Yoshida, pers. comm. 2009) is included in Figure 4.4, indicating an increase of **PY of 77 kg/ha/yr since 1990. Thus the current rate of PY progress is estimated to be 0.7% p.a. of the yield of Momiroman.**

Higher yielding cultivars with moderate eating quality have also been released—for example, the Japonica cultivar Akita 63 was released in the late 1980s. This cultivar has recorded an average yield of 11 t/ha over 3 years in the somewhat favoured Akita Prefecture in the north-west of Honshu (Mae et al. 2006). Another new cultivar, Hokuriku 193, yielded an average of about 13 t/ha in 2008 and 2009 (Mae 2011). The highest PY value shown in Figure 4.4, reached during past decade, is supported in the summary by Mae (2011) of the recent high yields achieved by these new varieties.

Japan's rice yield gap

If it is assumed that the 2008 PY is 11.8 t/ha (Figure 4.4), then **the PY to FY yield gap is 80%**. This gap reflects the apparent stagnation of Japanese yields as the consequence of the overriding emphasis on producing excellent food-quality rice for the limited home market.

All new high-yielding varieties will better respond to higher nitrogen levels than older ones. Newer varieties have also shown high nitrogen use efficiency (e.g. Katsura et al. 2007), and new agronomic techniques can substantially lift nitrogen recovery from fertiliser (Horie et al. 2005a). However, varieties for food rice continue to receive only moderate levels of nitrogen, and thus the low national FY is maintained.

It is not known whether higher PY values could be obtained if the aforementioned contest-winning management were applied to the latest non-food varieties, but there is some evidence to support this (e.g. San-oh et al. 2004). Contests have been discontinued, and contest-winning management practices—especially deep plowing, heavy organic matter dressings, transplanting of small seedlings and field draining at strategic stages—are neither commercially attractive nor (unfortunately it seems) investigated by agronomists these days.

Physiology of potential yield progress for rice in Japan

Several recent high-yielding varieties have Indica rice in their background—very erect leaves, large hidden panicles and sturdy stems. Others (e.g. forage types) are later flowering, and this trait allows more time for radiation capture and growth. There are also Japonica types with other morphologies. The best varieties have HI values around 0.53 (based on paddy rice yield) (Mae 2011).

The high PY cultivar Takanari has been studied in detail by various authors. In Kyoto, a comparison with the landmark 1963 release, Nipponbare, demonstrated higher numbers of filled spikelets per square metre, and higher crop growth rate during the late reproductive period (just before heading) for Takanari (Takai et al. 2006). Compared with Nipponbare, the Takanari results were associated with higher RUE (2.11 g/MJ) and higher non-structural carbohydrate content at heading.

Katsura et al. (2007) confirmed the above comparison, also in Kyoto. These authors recorded a high RUE for Takanari in the pre-heading stage (1.96 g/MJ) and a tendency to take up more soil nitrogen—although specific leaf nitrogen (SLN) was not found to be superior. The same authors explained increased crop growth rate as due to greater daytime canopy photosynthesis, rather than any genetic difference in respiratory parameters among the tested cultivars (Katsura et al. 2009). Meanwhile, Ohsumi et al. (2007) compared Takanari with other high-yielding cultivars, and demonstrated its higher maximum photosynthetic rate (P_{max}) was associated with greater stomatal conductance, also confirmed by Hirasawa et al. (2010) who—in contrast to Ohsumi et al. (2007)—also recorded higher SLN. Finally, Taylaran et al. (2011) proposed that high stomatal conductance was at least partly due to a greater hydraulic conductance arising from larger root surface, leading to better maintenance of leaf water potential under periods of higher vapour pressure deficit.

When another higher yielding Indica cultivar, Habataki, was compared with a lower yielding Japonica cultivar, Sasanishiki, Adachi et al. (2011) reported very similar traits associated with higher PY (i.e. P_{max} , SLN, stomatal and hydraulic conductance). Saitoh and Trinh (2010) compared the high-yielding cultivar, Momiroman, to the 1963 Nipponbare. They found a 42% yield increase in Momiroman to be associated with higher nitrogen uptake and greater P_{max} . Mae (2011) showed that the superior yield of the Japonica cultivar Akita 63 was related to both greater nitrogen uptake and greater reproductive sink formation (spikelets) per unit nitrogen uptake.

When the above results are considered together, a fairly consistent pattern of physiological associations with higher PY emerges for rice in Japan. This pattern shows higher yield due to a larger reproductive sink (filled spikelets) was accompanied by greater nitrogen uptake, crop growth rate, RUE, P_{max} and stomatal conductance in the critical period leading up to flowering. All of these traits may contribute one way or another to greater spikelet number.

Conclusion for rice in Japan

Japan led the world in rice research for many years, and continues to invest heavily in rice improvement through traditional and molecular routes. However, FY progress in Japan appears almost stagnant. This is not because any biological limit has been reached, rather because FY is constrained by the need to produce excellent eating-quality rice and—as in China—policy to avoid surplus production of high-cost, uncompetitive product.

Because rice physiology research is strong in Japan, we might expect Japan to lead in genetic engineering technologies for extra yield or yield efficiency. Unfortunately, early and otherwise promising reports (e.g. C_4 leaf traits and suppressed panicle cytokinin oxidase) seem to have languished. In the meantime conventional breeding of rice for forage, feed and fuel suggests that PY is as high as in similar environments in eastern China and continues to progress slowly.

The physiological basis of these improvements in rice PY in Japan parallels what has been seen in recent wheat improvement in the United Kingdom (Section 3.8):

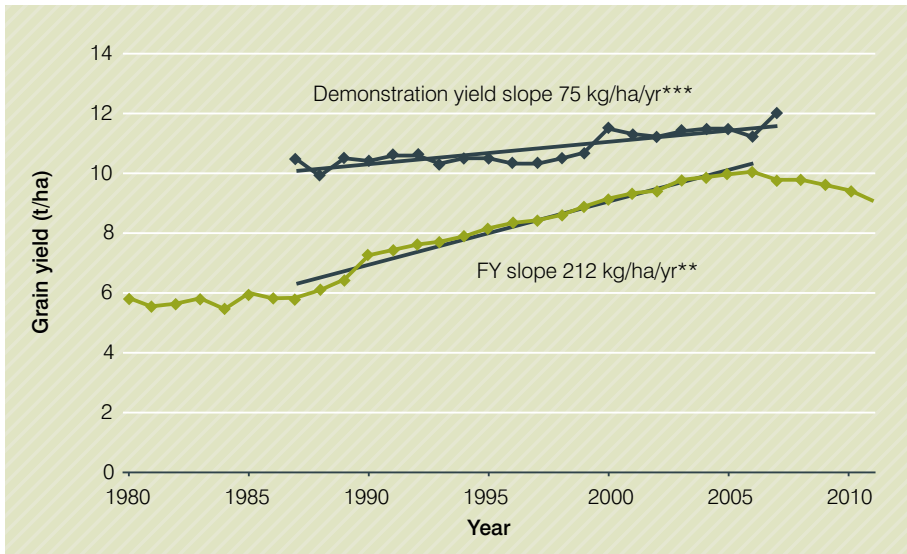
- higher crop growth rates before flowering
- greater maximum photosynthetic rate (P_{max})
- greater stomatal conductance
- more stored carbohydrates at flowering.

Unique components of improved PY appear to be greater nitrogen uptake, greater reproductive sink formation per unit nitrogen uptake and greater hydraulic conductance.

4.6 RME4—Egypt

RME4—the most favourable environment for irrigated rice—is found in places with comparatively hot, dry summers at intermediate latitudes. Egypt well represents RME4 and is the highest yielding rice nation, growing rice in its Delta Region (see Map 3.4). Despite the small rice farm size that averages only 0.6 ha (Dawe et al. 2010), Egypt's farmers have **made good progress in rice FY over the 20 years, at a rate of 2.1% p.a. of the 2006 FY of about 10 t/ha** (Figure 4.5). As progress in FY has occurred, rice area has expanded annually at a rate of 1.5% to reach almost 0.7 Mha in 2006. However, since 2006, FY has slipped somewhat due to policy change so the trendline in Figure 4.5 has been stopped at 2006.

The 2006 FY of 10 t/ha in Egypt was higher than that of California, USA (9.0 t/ha) and Australia (9.6 t/ha) at the time, both of which experience relatively similar climates. It is noteworthy that there has been no significant progress in FY in either California or Australia in the past 20 years, as breeders have focused on improving quality, and overcoming cold-induced sterility in Australia.



*** $P < 0.01$

Figure 4.5 Rice farm yield (FY) and on-farm demonstration yield changes in Egypt, plotted against year—1980 to 2010 (FY) and 1987 to 2007 (demonstrations). Source: FY from FAOSTAT (2012); demonstration yields from Badawi (1998) and Draz (2008)

As data on PY and progress (as defined here) are not available, Figure 4.5 shows the progress in average yield of on-farm demonstrations, as conducted using best technology. Progress here has occurred at a rate of 0.6% of the 2007 demonstration yield of about 12 t/ha.

The yield gap of about 20% between 2006 FY and demonstration yield was quite small. It is possible that demonstration yields underestimate PY—and hence the true yield gap—because on-farm demonstration plots are usually not as well managed as breeder trials. Even so, yields from breeders' best inbred lines in 2010 did not exceed 11 t/ha, and hybrid rice with greater PY continues to face quality and seed cost problems (A. Draz, pers. comm. 2011).

The apparently rapid closure of yield gap over the past 20 years is particularly interesting. It has been suggested (Cassing et al. 2007) that the Egyptian situation reflects:

- a physically concentrated rice industry
- strong research and extension effort
- policy reform (from the late 1980s) that removed price disincentives for most crops (including rice).

Peak FY (and area) were reached around 2006 (Figure 4.5). Both have since declined somewhat, as water scarcity now dictates policy measures to reduce rice area and prices. The 2010 FY and the yield gap are now closer to 9.5 t/ha and 25% of FY, respectively.

4.7 RME3 and RME6—Brazil

Introduction

Brazil is a tale of two mega-environments.

Rice area peaked in Brazil at over 6 Mha in the late 1970s, but the crop was low yielding and predominantly rainfed upland rice (RME6). By 1990 the area had fallen to 4 Mha, of which 25% was irrigated. Currently about 3 Mha of rice is grown, but irrigated area has increased to around 50%, largely in the temperate southern state of Rio Grande do Sul (RME3) (Map 4.6).

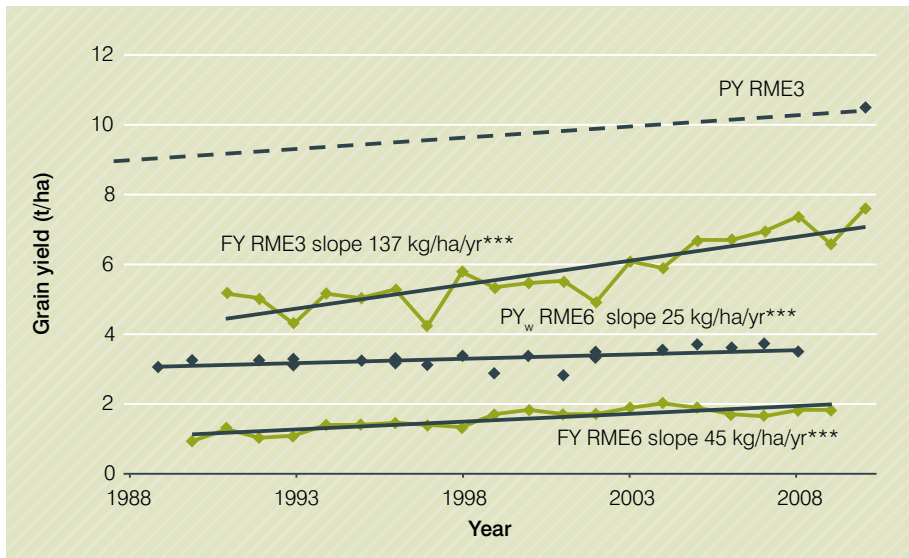


Map 4.6 Major rice regions of Brazil

Curiously, the temperate irrigated regions grow Indica rice, while the tropical upland system grows Japonica. Brazilian production is 12 Mt, while the estimated FY is just over 4 t/ha, having progressed over the past 20 years at 117 kg/ha/yr ($P < 0.01$)—a rate of progress of almost 3% p.a. of the current FY. The yield increase is partly a consequence of the rise in proportion of irrigated rice, but there have also been substantial productivity rises in each of the two major rice systems, which are thus shown separately in Figure 4.6.

RME3—irrigated rice in Rio Grande do Sul

Rio Grande do Sul grows 1.1 Mha of irrigated rice (RME3) between 29 °S and 34 °S under medium-to-large scale mechanisation, on medium-size farms (~50–100 ha rice per farmer). The rice system supplements moderately high summer rainfall with irrigation largely sourced from on-farm surface storage.



*** $P < 0.01$

FY for irrigated rice in the state of Rio Grande do Sul, Brazil (RME3), and rainfed rice in all of Brazil (RME6)

PY for irrigated rice in the state of Rio Grande do Sul (RME3) and estimated change (dashed line), and PY_w in rainfed areas of Brazil (RME6)

Figure 4.6 Farm yield (FY) for irrigated and rainfed rice in Brazil plotted against (planting) year, and potential yield (PY) or water-limited potential yield (PY_w) plotted against year of variety release from 1990 to 2011. Source: F. Breseghello (pers. comm. 2011) for FY from the Brazilian Institute of Geography and Statistics—*Instituto Brasileiro de Geografia e Estatística*; Breseghello et al. (2011) for PY_w

FY progress in Rio Grande do Sul over the past 20 years has been impressive (Figure 4.6). Using **the estimated 2010 FY of 7.0 t/ha, the rate of FY progress amounts to 2.0% p.a. over the past 20 years**—although, from Figure 4.6, it would appear that progress accelerated somewhat after about 2002.

Progress in PY has been hard to ascertain, but Moura Neto et al. (2009) presented data suggesting that during 1979–2008, **genetic improvement alone raised yield at a rate of about 0.7% p.a. (calculated relative to yield of 2008 cultivars)**.³⁶ After about 1990, the breeding effort had to focus on overcoming problems associated with the important weed, red rice, while always striving to maintain rice quality. Initially red rice was managed through later planting—a practice that required earlier-maturing rice varieties. At a later stage, natural resistance to the herbicide imidazole was incorporated to increase options for managing this weed, and finally imidazole resistance was built into later varieties with higher PY (S. Lopes, pers. comm. 2012).

Field demonstrations of the *Instituto Rio Grandense do Arroz*—Rio Grande Rice Institute (IRGA)—suggest that the latest variety releases appear to have a PY of close to 11 t/ha and **PY in 2010 is estimated at 10.5 t/ha** (Figure 4.6). The estimated breeding progress of Moura Neto et al. (2009) is added to the PY data point as the dashed line in Figure 4.6. Recently appearing hybrids may have slightly higher PY, but these hybrids still have problems associated with quality and seed cost. For example, it was recently reported that the new hybrid BRSCIRAD 302, released by the Brazilian Agricultural Research Corporation, Embrapa, produced 13 t/ha of good-quality rice (Coutinho and Chaves 2011). However, seed costs remain very high and hybrid rice currently occupies less than 2% of the rice area in Brazil. Using **a PY of 10.5 t/ha establishes a RME3 yield gap of 3.5 t/ha or 50% of 2010 FY**, a moderate gap likely to close further given the effective on-farm extension now in place.

The recent progress in FY in irrigated rice undoubtedly reflects the intensive 2003–06 extension campaign initiated by IRGA of the state of Rio Grande do Sul, aided by the Latin American Fund for Irrigated Rice (FLAR) (Pulver and Camora 2010). By 2006, almost half of the state's farmers had been reached by research-linked public extension agents and farmer leaders, all supported by widespread on-farm demonstrations. The agronomic recommendations included:

- earlier planting
- lower seed density (mechanically sown, often with zero-till)
- seed treatment for pests
- application of urea to dry soil before seeding
- weed control by herbicides, and integrated weed management for control of the difficult weed, red rice
- early initiation of permanent flooding.

³⁶ Moura Neto et al. (2009) show average trial yields between 1983 and 2011 increasing at about 1.4% p.a. relative to the 2011 average yield, but this is not presented as PY progress for lack of information on changes in trial management. However, the figure could include agronomic innovations developed over the period.

Yield benefits from these practices have been large and approximately additive, and are widely adopted today, although red rice remains a problem. For example, median seeding date has moved from mid November to late October, and could move even earlier. At the same time, better farmers are adding refinements, such as balanced nutrition (including phosphorus and potassium) and in-crop fungicide. The top 7% of farmers achieved 8.5 t/ha in 2008–09, and further FY progress can be anticipated in this system of medium-sized rice farms. Although this level of progress is unique in the developing world, it is matched by developments in irrigated rice in northern Uruguay and north-eastern Argentina, just across the border from Rio Grande do Sul.

RME6—rainfed upland rice in the Cerrado region

4

The decrease in rainfed upland rice area, which began in the late 1970s, has now ceased and appears to have stabilised at about 1.5 Mha. The Brazilian RME6 crop now contrasts starkly with Asia, where RME6 rice is grown by impoverished farmers of smallholdings in cultivated, highly erodible hill slopes for very poor yields (<1 t/ha). In Brazil, however, rainfed rice is grown predominantly on large mechanised farms, in the gently undulating new croplands of the vast tropical savanna eco-region known as the Cerrado (see Map 5.5b, Box 5.5).

Tolerant to soil acidity, rice was a useful pioneer cash crop, but now it is seen as a viable crop for diversification of the dominant soybean–maize double-crop rotation of the Cerrado. It benefits from the heavy doses of phosphorus required on the dominant soils (Oxisols), and is usually direct-seeded without cultivation. Under these conditions, **RME6 FY has been progressing notably over the past 20 years (Figure 4.6) at a rate that is 2.2% of the 2010 FY of 2.0 t/ha.**

Embrapa (and others) conduct the national upland rice-breeding program, which each year involves a standard yield trial at over 20 locations across the whole region of upland rice. Breseghello et al. (2011) performed a mixed-model analysis on the 1984–2009 results to calculate the effect of ‘year of first entry’ into the trials for each variety. Trials were not protected with fungicide (e.g. for blast control), but evidence suggests that disease resistance breakdown did not have a large confounding effect (F. Breseghello, pers. comm. 2011).

Yields of entries over the past 20 years are shown in Figure 4.6 as water-limited PY (PY_w) values. **The PY_w progress resulting from this breeding program is calculated to be 0.7% of the current PY_w of 3.6 t/ha,** with no evidence of a yield plateau. The result confirms that of Souza et al. (2007) who studied upland rice varieties (1951–2001) in a vintage experiment.

Breseghello et al. (2011) found little change in days to flowering in the varieties produced over the past 20 years—apart from elimination of late lines since the mid 1990s—but noted that plant height has been steadily reduced to now approach 95 cm. Since dry spells during the growing season are a major constraint on PY_w , breeders believe that breeding progress in yield is related to better root systems, and thus this

trait is actively selected. As with most rice improvement, grain quality is another critical selection goal.

Figure 4.6 also indicates that FY progress in RME6 has exceeded PY progress.

The yield gap is still large at 1.6 t/ha—or 80% of the 2010 FY—but has closed significantly from almost 250% in 1990. As rice moves to become an important crop in the Cerrado, it is likely that large, well-resourced farmers of this region will continue to overcome farm-level yield constraints.

Conclusion for rice in Brazil

The rapid increase in irrigated rice yields in Rio Grande do Sul is a unique example of an effective, targeted extension strategy for improving irrigated rice agronomy—a strategy involving agents from both public (IRGA, FLAR) and private (farmer group) sectors—combined with strong breeding efforts. FLAR and IRGA provided the catalyst and improved varieties, but it was the farmers—with their moderate property sizes, good resources and strong organisations that include levies for research and development—who quickly adopted and applied new practices and technologies.

The experience in Brazil has also shown that upland rainfed rice yields can be raised—in this case, through strong breeding programs. However, FY progress is still confounded somewhat by the large decrease in area of rainfed rice. Even so, for the RME6 rice agroecology, FY in Brazil is about twice the yield achieved in Asia (Section 4.8 on rainfed rice). Along with the RME3 progress, this means that Brazil could soon become an important net rice exporter.

4.8 RME5 and RME6—rainfed rice in India, North-East Thailand and elsewhere in Asia

According to IRRI (2012), the largest areas of rainfed rice (lowland RME5 and upland RME6) are found in India (~19 Mha) and North-East Thailand (7.5 Mha), with the next most significant areas in Indonesia and Vietnam (3 Mha each). Rainfed lowland rice (RME5) predominates in the rainfed areas of Thailand, Indonesia and Vietnam. RME5 rice also predominates in India (14 Mha), but a significant area (5 Mha) of rainfed upland rice (RME6) is also grown there.

Both RMEs face similar problems, largely due to uncertain rainfall. An important difference is that rainfed lowland fields (RME5) are subject to intermittent flooding, which few crops other than rice can tolerate. In contrast, many crops can compete with rice in the well-drained rainfed uplands (RME6).

RME5 and RME6—rainfed rice in India

Officially reported rice yields in India are not separated by irrigation status. Siddiq (2000) estimated that, for the late 1990s, Indian rainfed lowland rice FY was 2.2 t/ha and rainfed upland rice FY was 1.0 t/ha. Using statistics from Indian states with little irrigated rice (IRRI 2012), the 2010 FY for Indian rainfed rice can be estimated as 2.1 t/ha across both RME5 and RME6. This agrees with the work of Janaiah and Xie (2010), who reported a current rainfed FY of 2.2 t/ha in 2005–07. Their data suggest that Indian rainfed yield increased at a rate of 0.9% p.a. between 1990 and 2007.

Rainfed rice is concentrated in eastern India (see Map 4.4), although only one Indian state, Jharkhand, grows only rainfed rice (essentially two-thirds RME5, and one-third RME6). Jharkhand average FY is 2.4 t/ha, but records are limited because the state was only formed in 2000. Madhya Pradesh is the next most dominant state for rainfed rice, but to provide a longer record for the purposes of this book, reference to this area includes the state of Chhattisgarh, which split from Madhya Pradesh in 2000. The post-2000 Madhya Pradesh now grows 5.4 Mha rice, with a reasonably steady proportion of 25% irrigation. FY for the original Madhya Pradesh (including Chhattisgarh) has been quite variable over time, but the past 30 years of data (1978–2007) reveal very highly **significant linear progress of 22 kg/ha/yr ($P < 0.01$). This equates to a rate of progress of 1.2% p.a. of the 2007 FY of 1.8 t/ha.**

Estimates of PY_w are available for Madhya Pradesh from two studies. First, an experimental PY_w of 3.7 t/ha compares with a simulated value of 5.3 t/ha using the 'InfoCrop' rice model, 10–20 years of weather data and a transplanting date determined by onset of the monsoon (Aggarwal et al. 2008). A second PY_w estimate of 4.0 t/ha and a yield gap of 150% of FY were reported by Siddiq (2000). For the purposes of this book, **it is assumed that the PY_w is now 4.5 t/ha, and hence, with a current FY of 1.8 t/ha, the yield gap remains at about 150% of current FY.**

It has not been possible to locate data on recent PY_w progress, despite some recognisable progress attributed to improved varieties for rainfed rice that have been available since the 1990s (Siddiq 2000). More recent breeding progress, associated with direct selection for yield under multiple managed-drought sites, continues to increase PY_w (Verulkar et al. 2010; D. Zhao et al. 2010). This may soon be aided by the surprising discovery of a few strong molecular markers for drought tolerance (Bernier et al. 2007), some of which appear to be related to rooting depth (Venuprasad et al. 2011). One marker has been identified for tolerance to submergence (Septiningsih et al. 2009), a common hazard for young plants in rainfed lowland rice. These recent advances in understanding of drought and submergence tolerance in rice amount to a significant breakthrough that is beginning to have an impact on rainfed FY, as reviewed by Serraj et al. (2011).

In addition to slow adoption of improved varieties in rainfed areas, further constraints to rainfed rice FY in South Asia were estimated by IRRI (2008) and are given as a percentage of FY—23% from poor nutrition, 15% from disease and 12% from weeds. Aggarwal et al. (2008), and earlier Siddiq (2000), also emphasised poor crop nutrition (primarily low nitrogen, but also phosphorus, sulfur, zinc and boron) and soil acidity as key constraints to rainfed rice yield in India, along with late transplanting in years when the monsoon was late.

IRRI (2008) further suggested that with substantial expenditure in research, development and extension, the yield gap with rainfed rice could be closed at a rate equivalent to 1% p.a. of FY over the next 15 years.

RME5—rainfed rice in Thailand

North-East Thailand, with 5.3 Mha of rainfed lowland rice, represents a very large area of contiguous RME5 (Map 4.2). This very difficult rice environment is typified by:

- hot climate
- erratic annual average rainfall (1,000–1,500 mm), especially at the onset and end of the monsoon
- sandy, infertile and sometimes saline soils
- highly variable field topography (a major factor governing performance).

According to IRRI (2012), the latest FY data from North-East Thailand (main crop only, excluding the small areas of irrigated rice in the dry season) show that over the past 20 years (to 2006), **FY has increased at the highly significant rate of 34 kg/ha/yr ($P < 0.01$), or 1.6% of the 2006 FY of 2.1 t/ha.**

The yield gap has historically been considered very large. Kupkanchanakul (2000) estimated that PY_w in the late 1990s was about 5 t/ha for rainfed lowland rice, indicating a yield gap greater than 150%. Sound new PY_w numbers are currently unavailable, but as PY_w is unlikely to have changed much, **a yield gap of 140%** can be derived from the Kupkanchanakul (2000) PY_w figure against the 2006 FY of 2.1 t/ha.

Plantings continue to be dominated by several old, high-quality and strongly favoured commercial cultivars, such as the 1959 release, KDML 105. Although newer lodging-resistant, nitrogen-responsive and disease-resistant varieties can surpass these older cultivars in terms of PY_w —and notwithstanding substantial breeding effort over the past 15 years—newer varieties still generally lack the eating quality of the older ones (B. Jongdee, pers. comm. 2011). In addition, for the small Thai farm (~2.5 ha median size), agronomic constraints (especially crop establishment and weed control) are amplified by the gradual shift to direct seeding as labour supply in the region becomes scarcer.

Other significant studies of rainfed rice in Asia

Boling et al. (2010) looked at yield gaps on the sloping landscape of Java, Indonesia, where a two crop per year, rainfed lowland rice system (RME5) operates. Compared with Thailand, this is a quite favourable rainfed environment, with average annual rainfall greater than 1500 mm. Over 2 years, across four villages and on four toposequence positions, Boling et al. (2010) measured average FY to be 3.4 t/ha. Using the ORYZA2000 crop simulation model, these authors determined a simulated PY_w of 5.2 t/ha, suggesting a yield gap of only 50%—although the gap was somewhat greater in the upper toposequences than the lower ones.

Saito et al. (2007) reported in detail on the rainfed upland hills of Lao PDR (RME6) where rice is grown by subsistence farmers in a slash-and-burn farming system. Farmer practice produced an average FY of 1.8 t/ha, while improved 'aerobic' varieties with nitrogen plus phosphorus fertiliser raised this to 3–4 t/ha, pointing to a yield gap of greater than or equal to 100%. Affholder et al. (2013) surveyed upland rainfed rice fields in the hills of northern Vietnam (annual rainfall >2000 mm) where a similar slash-and-burn, subsistence farming system operates. Here FY averaged only 0.7 t/ha (range 0–2 t/ha), and modelled PY, using traditional upland varieties, was only 2.2 t/ha. Improved varieties should have lifted modelled PY by at least 50%, judging by the results of Saito et al. (2007); thus the true yield gap was probably more than 300%, with major scope for yield gap closing. Switching out of upland rice to commercial maize greatly improved the economic prospects in the Vietnam study area.

Conclusion for RME5 and RME6 in Asia

Rainfed rice areas of Asia, dominated by the rainfed lowland ecology (RME5), were considered to have been bypassed by the green revolution. It is clear, however, that there has been FY progress in this system in India and Thailand over the past 20–30 years at relative rates no less than that in the irrigated rice systems. This progress is probably mostly agronomic (achieved especially through increased fertiliser use), since modern varieties have been slow to move into these areas, often lacking desirable grain quality. More recently, promising PY_w progress has become apparent as a result of breeding to specifically target these difficult drought-prone environments.

Yield gaps are large in the Indian and Thai systems (>100%), but these rainfed lowland areas offer good scope for yield gap closing. It is likely that rainfed upland areas of rice will decrease further as these often remote areas become more accessible and begin to import cheaper rice, both factors favouring the introduction of more appropriate and productive crops in the uplands, such as maize, vegetables and/or tree crops.

4.9 Summary of yield progress in rice

This section summarises the case studies discussed in this chapter.

Current farm yields, potential yields and yield gaps in world rice

Table 4.5 summarises the situation for rice, showing **current FY, PY and yield gap for the major rice growing regions** discussed in this chapter. Average FY shown in Table 4.5 is somewhat greater than the global average of 4.3 t/ha (Table 4.1). Similarly, the average rate of FY progress in Table 4.5 (1.19%) is greater than the global average of 1.0% (Table 4.1). This suggests that the case studies reported in this book represent, on average, more favourable conditions than the overall world situation, but the figures in Table 4.5 reveal no relationship between relative rate of FY increase and FY level.

The average yield gap shown in Table 4.5 is 76%, which is greater than the wheat average of 48% (Table 3.6). The gap is clearly narrower in irrigated (59%) compared with rainfed rice systems (123%). Generally, there was more variability in rates of progress and yield gaps across the rice case studies than for wheat, but there was also more evidence of yield gap closing.

Lobell et al. (2009) summarised rice yield gap estimates in which PY came from simulation models, experimental trials or maximum farmer yields. The figures, based on earlier studies than reported in this book, are remarkably similar to the figures shown in Table 4.5. Across developing country regions (but dominated by Indian states), Lobell et al. (2009) calculated yield gap (as defined in this book) to be 55% for irrigated rice ($n = 34$; range 18–233%) and 153% for rainfed rice ($n = 7$; range 87–233%). In addition, these authors commented that in their dataset, modelling produced very similar PY values to trials for a given region, and that extreme values may reflect measurement errors.

Rates of change of yield and yield gaps in world rice

Rates of PY (and PY_w) change were difficult to estimate, largely due to lack of data. Nevertheless, the estimates here show a narrow range (0.6–1.3% p.a.) **for an average PY change slightly greater than that for wheat (0.78% vs. 0.61%)**. Thus there is no evidence of breeders having reached a plateau in rice PY, but better measures of recent progress are definitely lacking.

Table 4.5 Summary of global rice farm yields (FY), potential yields (PY) and yield gaps in 2009 or 2010, and current respective annual rates of change over the past 20–30 years

RME	Region	Estimated yield (t/ha) and yield gap (%)			Rate of change (% p.a.) ^a		
		FY	PY	Yield gap	FY	PY	Yield gap ^c
1	Central Luzon, the Philippines (wet season)	3.9	7.0	79	0.6	0.7	0.1
1	Central Luzon, the Philippines (dry season)	4.6	9.5	107	0.6	0.7	0.1
1	Philippines	3.7	5.6	51	1.6	0.7	-0.9
1	Indonesia	5.0	6.5	30	0.7	1.3	0.6
1	Southern Vietnam	5.2	na	na	1.9	1.0	-0.9
2	Jiangsu, China	8.0	11.0	38	0.7	1.2	0.5
2	Punjab, India	6.0	10.5	75	1.1	0.3	-0.8
3	Japan	6.6	11.8	80	0.2	0.7	0.3
3	Rio Grande do Sul, Brazil	7.0	10.5	50	2.0	0.7	-1.3
4	Egypt	9.5	12.0 ^d	25	1.1	0.6 ^d	-0.5
5	Madhya Pradesh, India ^b	1.8	4.5	150	1.2	na	na
5	North-East Thailand ^b	2.1	5.0	140	1.6	na	na
6	Central Brazil ^b	2.0	3.6	80	2.2	0.7	-1.5
Average (n = 11, 12 or 13)		5.0	na	76	1.19	0.78	-0.39

a All PY and FY slopes are significant at $P < 0.10$ or better. All rates of FY progress and gap closing contains the direct effect of CO₂ rise (~0.2% p.a., see Section 2.4); relative to 2009 or 2010 values.

b PY_w was estimated for these rainfed cropping regions, which commonly experience water shortage.

c Calculated as the difference between the rates of increase in PY and in FY (see Section 2.3)

d Based on on-farm demonstration yields; includes contributions of management and breeding progress.

na = not applicable

Source: Estimates from preceding sections of this chapter, excluding incomplete or uncertain estimates

The rates of PY progress shown in Table 4.5 do not include the **impact of hybrid rice** in any case study. By some 20 years ago, Indica hybrids had occupied all of southern China (RME1 and the warmer parts of RME2), amounting to 50% of China's rice area. Thus, this one-off benefit was already fully reflected in national PY and FY values by



about 1990. Hybrids have been shown to boost PY by 10–15% (or more) in RME1 and RME2 in South and South-East Asia, and in RME3 in the southern USA. However, adoption of hybrids has so far been low. Only 4.2 Mha (or 4% of rice area) was planted to hybrids in Asia outside China by 2010 (F. Xie, pers. comm. 2012).

The adoption of hybrids outside China is slowed by cost of seed production and lack of good grain quality in the hybrid varieties (Spielman et al. 2012). In the medium term, these barriers are being overcome by research and development, and any new studies of yield progress in these regions should start to see the influence of popular hybrids on rice yield. Experience would suggest that the relative yield advantage of hybrids could be even greater in rainfed situations, but cost of seed poses a greater barrier in such intrinsically lower yielding systems. Upland rice in Brazil—for which both public and private sectors have begun to develop hybrids, and where farmers are more attuned to new technology—will be a good rainfed testing ground for this development.

Rates of yield gap change were variable (range –1.5% to +0.6% p.a.), such that the average in Table 4.5 (–0.39% p.a.) has little meaning. Brazil had the strongest gap closing (–1.5% and –1.3%), where good policy and targeted extension has been applied, while Indonesia, China and Japan (and recently Egypt) showed gap widening.

While quality demands may slow PY breeding progress in many situations, as is seen in the case of Japan, it appears that **FY progress is also limited separately by quality demands; also policy factors loom large for FY** in several places; for example, Japan, China and lately Egypt. In such cases it would seem unwise to declare (as have some) that national rice yields are reaching biological limits, unless there are fundamental trade-offs between yield and quality. This seems to be the case in Japan, where high nitrogen fertilisation reduces eating quality.

At the same time, yield gaps remain large in many other situations, especially rainfed ones—usually associated with multiple agronomic constraints. Rice in particular faces a special hurdle of increasing costs (associated with water and labour) of the traditional Asian technique of hand transplanting into puddled fields. As Asia inevitably transitions by stages into mechanical transplanting practices and direct seeding (and possibly zero-till), yield progress will slow until these more efficient systems are optimised. There is no reason, however, why PY or PY_w should suffer in the longer term as a result of this transition.

Estimated rice yield and yield change by RME

As with wheat in Section 3.10, an attempt is made to estimate yields and rates of increase for the **major RMEs** (Table 4.6). The order of the columns in Table 4.6 differs from the presentation in Table 4.5 to highlight that PY and yield gap together contribute to FY. Only the world average FY and rate of change in FY in Table 4.1 are definite, having been obtained from FAOSTAT. Area weights come from Table 4.2; the other numbers are estimated from Table 4.5 and expert opinion.

Table 4.6 Estimates of 2008–10 farm yield (FY), yield gap and potential yield (PY), and rates of change for the past 20 years across rice mega-environments (RMEs)

RME	Weighting factor (fraction of total)		Estimated values for 2008–10			Estimated rate of change relative 2008–10 values (% p.a.)		
	Area	Production	FY (t/ha)	Yield gap (%)	PY (t/ha)	FY	Yield gap	PY
1	0.25	0.280	4.8	67	8.0	1.1	-0.4	0.7
2	0.16	0.250	6.8	62	11.0	1.0	-0.3	0.7
3	0.15	0.245	7.0	64	11.5	0.8	-0.1	0.7
4	0.01	0.020	10.0	20	12.0	0.5	-0.1	0.4
5 + 7	0.34	0.175	2.2	105	4.5	1.2	-0.6	0.6
6	0.09	0.030	1.4	114	3.0	1.2	-0.6	0.6
World average	1.00	1.000	4.3 ^a	72 ^b	7.4 ^a	1.0 ^b	-0.3 ^b	0.7 ^b

a Weighted by area of RME

b Weighted by production of RME

Source: Area fractions from Table 4.1; other parameters calculated and estimated by authors (see text). Estimates apply to 2008–10 when world rice area was 160 Mha and production was 692 Mt.

For completeness in Table 4.6, RME7—characterised by deepwater hydromorphology, and representing only 3% of global rice area—is placed within RME5, because no separate data are available for RME7. More than 90% of the world’s rice appears to be produced in RME1–3 and RME5. Even so, given the incomplete coverage of the examples in Table 4.5, it is hard to strike separate estimates for each major RME. More so than with wheat in Table 3.7, the rice numbers in Table 4.6 are tentative and need to be supplemented as more data become available.

Overall, the summary data suggest **that PY increase at 0.67% p.a. has contributed twice as much as yield gap closing (0.34% p.a.)** to the 1% p.a. rate of increase of world rice FY over the past 20 years. Another fairly solid conclusion is that closing of the current yield gap—i.e. increasing FY to meet attainable yield, leaving a minimum gap of only 30%—would recover less lost production in rainfed areas (35%) than in irrigated ones (65%) because the larger yield gap of rainfed areas is more than countered by their lower area and PY. On the other hand, rainfed systems (RME5 and RME6) appear to have shown faster FY progress than other RMEs, as a result of greater yield gap closing.

Physiological patterns of potential yield change in world rice

Clearly Japan has dominated research on rice physiology. Research there shows a pattern emerging in which PY progress is associated with higher number of grains (GN, in the case of rice filled spikelets/m²), and sometimes also greater grain weight (GW). This outcome is associated in the lead-up to panicle emergence with:

- greater crop growth rate
- greater nitrogen uptake
- higher RUE
- greater maximum photosynthetic rate (P_{max}) and stomatal conductance
- higher leaf nitrogen per unit leaf area.

These observations parallel those seen with PY progress in wheat in several situations (see Section 3.10). However, a unique aspect for rice is the report of lower stomatal sensitivity in the modern varieties to higher vapour pressure deficit due to greater plant hydraulic conductance, possibly associated with more effective roots. The greater nitrogen uptake is also likely to be linked to root activity.

Apart from consistent associations between yield progress and GN, the picture is not so clear from Chinese physiological studies on 'super' rices, and even less clear from the intensive recent physiological studies of rice PY at IRRI.

Everywhere the canopies of modern rice varieties are extremely erect. In contrast to modern wheat varieties, the uppermost rice leaves are long and large, and the weakly photosynthetic panicle is hidden below.

There have been a few occasions when **physiology has clearly contributed to rice yield improvement**. The first was the advent of semi-dwarf erect-leaved tropical rices from IRRI in the mid 1960s. This was followed by another IRRI effort at ideotype breeding under the NPT initiative in the 1980s and 1990s. The impact of the latter, however, was seen not at IRRI, but in China's 'super' rice project. The third occasion of contribution from physiology is currently unfolding at IRRI and in India with targeted selection for performance in rainfed environments, including tolerance to dry spells, temporary submergence and salinity. Molecular markers for major variation in these traits are now playing an important role in breeding. Finally, specific targeting of cold tolerance at meiosis has recently delivered an improved variety for RME4 in south-eastern Australia (Reinke et al. 2010).

Although there is no evidence that photosynthetic activity has reached a limit in rice, an IRRI-managed project to boost photosynthetic activity by introducing C₄ photosynthesis could one day constitute another successful physiologically inspired breeding achievement (see Section 9.4 'Increasing RUE' and Section 9.9 on genetic engineering).

Maize

5



Key points

- World maize production in 2008–10 was 833 Mt, well ahead of that for wheat and rice; global average yield (FY) is 5.2 t/ha. Growth in production is strong (2.2% p.a.), arising through harvested area increases of 0.9% per annum (p.a.), and global average yield progress of 1.5% p.a.
- For each of the major maize mega-environments (MMEs), detailed case studies presented in this chapter have explored farm yield (FY), potential yield (PY) and yield gap, and their respective rates of change over the past 20–30 years. Of these, six to eight case studies contributed to the values quoted in the key points below.
- In all cases, except in eastern Africa and Italy, the current rate of FY increase is significant ($P < 0.05$ or better), with rates of progress ranging between 0.5% p.a. and 2.8% p.a. (relative to FY around 2010).
- Based on these cases, in all situations, the current rate of PY increase is significant ($P < 0.05$ or better), ranging between 0.8% p.a. and 1.5% p.a. (relative to PY around 2010); the average rate was 1.1% p.a.
- The maize yield gap (as a percentage of FY) ranged greatly, from 36% in Iowa (USA), to 96% in China, to 400% in eastern Africa. Yield gaps appear to be closing at a moderately rapid rate (average change of -0.6% p.a.), but China and eastern Africa show no gap closing.
- F_1 hybrid varieties of maize dominate in most countries; as the major supplier, the private sector has invested heavily in PY progress. Hybrid varieties offer stress resistance as well as greater PY. Genetically engineered (GE) hybrids dominate in the USA, Brazil and Argentina.
- Advances in maize agronomy (higher plant density, earlier planting and/or zero-till) have interacted positively with genetic improvement to raise PY and close yield gaps in the Americas. In contrast, yield progress in Sub-Saharan Africa has been constrained by low soil fertility, weeds, limited labour and lack of access to improved hybrids and varieties.
- Physiological studies in temperate regions show that PY increase has been associated with greater plant density tolerance, leading to higher dry matter (DM) at steadily increasing plant densities but with a high and stable harvest index (HI); associated with this is improved tolerance of the photosynthetic system and of grain number (GN) to other stresses. Maize in the tropics appears to be following the same path, but lags in HI.

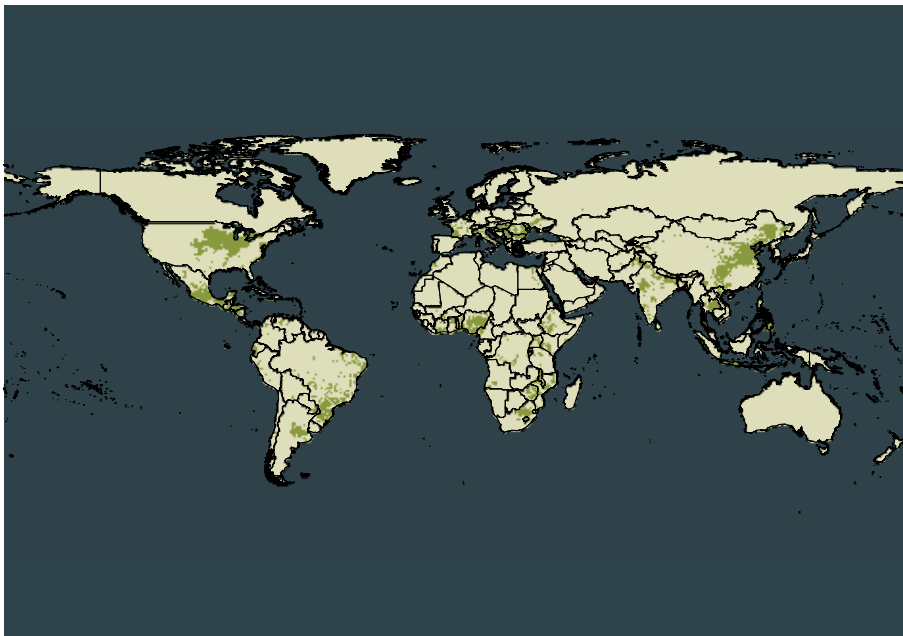
Maize



5.1 World maize and its mega-environments

5

Maize (*Zea mays*) is the cereal with the largest global production. Production surpassed rice in 1996 and wheat in 1997, and is now close to 850 Mt (Table 5.1); moreover, production is increasing at twice the annual rate of rice and three times that of wheat. Market factors driving this increase are the burgeoning demands for maize for feed and biofuel. Ethanol production currently uses ~120 Mt (or 40%) of the maize produced in the United States of America (USA), and this figure is equivalent to ~15% of global production (NCGA 2011).



Map 5.1 Global distribution of maize area circa 2000. Source: Harvest Choice project, International Food Policy Research Institute; data from You et al. (2009a)

The global distribution of maize area around 2000 is shown in Map 5.1. At the continental level, the largest producers of maize are North America (41% of the global maize crop), Asia (28%), Europe (10%), South America (10%) and Sub-Saharan Africa (6%). Table 5.1 reveals the four largest maize producing countries to be the USA (38% of the global crop), China (20%), Brazil (7%) and Mexico (3%).

Although maize production in Sub-Saharan Africa is relatively low, maize plays a critical role in food security there. The proportion of maize grain used directly as food in 1995–97 averaged ~70% in Sub-Saharan Africa; other high food consumption was seen in Mesoamerica (56%) and the Andean zone (47%), with ~20% consumed as food in Asia (CIMMYT 2001). By comparison, the proportion of maize grain used directly as food in North America was only 3%. In the developing world these proportions are continuing to decline as production rises and as consumers substitute other foods for maize in their diets.

Table 5.1 Annual maize production, harvested area, and yield in 2008–10 for major producing countries, and annual rates of change from 1991 to 2010

Country or region	Average 2008–10			Rate of change ^d (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^c (t/ha)	Area	Yield
World ^a	833.4	161.8	5.15	0.9	1.5
USA	318.6	32.3	9.86	0.8	1.5
China	169.2	31.2	5.43	1.7	0.8
Brazil	55.0	13.6	4.05	ns 0.2	2.6
Mexico	22.6	6.9	3.27	-0.5	1.9
India	19.4	8.3	2.33	1.8	1.9
Argentina	19.3	2.9	6.61	ns 0.7	2.6
Europe ^b	87.4	14.4	6.05	0.5	1.2
Sub-Saharan Africa	53.4	29.5	1.81	1.0	1.4

a Listed countries are major producing regions, not all world production

b Including the Russian Federation and Ukraine

c What FAOSTAT calls 'yield' this book calls 'farm yield' (FY); see Chapter 2.

d Relative to the 2008–10 average; all slopes highly significant at $P < 0.05$ except Mexico area ($0.05 < P < 0.10$) and ns = not significant at $P > 0.10$

Source: FAOSTAT (2013)

In the 20-year period between 1991 and 2010, global maize production increased by 2.2% p.a. The relative increase in planted maize area has been significant at a global rate of 0.9% p.a., again in contrast to wheat and rice. This increase has been greatest in parts of Asia (Vietnam 3.6%, India 1.8% and China 1.7%) and in the Russian Federation (3.6%), least in Europe (0.5%) and negative in Mexico (-0.5%), the home of maize. In this same period, global average yield increased at a rate of 1.5% p.a. (Table 5.1), and

FY increase rates were high (>1.4% p.a.) in every nation in Table 5.1, except China (0.8% p.a.) and some parts of Europe and Sub-Saharan Africa.

World trade in maize 2008–10 averaged 104 Mt, or 12% of production, with the USA dominating (51 Mt exported annually), followed by Argentina (14 Mt), Brazil (8 Mt) and France (6 Mt); Japan is by far the largest importer (16 Mt).

A maize mega-environment (MME) is defined as an area growing >1 Mha of maize, within which interactions of variety with environment are relatively minor (in other words, varieties perform similarly across the whole mega-environment). Maize mega-environments can be defined by:

- day length (maize is a short-day plant, and tropical maize can be highly sensitive to photoperiod; Edmeades et al. 2000)
- temperature (e.g. highland vs. lowlands)
- incidence of disease.

Maize varieties adapted to lowland tropical environments are generally not well adapted to summer growing seasons at latitudes more than 30° from the equator. Temperate varieties have adapted to these higher latitudes and are only mildly sensitive to day length.

The International Maize and Wheat Improvement Center—otherwise known as *Centro Internacional de Mejoramiento de Maíz y Trigo* (CIMMYT)—has defined six major MMEs for the tropical environments (latitudes <30°) of Sub-Saharan Africa (Hodson 2004). The descriptions apply also to other geographies (Hartkamp et al. 2000). In the tropics, the major mega-environment divisions are between highland (germplasm adapted to elevations >2,000 metres above sea level (masl), vs. all other germplasm; Table 5.2). These divisions are based on temperature response, since highland germplasm has been shown to have a lower optimal temperature for development and growth (Ellis et al. 1992; Eagles and Lothrop 1994). There are smaller adaptation differences between lowland (<1,200 masl) and subtropical (1,200–2,000 masl) germplasm groups, and these MMEs are defined more by differences in disease resistance. A further subdivision (wet vs. dry) can be made within mid-altitude and lowland zones, on the basis of growing season rainfall or use of irrigation, giving six MMEs in the tropical or subtropical regions (Table 5.2).³⁷

Table 5.2 reveals descriptions of temperate maize areas at latitudes greater than 30° from the equator (wet MME7 and dry MME8), which have been added by this book to the six major tropical MMEs defined by CIMMYT, to give a total of eight mega-environments. The area of maize in each MME has not been determined recently, but an estimate based on data cited by Hartkamp et al. (2000), and expert experience,

³⁷ Windhausen et al. (2012) recently analysed >500 maize hybrid trials in eastern and southern Africa between 2001 and 2009 and where these six MMEs are all found. Surprisingly, Windhausen et al. (2012) showed that the above MME groupings did not explain as much of the genetics-by-environment interaction for grain yield as did simple grouping into low (<3 t/ha) and high (>3 t/ha) yield sites.

suggests that MME7 (wet temperate) accounts for the largest area. This is followed by MME8 (dry temperate) and MME5 (wet lowland tropical). Across moisture regimes, temperate MME7 and MME8 account for 52% of global planted area; lowland tropical MME5 and MME6 account for 29%; mid-altitude subtropical mega-environments MME2–4 account for 16%; and the highland tropical MME1 accounts for only 3% (Table 5.2).

Distribution by production obviously differs from that by area, since potential yield (PY; see Chapter 2) varies with mega-environment. However, MME7 clearly dominates global production (see also 'Estimation of maize yield and yield exchange by maize mega-environment' in Section 5.7)). The PYs of maize hybrids in MME1–3, MME5 and MME7 shown in Table 5.2 are based on relationships between temperature and radiation for non-water-limited environments, as described by Muchow et al. (1990). Their simulations showed that warmer temperatures reduced crop growth duration more rapidly than it increased crop growth rate, thereby reducing yields. By comparison, the PYs for MME4, MME6 and MME8 shown in Table 5.2 are estimates of water-limited potential yield (PY_w). Lack of water is not uncommon in these MMEs and maize is particularly sensitive to water stress. Heisey and Edmeades (1999) estimated that 21% (tropics) and 14% (subtropics) of area dedicated to maize is 'often water stressed'. The PY estimates in Table 5.2 provide a general guideline to the climatic constraints to yield in the major maize-growing environments. The following sections in this chapter will attempt to refine estimates in key situations.

Maize breeding focuses within mega-environments, and varieties or hybrids rarely cross from the tropics or subtropics to temperate regions without modification because of different day length sensitivities. What makes maize unique these days, however, is that F_1 hybrid varieties (see Box 5.1), simply known as hybrids, have come to dominate improved open-pollinated varieties (OPVs) in almost all situations.

Box 5.1 Maize hybrids—a win-win product

Maize is a naturally cross-pollinating plant; improvement initially began with farmer selection among such openly pollinated plants. By 1910, studies of inbreeding (controlled self-pollination) and hybrid vigour (increased vigour and yield when two inbred lines are crossed, also known as heterosis) were underway in the race of temperate maize in the Corn Belt of the USA, soon leading to development of the first commercial hybrids. Initially inbreds were developed randomly from parent populations, but heterotic patterns soon emerged, revealing the best combining inbreds (Lee and Tollenaar 2007). From about 1960, two main heterotic groups (collections of related germplasm) have been termed stiff stalk (SS) and non-stiff stalk (NSS). The genetic distance between SS and NSS groups has widened consistently with time (Cooper et al. 2004) as representatives of one heterotic group have been used as testers for hybrid vigour by crossing with inbred lines from the other group. Thus genetic diversity in US inbreds and hybrids remains relatively high (Mikel 2008).

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The rapid increase in temperate hybrid yield has been due more to increased yield of inbred lines than to increases in hybrid vigour per se (Duvick et al. 2004). Breeding methods used in tropical maize have evolved rapidly from family-based recurrent selection schemes based on open-pollinated populations, to conventional pedigree breeding schemes with control over pollination. Heterotic groupings in tropical germplasm are not strongly defined, but are mainly based around the Tuxpeño landrace from Mesoamerica, and a loosely defined non-Tuxpeño group that includes Suwan germplasm developed in Thailand.

Inbred lines traditionally take 3–5 years to develop and characterise. New technologies have shortened that phase considerably. For example most temperate commercial inbreds are now generated from doubled-haploid lines (the maternal plant when crossed with an ‘inducer’ produces ~10% haploid seeds, whose chromosome number is then artificially doubled at the seedling stage), creating a suite of untested but fully homozygous inbred lines for subsequent evaluation (Wegenast et al. 2008). Doubled-haploid technology has recently been adapted so that it can be used for tropical hybrid development.

A key step in the development and identification of today’s high-yielding, stress-tolerant hybrids has been the use of extensive multilocation trials of test crosses and hybrids at high plant densities. This is especially true of the private sector where a hybrid may be tested in thousands of yield plots over many environments before it is commercialised.

In highly developed seed markets, commercial hybrids are all single-crosses (two inbred lines are crossed to give F_1 seed), while in less sophisticated markets, hybrids are often three-way crosses formed by crossing an inbred line with a single-cross female parent or a (synthetic) mixture of lines. Seed of three-way crosses are cheaper to produce but also lower yielding.

Farmers are generally happy to buy fresh F_1 hybrid seed each year, since sowing F_2 seed (open-pollinated seed from the F_1 plants) from their own fields results in a decline in yield of 15–40%. The hybrid seed industry is a win-win value proposition, in which farmers benefit from improved yields through hybrid vigour, and the commercial sector has a product to sell every season. The outcome has been a large private sector investment in maize breeding that is unparalleled in other staple crops. The adoption of hybrids is now occurring rapidly in less-developed agricultural economies, where hybrid seed sales are spurring the development of the private seed industry.

Improved open-pollinated varieties (OPVs) continue to have their place in lower yielding environments and in economies where the private seed sector is less developed (e.g. lower yielding areas of Sub-Saharan Africa). Farmers can save seed each year from their own fields of OPVs with little loss in yield, but in general OPVs are $\geq 15\%$ lower yielding than the best hybrids made from the same populations. Improved OPVs have proven a useful step in the evolution of a mature private seed sector, but are now rapidly losing ground to hybrids in most developing economies.

Table 5.2 Maize mega-environments (MMEs), relative areas, potential yields and major producing regions

MME	Description ^a	Altitude (masl)	Proportion total area (%)	Potential yield (t/ha)	Major regions
1	Highland tropical >350 mm, 18–24 °C	>2,000	3	11	Ethiopia, Mexico, Andean zone
2	Wet upper mid-altitude subtropical >600 mm, 24–28 °C	1,600–2,000	3	13	Ethiopia, Kenya, South Africa, central America
3	Wet lower mid-altitude subtropical >600 mm, 28–30 °C	1,200–1,600	5	13	Uganda, Kenya, South Asia (winter plantings), central Brazil
4	Dry mid-altitude subtropical 350–600 mm, 24–30 °C	1,200–2,000	8	9 ^b	Tanzania, eastern Kenya, central Mexico, Nepal
5	Wet lowland tropical >800 mm, 30–34 °C	0–1,200	15	9	Thailand, Nigeria, coastal central America
6	Dry lowland tropical 350–600 mm, 30–36 °C	0–1,200	14	6 ^b	Coastal eastern Africa, central America, India, North-East Brazil
7	Wet temperate >600 mm, 26–34 °C	0–1,500	35	14	US Corn Belt, ^c western Europe, Argentina
8	Dry temperate 300–600 mm, 26–36 °C	0–1,500	17	9 ^b	Eastern Great Plains USA, eastern Europe, north-western China

a Stratified by altitude, rainfall, temperature and day length, approximate proportional areas. Rainfall in growing season (the five consecutive months with the greatest precipitation to evapotranspiration ratio). Average daily maximum temperature for the middle 70% of the growing season. Day length associated with the longest day during a summer growing season. Thus MME1–6 are mainly in latitudes of <30° with shorter days than MME7 and MME8 in latitudes 30–60 °N or S.

b Water-limited potential yield (PY_w)

c 'Corn Belt' refers to the maize-growing areas within Mid West USA (the 12 adjacent states from Kansas to Wisconsin, and North Dakota to Ohio); irrigated areas of western USA are also included in MME7.

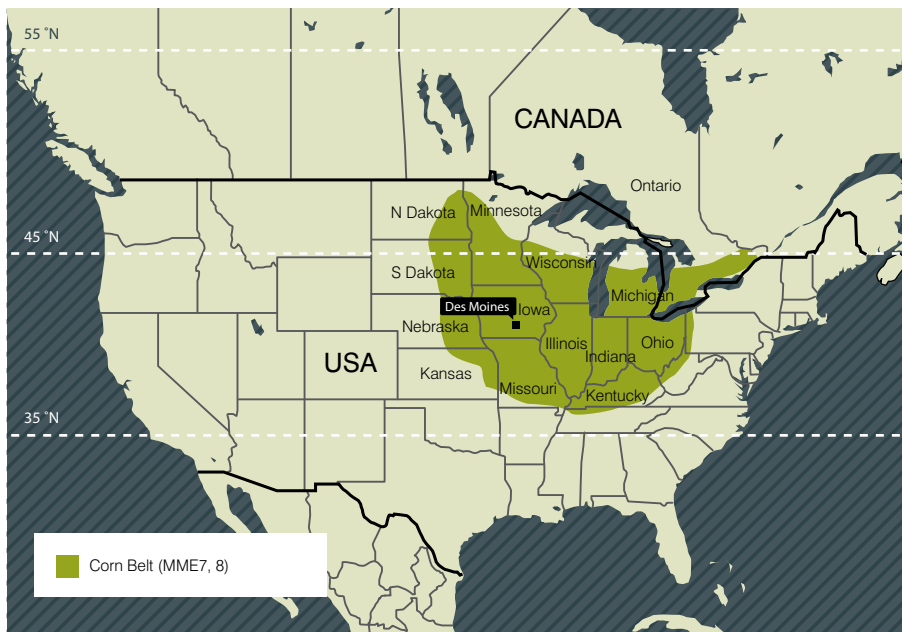
masl = metres above sea level

Source: Potential yield (PY) is an estimate based on temperature and radiation receipt, as outlined by Muchow et al. (1990). MMEs are adapted from Hartkamp et al. (2000) and Hodson (2004) and are relevant to around the year 2000 when world maize area was 137 Mha.

5.2 MME7—Corn Belt of the USA

Introduction to the Corn Belt and the US state of Iowa

The Corn Belt, located within the Mid West region of the USA (Map 5.2), produces more than 30% of the world's maize crop. This area is dominated by five states: Illinois, Iowa, Nebraska, Indiana and Minnesota. Combined, these five states produce two-thirds of US maize. Adjacent areas in the states of South Dakota, Wisconsin, Missouri and Kansas produce another one-sixth.



Map 5.2 The traditional US Corn Belt, its constituent states, and maize areas in adjacent Ontario, Canada

Globally, the Corn Belt represents the majority of MME7 (well-watered, temperate maize environment). It receives on average ≥ 600 mm of rainfall during the crop season, and a total annual precipitation (rainfall plus snow) of ~ 850 mm. The western and northern portion of the Corn Belt is drier and could be considered part of MME8 (dry temperate) given that average annual precipitation is < 800 mm in Nebraska and Kansas. Data for 2007 reveal that $> 60\%$ of planted area was irrigated in Nebraska, compared with just 2% in Iowa (USDA 2011).

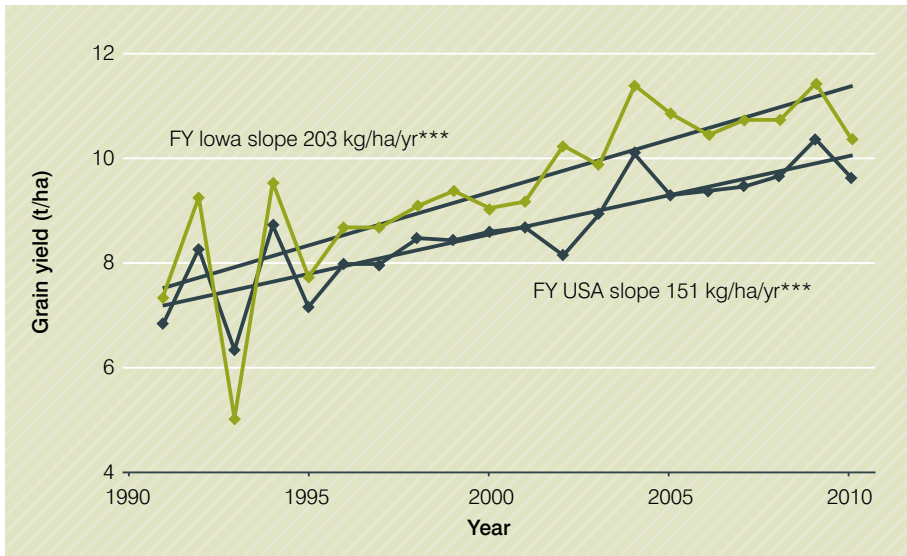
Maize hybrid development for the Corn Belt has attracted substantial private investment in plant breeding and agronomy, which has led to remarkable results that have been sustained since the 1930s (Duvick 2005b). The Corn Belt—and Iowa in particular—dominates global maize production and is the major battleground for the large, transnational maize breeding companies (Monsanto, DuPont and Syngenta). In 2007, global expenditure on maize hybrid improvement and associated farm-level agronomy research by the private sector was estimated at US\$1.1 billion per year (USDA 2011).

Iowa, with 5 Mha planted to maize, produces more maize grain than any other state in the USA, and therefore serves as a principal example of maize production in the Corn Belt. From 1991 to 2010, the rate of progress in maize FY has been strong and steady in Iowa, increasing at 203 kg/ha/yr (Figure 5.1). **This rate of FY increase equates to 1.8% p.a. of the 2010 estimated FY of 11.4 t/ha in Iowa**, and surpasses the USA as a whole at 1.5% p.a. of the 2010 estimated FY of 10 t/ha (Figure 5.1), although the slopes are not significantly different ($P > 0.10$). Observed rate of FY progress has accelerated since 1990, helped statistically by flooding and cool conditions, which resulted in a very low-yielding year in 1993.

The impact from deployment of genetically engineered (GE) hybrids continues to be felt throughout the USA. In Iowa, adoption of GE hybrids dates from 1996. By 2010, 90% of Iowa maize area was GE-hybrid, with 61% planted to hybrids carrying both herbicide- and insect-resistant traits, and a further 29% carrying one or other of these traits.

Specific breeding and agronomic factors contributing to yield progress are discussed below, but two other factors merit mention here. One factor has been the increase in maize profitability arising from regulations stimulating ethanol production from maize. It is no surprise that the real price of maize land in Iowa, for example, has increased by almost 50% in the past 10 years (M. Duffy, pers. comm. 2012). The second factor has been a favourable 1982–2002 climate trend in the Corn Belt, with higher precipitation and lower summer temperature, but warmer springs leading to earlier planting (Twine and Kucharik 2009). Using climate data to simulate maize yields, Twine and Kucharik (2009) suggested that 20–25% of the upwards yield trend could be attributed to these climate trends. However, Lobell et al. (2011b), using a statistical approach, found no evidence of temperature change or impact on US maize yield over a similar period.

Yields in 2011 were on a par with 2010, but the 2012 production year was unusually hot and dry in the USA, and average yields fell by 22% (compared with the 2008–10 mean) to 7.7 t/ha, a level last seen in 1995. In Iowa yields declined by 19% to 8.8 t/ha, though in Illinois, Indiana and Missouri, reductions ranged from 35% to 43% (USDA 2012). To the north, the rainfall deficit was less, so that there was no yield reduction in Minnesota. There is yet to appear an analysis-based consensus on how the relative yield losses in rainfed states in 2012 relate to those in comparable earlier droughts. The reduction in 2012 US maize yield represents an 8% reduction in global maize production, and resulted in significant increases in global maize grain prices.



*** $P < 0.01$

Figure 5.1 Maize farm yield (FY) in the USA vs. the US state of Iowa from 1990 to 2010. Source: FAOSTAT (2013) for USA; USDA (2012) for Iowa

Maize farm yield progress in Iowa—improved hybrids and better management practices

Cardwell (1982) estimated that 58% of 1930–80 progress in maize FY in Minnesota (a state bordering Iowa) was due to improved genetics and the remainder due to agronomy—this was one of the earliest attempts to partition FY progress. Duvick (2005a)—who conducted evaluations of commercially important hybrids released each decade during 1930–2002 (the ‘ERA hybrid set’ of vintage comparisons)—attributed FY progress equally to genetics and cropping practice.

More recent studies of breeding progress, however—and even Duvick’s work—have revealed that in the case of maize, **breeding progresses are inextricably interwoven with changes in crop management** (see also Chapter 2, Box 2.1 on variety-by-agronomy interaction and PY progress), such that it is futile to attribute gains to breeding or agronomy individually, since both are essential. Key elements of this positive (hybrid) breeding-by-management interaction are considered below.

The major change in crop management practice over the past 70 years has been a doubling of **plant densities**. Maize is a unique cereal in that it does not tiller and its yield organ, the maize cob, is not terminal (rather it is subtended by a leaf buried in the crop canopy). Under today’s densities, older hybrids respond with a significant degree

of barrenness (plants without grain-bearing cobs) and/or lodge (do not remain standing). By comparison, Duvick (2005a,b), and Tollenaar and co-workers (Tollenaar and Wu 1999; Tollenaar and Lee 2002; Lee and Tollenaar 2007) have documented a remarkable increase in tolerance to plant density in more modern hybrids. As a result of this genetic change, the optimum plant density for maize grain yield has risen at a rate of ~800 plants/ha/yr for the past 40 years in Iowa. Plant density in Iowa today averages ~80,000 plants/ha, compared with 40,000 plants/ha in the 1960s. This increase in planting density shows no sign of abating, even though seed prices more than doubled from 2001 to 2009, reaching a 2009 cost of US\$185/ha, or ~10% of gross crop revenue (Wilson and Dahl 2010). Yield contest winners currently plant ~100,000 plants/ha on irrigated sites and 85,000 plants/ha under rainfed conditions (Jeschke and Butzen 2012).

The second important hybrid-by-management interaction has been the dramatic **increase in nitrogen fertiliser application** from first use in ~1950 until ~1985 (see Figure 11.2). Nitrogen use on maize in USA (and in Iowa) peaked at ~160 kg N/ha in the mid 1980s, then fell to as low as 140 kg N/ha in the mid 1990s, before increasing again gradually to again reach ~160 kg N/ha in 2010. Modern hybrids respond with more grain than older hybrids to each unit of applied nitrogen. Since nitrogen rates have increased little in the past 20 years, this positive interaction has not played a major role in recent yield increase. During this period, however, improvements in nitrogen management (timing, placement and/or forms of fertiliser), and increased hybrid PY, continue to drive substantial increases in nitrogen use efficiency (NUE; see Section 11.3).

Planting dates have also changed with time. Because maize is now **planted earlier** in the Corn Belt than in the 1960s, a longer growing season and a longer duration hybrid can be used. Kucharik (2008) estimated that early planting may account for one-half of the annual increase in grain yield in Iowa in the past 30 years, since crops are now planted on average 12 days earlier. In neighbouring Illinois, the maize crop sown in 2005 reached the 50% planted area fully 3 weeks earlier than in 1965 (Irwin et al. 2009). Date of planting studies in Illinois indicate that a delay of a month in planting after 20 April will reduce yields by 15% (Irwin et al. 2009). The following factors play important roles in the shift to earlier plantings; this is a further example of hybrid-by-management interactions contributing to yield progress:

- hybrids tolerant to cold conditions and waterlogged soils
- hybrids with herbicide resistance
- improved seed fungicide dressings
- use of large, high-speed planters adapted to conservation tillage practices.

Water supply, both deficit and excess, has had a notable effect on yields in Iowa in the past 30 years. Yields in Iowa fell below trend by 33% in the widespread drought of 1988 (19% in the hot and dry 2012), and by 37% in the extremely wet and cool year of 1993. In recent seasons, yields have fluctuated considerably less (Figure 5.1). Good evidence, reviewed below, suggests that part of the reduction in variability in crop yield has arisen through **improvement in drought tolerance of hybrids**. The relative yield advantage of modern hybrids is greater under water shortage than in its absence. There is little doubt

this response of modern hybrids has helped to stabilise yields in the Corn Belt. Water use efficiency (WUE) has also increased along with the increased yields (see Section 11.2).

Many other agronomic changes are helping FY progress, but it is not clear whether these also interact positively with modern hybrids. For example, greater **use of precision planters** has resulted in a small increase in yield from improved plant-to-plant uniformity (Liu et al. 2004). Further, costs can be reduced by precision farming, which allows inputs to be adjusted to demand in response to monitored within-field variation in fertility and plant-available water (e.g. Schmidt et al. 2002). This practice increases resource use efficiency, rather than increases yield.

Foliar fungicide applications are becoming more common, even when disease is not very evident. Other management factors noted in yield contest-winning plots are a trend toward **narrower rows, improved drainage, application of trace elements** (especially zinc and sulfur) and **deep tillage** (Butzen 2010). Leading farmers also recognise that **crop rotation** offers benefits in terms of requirements for nitrogen fertiliser and/or in terms of improved soil health. A survey of contest-winning maize yields in the USA showed the majority (~60%) came from maize following soybean, rather than maize following maize (20%) (Butzen 2010). Although 63% of maize currently follows soybean in Iowa, the proportion is decreasing as maize-after-maize has steadily increased since 2000 due to economic reasons (R. Elmore, pers. comm. 2012).

In summary, full benefits to FY of changed growing practices are seen only when complemented with hybrids developed to exploit those practices—thus maize exemplifies the importance of **positive genotype-by-management interactions**. This complementation has become increasingly important as yield levels have risen, at least with respect to greater plant density, higher soil fertility, drought tolerance and earlier planting.

Farmer benefits from GE were originally perceived as increasing efficiency through reduced agrochemical costs and greater ease of management, rather than extra yield. However, other indirect yield benefits are now recognised, including:

- greater yield from earlier planting, made possible with GE herbicide-resistant hybrids
- better root growth and improved drought tolerance of GE hybrids resistant to maize rootworm
- reduced incidence of ear rot with GE hybrids resistant to ear worms.

These are examples of yield-enhancing and yield-stabilising benefits of GE-technologies, because the pests involved were not completely controlled beforehand with biocides. Thus GE traits have undoubtedly contributed to the rapid increase in maize FY in the Corn Belt in recent years (see also Section 9.9 on GE using transgenes), although the major contributions to yield have been from non-GE factors.

Most of the changes described above apply to the Corn Belt as a whole, including irrigated maize on the western margin, as illustrated in later chapters (see Sections 8.2 on causes of yield gaps and 11.3 on NUE). Since crop management is already at a very high

level there—and farmers are well informed and responsive to new technologies—it seems likely that the genetic component of yield increase will become increasingly important for further FY improvement.

Potential yield for maize in Iowa and its progress

Determining PY and its progress for maize in USA is not easy because reliable breeding company data are rarely published. Estimates for Iowa and nearby Corn Belt locations, presented in Table 5.3, are derived from assessments of yield progress with breeding, research trials, modelling studies and yield contests. Available estimates vary considerably for reasons that cannot always be clearly identified. Breeding trial data are from the 'ERA hybrid set', released 1930–2002 by Pioneer Hi-Bred (Duvick 2005b); Pioneer releases up to 2006 (Hammer et al. 2009); DeKalb releases in 2000–06 (Edgerton 2009); and parent–progeny comparisons made in the private seed sector (Mikel 2008). High-yield plots were mainly developed in Nebraska to calibrate the 'Hybrid-Maize' simulation model using irrigation, high plant density and plentiful nitrogen on hybrids released during 1999–2001 (Yang et al. 2004). Hybrid-Maize produced simulations constrained for only radiation, temperature and soil type, as did initially the older 'CERES-Maize' model.

Table 5.3 Summary of estimates of maize potential yield^a (PY) in Iowa and the nearby Corn Belt locations in the USA, from assessments of breeding progress (vintage trials), high-yield plots, simulation and on-farm yield contests

Trait	Vintage trials ^b	High-yield plots ^c	Simulations ^d	Yield contests ^e (irrigated)	Yield contests ^e (rainfed)
No. of observations	7	13	9	84	114
Mean PY (t/ha)	12.4	14.5	17.7	19.8	17.5
Mean rate of PY increase (kg/ha/yr)	100	na	na	189	211
Rate of PY increase (% p.a.)	0.8	na	na	1.0	1.2

a All estimates of PY use 2006 as the average year of hybrid release. Gains from vintage hybrid evaluations are estimated against year of release and progress is relative to the most recent year of release.

Source:

b Cooper et al. (2004); Duvick (2005a,b); Edgerton (2009); Hammer et al. (2009); Mikel (2008)

c Coulter et al. (2010); Castiglioni et al. (2008); Edwards et al. (2005); Grassini et al. (2009b), (2011b); Kiniry et al. (2004); Lindquist et al. (2005); Mason et al. (2008); Setiyono et al. (2010); Teal et al. (2006); Wortmann et al. (2009); Yang et al. (2004)

d Bannayan et al. (2004); Dobermann et al. (2003); Grassini et al. (2009b, 2011a,b); Lobell et al. (2009); Ritchie and Basso (2008); Yang et al. (2004)

e Duvick and Cassman (1999); NCGA (2011); Jeschke and Butzen (2012)

Mean values of PY of each class of estimate shown in Table 5.3 vary from 12.4 t/ha (Pioneer) for the most recently released (~2006) hybrids evaluated in vintage trials, to 14.5 t/ha in high-yield plots (also 16 t/ha in Nebraska; Yang et al. 2004) and 17.7 t/ha for simulated yields (Grassini et al. 2011a).

Contest yields are reluctantly (for reasons already mentioned) considered here because of uncertainties about other PY sources, and because these yield measures are widely cited by others. Yields from contest-winning rainfed maize in Iowa are now approaching 17 t/ha (R. Elmore, pers. comm. 2009). Yield contest results used in Table 5.3 were obtained from Iowa or Nebraska contests, cited by Duvick and Cassman (1999) or obtained from the published yields of the three highest yielding entrants in each of eight classes of the National Corn Growers' Association annual yield contest (NCGA 2011).³⁸ National yield contest winners 2005–10 have averaged 19.8 t/ha under irrigation and 17.5 t/ha under rainfed conditions. These absolute values cannot be used as a measure of PY, although their rate of change (or lack thereof) may indicate something about PY progress.

Thus it is concluded here that **PY in Iowa stands in 2010 at ~15 t/ha** and this PY is probably very similar for the rest of the Corn Belt. This value is somewhat higher than the estimate suggested from vintage trials in Table 5.3, but that average was for 2006 and dominated by the relatively low-yielding site in Johnson, Iowa, USA, as used by Duvick (2005a, 2005b) and Hammer et al. (2009). A current PY value of 15 t/ha in Iowa indicates that **the yield gap is 36% of the 2010 FY**. This is only somewhat in excess of the likely minimum exploitable yield gap (i.e. about 30% of FY—see Section 2.1 on definitions). It is notable that van Wart et al. (2013b), using simulation modelling for PY determination, concluded the yield gap over the whole Corn Belt was 36% for rainfed maize (and 29% for irrigated maize).

Duvick and Cassman (1999) suggested that maize PY in the Corn Belt has been static over time. Yield per plant under spaced (or low density), unstressed conditions has indeed remained unchanged for many years (Duvick 2005a). However, where plant density is increased, it is clear that newer hybrids can tolerate conditions of stress much better than older hybrids, which constitutes an increase in PY. The vintage trials (Table 5.3), **at optimum plant density, estimate that PY appears to be increasing at a rate of 0.8% p.a.**; relative to the 2010 PY this is equivalent to ~120 kg/ha/yr.

The figure of 0.8% p.a. is supported by the relative increase in contest-winning yields over time. Although yield from contest-winning irrigated maize in Nebraska appeared to show little apparent change between 1984 and 2002 (Cassman et al. 2003), gains in yields of national contests from 2002 to 2011 were 1.0% p.a. (irrigated) and 1.2%

³⁸ Estimates from Butzen (2010) were computed from the mean of the top three yields in the irrigated and rainfed classes of the NCGA contest in each year. These monitored yields are on much larger plots (4 ha of a single hybrid) than those used in other PY estimates, but the level of inputs applied to the plots is often well above the economic optimum (Butzen 2008). It is noteworthy that contest winners were not confined to the Corn Belt, with several each year from eastern states and from Texas.

p.a. (rainfed) (Table 5.3; Jeschke and Butzen 2012). Note that with maize, PY progress derives from improved hybrids interacting positively with agronomic changes (as discussed above), in particular to increased density and earlier planting.

Other data on Pioneer's vintage hybrid sets from outside the Corn Belt also offer reassuring evidence of steady PY increases. PY of 2002 maize hybrids under irrigation in California was estimated at 16 t/ha, with progress occurring at a rate of 84 kg/ha/yr, or 0.5% p.a. (Barker et al. 2005). A subset of the same hybrids, when grown under irrigation in a cooler irrigated Chilean environment, showed PY increases of 210 kg/ha/yr (1.1% p.a.) with the hybrids released in the 1995–2001 period averaging 19.9 t/ha (Campos et al. 2004, 2006).

Thus there is no compelling evidence that relative progress in PY has slowed dramatically in temperate maize grown in the Corn Belt, but on balance, the relative rate of PY increase appears to be less than that for FY. This implies that the yield gap is closing and points to a likely slowdown in FY progress in Iowa—and probably in the USA—from the current level of 1.8% p.a. (1.5% p.a. for the USA).

This likely slowdown in FY progress contrasts with Monsanto's 2008 prediction that the 2000 national FY of 8.5 t/ha could double to reach 17 t/ha by 2030, attributable mainly to advances in molecular breeding (Edgerton 2009). If linear throughout, this prediction would imply an FY increase of 283 kg/ha/yr, or 2.8% p.a. relative to the 2010 FY level; such rate of gain is unlikely to be achieved.

One element of the Monsanto claim is their plan to commercialise a line of hybrids (marketed under the name DroughtGard™) in 2013, which will carry the transgene *MON87460*, a cold-shock protein gene (*cspB*) isolated from the soil bacterium *Bacillus subtilis*. Early field trials of this gene suggested it could deliver as much as 15% yield advantage when the general yield level was reduced by around 50% by drought (Castiglioni et al. 2008). This would be the first ever drought-tolerant GE-cultivar released, but there is insufficient recent information on the performance of these hybrids to attach a high level of confidence in these claims. Indeed the performance advantage under the 2012 drought conditions in the Corn Belt was around 7% (Edmeades 2013). A related development is the 2011 launch by Pioneer of AQUAMax® hybrids; these hybrids do not contain any GE drought-tolerance traits, but were selected under drought stress and offer a claimed 6–8% advantage over normal hybrids under drought conditions, something Pioneer believes has been confirmed in the 2012 drought over hundreds of sites.

Physiological basis of improved potential yield through stress tolerance in Corn Belt maize hybrids

The following analysis draws mainly on the principles of crop physiology outlined in Section 2.6, as well as observations from the 'ERA hybrid set' (Duvick 2005a) and a more physiologically orientated set of studies in Ontario, Canada (a province adjacent to the US Corn Belt) of hybrids released 1959–2004 (Tollenaar and Lee 2011).

Table 5.4 summarises the major changes in maize plants resulting from the intensive and prolonged breeding effort, which explicitly targeted only four traits—yield increase across many sites, stalk strength, disease defensive traits, and fast dry down at maturity.

Table 5.4 Significant ($P < 0.05$) changes in key traits of Corn Belt maize hybrids following multilocation testing and selection for 40–70 years

Trait	Trait change/yr ^c	Comment on change over time	Source
Morphology and phenology			
Leaf angle score ^a	0.1	Leaves more erect	2
Tassel weight (g)	-0.05	Smaller tassels	2
Plant height (cm)	ns	Plant height maintained	2
50% anthesis (GDD, °C days) ^b	ns	Maturity maintained	2,5
Grain-fill duration	ns	Increased	1
Productivity of grain and biomass			
Grain yield under competition (kg/ha)	90	Yield increased	1
Leaf staygreen score ^a	0.12	Final leaf senescence is delayed	4
Grain weight (mg)	0.7	Grain weight increased	2
Harvest index, unstressed (%)	0.1	Slight increase	2
Grain protein (%)	-0.03	Less grain protein, more starch	2
Leaf photosynthesis, unstressed	ns	Unchanged	3
Stress tolerance—abiotic			
PY _w flowering drought (kg/ha)	120	60% of the gain under irrigation	5
PY _w grain-filling drought (kg/ha)	50	25% of the gain under irrigation	5
ASI ^b flowering drought (GDD, °C days) ^b	-2.6	Synchrony improved	5
Ears per plant	0.002	Less barrenness	2
Grains per ear	1.6	Larger ears under drought	5
Root lodging (%)	-0.9	Stands better	2
Leaf rolling score ^a	0.035	Roll more readily	4
Cold, heat tolerance	na	Improved	1,3
Stress tolerance—biotic			
Northern leaf blight score ^a	0.07	Improved resistance	2
European corn borer score ^a	ns	Improved resistance	2

a Scores are from 1 (putatively least desirable) to 9 (putatively most desirable). These data represent a 40–70-year period; thus a score change of ~0.035 p.a. represents a change of ~2.5

b GDD = growing degree days, as defined in Section 2.6; ASI = anthesis-to-silking interval

c ns = not statistically significant; $P > 0.10$

Source: 1 Duvick (2005a); 2 Duvick (1997); 3 Tollenaar and Lee (2011); 4 Barker et al. (2005); 5 Campos et al. (2006)

This analysis reveals how modern maize hybrids are distinctly different from their predecessors in morphology and many other respects (Table 5.4). In contrast, they have changed little in terms of height and phenology (though little is known of changes in rooting characteristics). The ability to stand and yield under densities that have doubled over the past 50 years has been the main driver of improved productivity. Some morphological changes have obviously tuned the plant to high densities: upright leaves result in more efficient light interception, and small tassels intercept less light and do not compete as strongly with the growing ear at flowering.

In contrast to wheat and rice, yield progress has been accompanied **by increases in final dry matter (DM)** at almost the same relative rate as yield itself. Thus harvest index (HI) has increased only slightly, to reach 0.55 in mid-maturity modern hybrids. Increased DM has occurred because **denser crops intercept more solar radiation** (especially early in the crop life cycle before silking), and because of **higher radiation use efficiency (RUE)** after silking (aided by prolonged 'staygreen'), meaning delayed leaf senescence and longer grain-filling (Tollenaar and Aguilera 1992; Tollenaar and Lee 2002). Greater DM production during grain-filling has resulted in greater grain weight (GW) despite the fact that increased GN (grain number/m²) has been the dominant route to greater yield.

Better disease resistance is also part of the improved canopy performance, resulting in stronger, healthier lower stalks and roots in the latter half of grain-filling, when the crop normally remobilises DM stored in the stem to fill grain. Thus there are marked improvements in stalk and root lodging resistance, traits for which the breeders have practiced selection.

Although this is a discussion about PY improvements, physiologists often describe maize improvements in terms of greater stress tolerance (e.g. Tollenaar and Lee 2002). Historically, maize has been highly susceptible to stresses coinciding with flowering, and this is reflected in a longer anthesis to silking (ASI) interval under stress, reduced grain number per cob, and more barren plants with no grains (Edmeades et al. 2000). High density, of course, has been one major stress that causes a long ASI interval and many barren plants in older hybrids; but as discussed above, breeders have unwittingly developed maize with greater tolerance to density stress. Moreover it seems that even under good management, other more subtle stresses often arise (e.g. brief drought, cold and/or hot spells). Improved tolerance to these subtle stressors have also been unwittingly achieved, no doubt through the breeders' strategy of multilocation testing across diverse environments.

Evidence of improved tolerance to drought comes from performance under a range of imposed water stresses. Campos et al. (2006), using an 18-hybrid subset of Duvick's vintage hybrids, reported relative progress in PY_w of 0.6–1.5% p.a. during conditions of controlled drought at different crop development stages, compared with 1.2% p.a. during drought-free conditions; the least progress occurred when drought was timed for late grain-fill. In similar studies in California, PY_w progress under flowering stress and grain-filling stress was 1.3% p.a. and 0.8% p.a., respectively, compared with 0.5% p.a.

under irrigation (Duvick 2005a). These studies point to a significant increase in drought tolerance, especially for stresses that coincide with flowering. Little, however, has been reported on the physiology underlying the abovementioned new putative drought-tolerant hybrids.

Part of the basis of this broad stress resistance appears to be an **increase in partitioning of assimilate to the developing cob** (also described as increased reproductive sink strength) from a very early stage, and a probable reduction in the threshold of the assimilate flux required to prevent cob abortion. These changes result in more rapid cob growth and vigorous silking (Barker et al. 2005), a shorter ASI interval (Edmeades et al. 2000) and more grains set for a given crop growth rate (Echarte et al. 2000).

During grain-filling, modern hybrids show associated gains due to increased radiation capture resulting from longer staygreen and better canopy health; an increase in RUE (Tollenaar and Aguilera 1992); and a delay in the age-related decline in photosynthetic rate, especially under nitrogen stress (Tollenaar and Lee 2011). This improved grain-filling performance (e.g. staygreen and photosynthetic rate) could be responding to feedback from the larger sink size formed in modern hybrids, but such causal links are always difficult to prove. Tollenaar and co-workers were unable to confirm an increase in maximum photosynthetic rate (P_{max}) in the modern hybrids, but did show that their photosynthetic rate recovered more quickly from drought and cold shocks (Dwyer et al. 1989; Nissanka et al. 1997). Thus the stress tolerance in modern hybrids may be related to **better assimilate supply** as well as to a stronger reproductive sink.

Modern hybrids also appear to acquire more water to match their increase in carbon capture. Hammer et al. (2009) suggested that this is achieved through deeper roots, which could explain part of their improved drought tolerance (Campos et al. 2004) and the observation of cooler canopies (i.e. greater stomatal conductance) under drought (Barker et al. 2005). Data on variation in rooting depth remain insufficient to assess its importance and determine the degree to which water supply is limiting rainfed maize yield in Iowa. However, in very dry years (such as 2012) and on coarser soils, lack of water is certainly an important source of yield instability.

Conclusion for maize in the US temperate zone

Improvements in maize yields over the past 20–30 years in the US Corn Belt—exemplified by the state of Iowa—have been spectacular and show no real sign of abating. Out of all the large cereal producing areas in the world, maize in the Corn Belt—with estimated FY approaching 11 t/ha in Iowa in 2010, and annual FY progress close to 200 kg/ha/yr (1.8% p.a.)—easily meets the rate of production increase needed to meet demand growth through to 2050. However, Iowa is certainly the exception to the rule: favourable prices, infrastructure, institutions, climate and soils, with the maize crop supported by large investments in breeding and agronomy research and up-to-date farmers.

Furthermore, because most maize in the Corn Belt is planted as part of a stable cereal–legume rotation (maize–soybean), and input use efficiency is already high and steadily rising, these yield increases appear environmentally sustainable (see also Chapter 11). However, some weaknesses do remain; for example a significant proportion of maize follows maize, glyphosate-resistant weeds are developing and there appear to be moderate losses of fertiliser nitrogen to the environment. Nonetheless, the energy efficiency (ratio of outputs to inputs) of properly managed centre-pivot irrigated maize systems in Nebraska is outstanding (averaging >5), while showing only low greenhouse gas emissions per kilogram of grain produced (Grassini and Cassman 2012; see also Section 10.5 on greenhouse gas emissions).

The era of GE maize, now around 15 years old, is still continuing to deliver stable high yields, while that of genomic selection is just beginning to deliver benefits. Since these technologies are focused on the Corn Belt (and being developed there), they may well deliver larger yield gains to this area in the future. However, the emergence of resistance in maize rootworm populations to the *Bt* transgene (Gassmann et al. 2011) and the appearance of glyphosate-resistant weeds will require careful management if yield gains are to be sustained.

The analysis presented here suggests that the yield gap in the US Corn Belt is around 36%, even in the heart of this maize-growing region. With the rate of PY progress at ~0.8% p.a., FY progress at double this rate has arisen almost equally from enhancing PY and filling yield gaps through increased focus on interactions between hybrid traits and management practices. However, because the yield gap is only 36% of FY, gap closing is likely to become more difficult, and FY rate of progress may soon decline to parallel that in PY.

The clear improvement in stress tolerance of maize hybrids that has accompanied rising PY is contrary to popular perception, and possibly unique among the major crops. The underlying physiological changes are incompletely understood, and such stress resistance may partly be a fundamental feature of the phenotypic uniformity and vigour associated with hybrids. If so, this should auger well for other crops moving down the hybrid route.

The key physiological outcome of PY improvement has been more DM and more grains per unit of crop growth rate around flowering, even as stress increases through higher density, leading to less growth per plant before anthesis. Grain weight is then maintained through improved crop photosynthesis and growth during grain-filling, even in the face of the higher density and multiple minor stresses. Critical questions are whether modern hybrids have better root systems (e.g. Hammer et al. 2009) and, for the future, whether DM can be increased further because HI at 0.55 must be close to its limit.

Section 5.2 considers Corn Belt hybrids in some detail because of the strategic importance of this source of germplasm and the global importance of the temperate MMEs. North American hybrids travel well to other key temperate production areas

such as northern China, Europe, temperate South America and Oceania, where they are often being directly released to farmers. In addition the major international seed companies have well-orchestrated programs for systematically introgressing Corn Belt germplasm into tropical germplasm in order to provide yield potential, standability, excellent plant morphology and abiotic stress tolerance. Thus Corn Belt hybrids have an impact well beyond the boundaries of the US Corn Belt and the state of Iowa.

5.3 MME7 and MME8—Northern China—large temperate maize mega-environments

5

Introduction to maize in China

In response to increased demand for animal feed in recent decades in China, the importance of maize has increased relative to other cereals. China planted 31 Mha of maize in 2008–10 (Table 5.1), similar to that area planted to rice, and almost as large as the maize area in the USA. Very small farms (0.2–1.0 ha) are a feature of maize production in China today, although the term ‘farm’ really refers to household management units. Land cannot be privately owned in China, so collective land is allocated to households under village and/or household responsibility.

Over the past 20 years, **maize area has expanded markedly at a rate of 1.7% p.a.**, although this has occurred through substitution of other crops such as soybean and (to some extent) wheat, rather than through expansion onto poorer land. Meanwhile, over the same 20-year period, Chinese maize **FY increased at a comparatively modest rate of 40 kg/ha/yr, or 0.7% p.a. of the estimated 2010 FY of 5.4 t/ha** (Figure 5.2). However, more rapid FY progress occurred immediately prior to 1990, at a rate of 104 kg/ha/yr as a consequence of policy reform, greater input use and improved hybrid varieties (H. Wang et al. 2009); at that same time, a similar situation was seen with increases in FY for both wheat and rice in China.

The 1998–2003 FY decline (Figure 5.2) before a reversal in 2004 partly reflects subsidy shifts surrounding maize (H. Wang et al. 2009) because, as with wheat and rice, the government is heavily involved in the maize economy. Chinese maize production now almost meets domestic consumption; for example, the 2008–10 net annual import averaged only 5 Mt (FAOSTAT 2013). In China, 70% of maize is used for animal feed, and only 4% is used for food (S. Zhang, pers. comm. 2011).

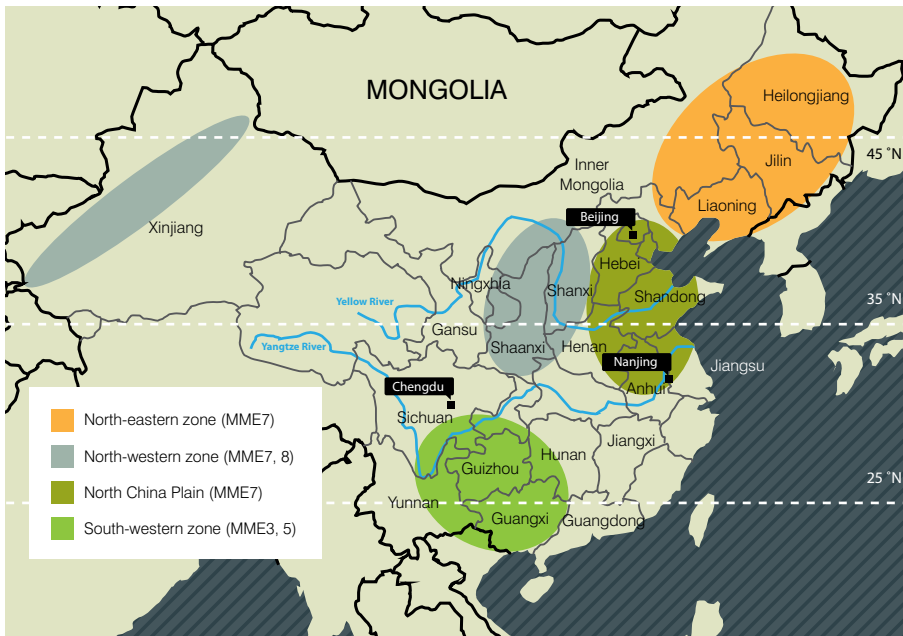
Because of their large latitudinal range (22 °N to 53 °N), maize agroecologies in China are complex (Meng et al. 2006; Zhang and Bonjean 2010). Besides this, for China as a

whole, ~60% of the crop is rainfed and ~40% is irrigated. Most maize is grown north of latitude 30 °N under temperate conditions in the following regions (Map 5.3):

- North China Plain (NCP)—41% of Chinese maize area; average FY of 5.5 t/ha
- north-eastern China—34% of Chinese maize area; average FY of 5.3 t/ha
- north-western China—10% of Chinese maize area; average FY of 5.8 t/ha.

As most of this temperate maize is well watered by summer monsoon rainfall and often supplemented by irrigation (especially in the northern NCP and far western areas), this area is considered as MME7 (wet temperate). However, some parts of north-western China—such as the wetter Loess Plateau regions of the province of Shanxi, and the provinces of Shaanxi and Gansu—are without irrigation and dry enough to be considered as MME8 (dry temperate).

Maize is also grown south of 30 °N, extending almost to the South China Sea. This region of southern and south-western China—termed collectively here as south-western China—grows 15% of the Chinese maize area, with an average FY of 4.7 t/ha. The region is mostly below 1,800 masl with ample rainfall, and hence maize growing in these southern areas is considered as either MME3 (wet lower mid-altitude subtropical) or MME5 (wet lowland tropical).



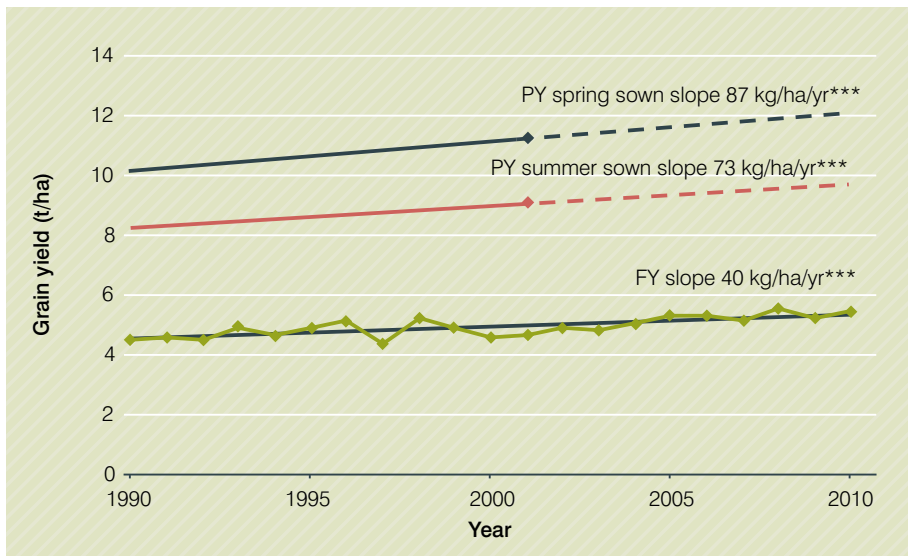
Map 5.3 Schematic distribution of major maize regions of China. International borders are approximate.

Cold winters of high latitude north-eastern and north-western China add complexity because maize is planted there as a sole crop in spring (April–May)—just as occurs in the US Corn Belt. In the NCP (especially the warmer, wetter parts), however, maize is usually planted in summer (June–July) following a winter crop of wheat, canola (rapeseed) or vegetables. In south-western China, summer maize is mostly planted in rotation, or intercropped, with one or two cool season crops, depending on altitude. In the warmest parts of the south there is some autumn and winter maize.

Overall, 64% of Chinese maize is early (usually spring) sown with generally greater yield potential than the 36% sown in summer. In China, maize is subject to natural disasters, especially from flooding during monsoon rains. Nonetheless, national yields are quite stable year to year (Figure 5.2) and the coefficient of variation of FY for 1990–2009 (6.1%) is less than that for USA (10.7%), reflecting that much of the crop is well supplied with water.

Yield progress in maize in temperate regions of China

In this section, analysis of progress focuses on MME7 and MME8, the two temperate mega-environments that comprise 85% of China's maize area. There is insufficient information to clearly separate these two MMEs in China. Even when maize is grown under the drier MME8 conditions, the crop is usually not subject to severe drought because of agronomic procedures (such as plastic inter-row mulching) that are designed to increase WUE.



*** $P < 0.01$

Figure 5.2 Maize farm yield (FY) for China, plotted against year, and estimated potential yield (PY) for spring and summer planted maize, plotted against year of release, from 1990 to 2010. Source: FAOSTAT (2013) for FY

Given the dominance of MME7 and MME8 in China, it can be assumed that FY progress statistics for the whole of China are a good estimate of progress for the MME7 and MME8 component of China maize area. **Thus, rate of FY progress over the past 20 years can be taken as 0.7% p.a.**—equal to the national rate shown in Figure 5.2.

Chinese maize breeding history and its current status, largely targeting temperate MMEs, is summarised in Box 5.2. In considering more recent breeding progress, T. Wang et al. (2011) and Ci et al. (2011, 2012) independently reported on separate groups of commercially important vintage Chinese hybrids. Both these experiments were conducted with the best hybrids released over the 40–50 year period up to ~2003, and both included a range of planting dates and plant densities (although density interactions were found to be small).

Combining results of both studies comprising six spring planting locations across three northern regions (north-eastern and north-western China, and the NCP), Chinese hybrid 1964–2003 releases, when grown at 52,000–75,000 plants/ha, achieved an average yield of 10.4 t/ha; this should be a good estimate of PY progress for spring sowing. Thus progress was highly significant, and across all locations the average rate of progress (i.e. taken here as **PY progress for spring maize**) was **87 kg/ha/yr, or 0.8% p.a. of the most recent hybrid yield**. Note that greater progress was reported by Ci et al. (2011) for spring plantings in the NCP (Beijing)—153 kg/ha/yr, or 1.3% based on the latest hybrids. However, for simplicity of analysis, the average rate of progress given here has been derived by lumping the NCP region with north-western and north-eastern China. By comparison, for two **summer planting locations in NCP, yield progress was 73 kg/ha/yr or 1.2% p.a. of the most recent hybrid yield**; since the average trial yield was only 6.0 t/ha this progress estimate was not used in the summary table.

Box 5.2 Maize breeding in China

Maize improvement in China has followed the steps outlined for the USA in Box 5.1. Over the past 60 years, since farmers stopped using maize landraces, progress has depended on combinations of local and exotic germplasm, the latter mainly from the USA. Single-cross hybrids were widely used from 1960s onwards, and currently 97% of maize area is sown to hybrids, although open-pollinated varieties (OPVs) can still be found in small areas in the mountainous south. Germplasm sources used in improvement are largely of Chinese (44%) or US (54%) origin (Li et al. 2006; T. Wang et al. 2011).

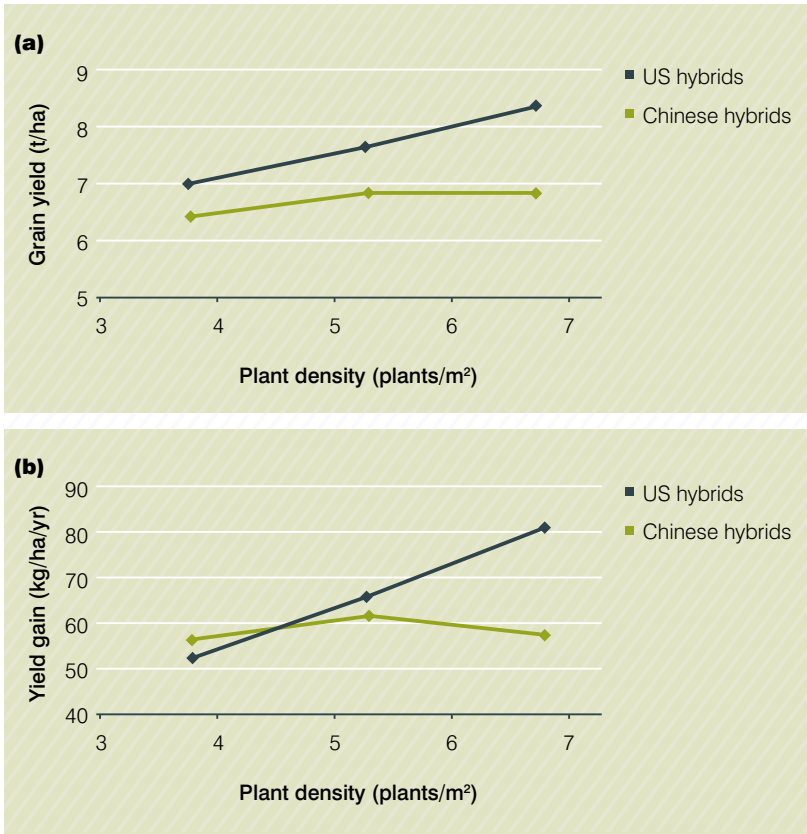
Chinese inbred lines can be categorised into four heterotic groups: stiff stalk (SS), non-stiff stalk (NSS), a domestic Chinese group and a group derived from hybrids developed by Pioneer and introduced into China in the 1980s (T. Wang et al. 2011). Much of the germplasm in use is relatively old. It is not

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surprising, therefore, that Y. Li et al. (2011) found Chinese elite hybrids to have lower yields and poorer breeding progress under high density than US hybrids (see box figure).

Today multinational seed companies are becoming more heavily involved in the Chinese seed market, often in joint-ventures with leading Chinese seed companies. However, availability of improved stress-tolerant temperate inbred lines and associated improvement technologies in China has been challenged by lack of effective protection of private intellectual property (T. Wang et al. 2011), and this will continue to slow progress unless it is resolved.



Grain yield of modern hybrids (a) and rate of breeding progress vs. plant density (b) in US vs. Chinese hybrids when both were grown in China. Source: Y. Li et al. (2011).

In a smaller study in north-eastern China, Hou et al. (2012) measured a PY progress of 122 kg/ha/yr (or 1.0% p.a. relative to yield of the latest hybrid) from five spring-sown varieties released from the mid 1950s to the mid 1990s. The older varieties may have been open-pollinated varieties (OPVs), and the result is not used here because of the old vintages involved.

Y. Li et al. (2011) showed that US hybrids performed better at high density in China than did Chinese hybrids (see Box 5.2). T. Wang et al. (2011) and Ci et al. (2011) also concluded that there is scope for Chinese breeders to further lift PY through selection for tolerance to higher densities than those currently used (~60,000 plants/ha). Such crops are better suited to machine harvesting, a practice that will become more common as Chinese rural labour supply continues to shrink (Liang et al. 2011). Specific targeting of summer vs. spring production environments by breeders may increase rates of progress, since there is a need for hybrids adapted to each rather than both. Management of drought stress environments for screening prospective hybrids is also likely to accelerate the trend toward stable and higher yielding hybrids for the future.

The above estimates for rate of PY progress are probably reasonable, but it remains questionable whether the relatively low trial yields truly reflect current PY. Unfortunately, other recent reports of experimental data that could have provided clarification have often lacked information on key factors; for example, information about whether spring or summer maize was used, or whether the trial was conducted with or without supplemental irrigation.

Approximate mean experimental PY values for recent **spring maize hybrids** range from 9.2 to 15.2 t/ha (Binder et al. 2008; B. Zhao et al. 2010; Chen et al. 2011; Hou et al. 2012), giving a **mean PY of 11.4 t/ha**. This average may be distorted by the inadequately described results of Chen et al. (2011)—13.0 t/ha from integrated soil–crop management experiments and 15.2 t/ha from high-yield experiments. For **summer maize**, approximate mean experimental PY values are lower, with a smaller range; an **average PY of 9.1 t/ha** is derived from a range of 6.0–10.7 t/ha (Binder et al. 2008; B. Zhao et al. 2010; Liang et al. 2011; T. Wang et al. 2011; S. Zhang et al. 2011).

These estimates of PY for spring and summer maize are used in Figure 5.2 to represent PY of hybrids released in 2001, along with the rates of PY progress reported above. Assuming China plants 64% spring maize and 36% summer maize, the **2001 weighted whole-of-China PY is ~10.4 t/ha** and the **yield gap was therefore almost 100% of FY**, and has likely little changed since then.

It is noteworthy that these estimates of spring maize PY are significantly less than for maize in the US Corn Belt (15 t/ha, see Section 5.2). Besides the lower yield of Chinese hybrids (Box 5.2), their climates also differ significantly (Box 5.3) such that lower PY in China could be partly explained by lower solar radiation. Even so, some argue that in China hidden water stress in spring-sown crops and small farm plots sizes have unwittingly reduced PY estimates from spring sowings (W. Liang, pers. comm. 2012), including those from the high-yield experiments reported above by Chen et al. (2011).

Box 5.3 Boosting maize potential yield (PY) in the North China Plain through planting date and hybrid maturity

Recent simulation studies by Chen et al. (2011) for north-western and north-eastern China, and the North China Plain (NCP), have shown considerable opportunity for greater maize yields through changes in planting date, hybrid maturity and fertiliser management. The studies identified the key technologies to be:

- use of modern maize germplasm planted as a sole crop at densities of ~90,000 plants/ha
- limited but balanced supply of nitrogen throughout the season
- delayed plantings of later maturing high PY hybrids.

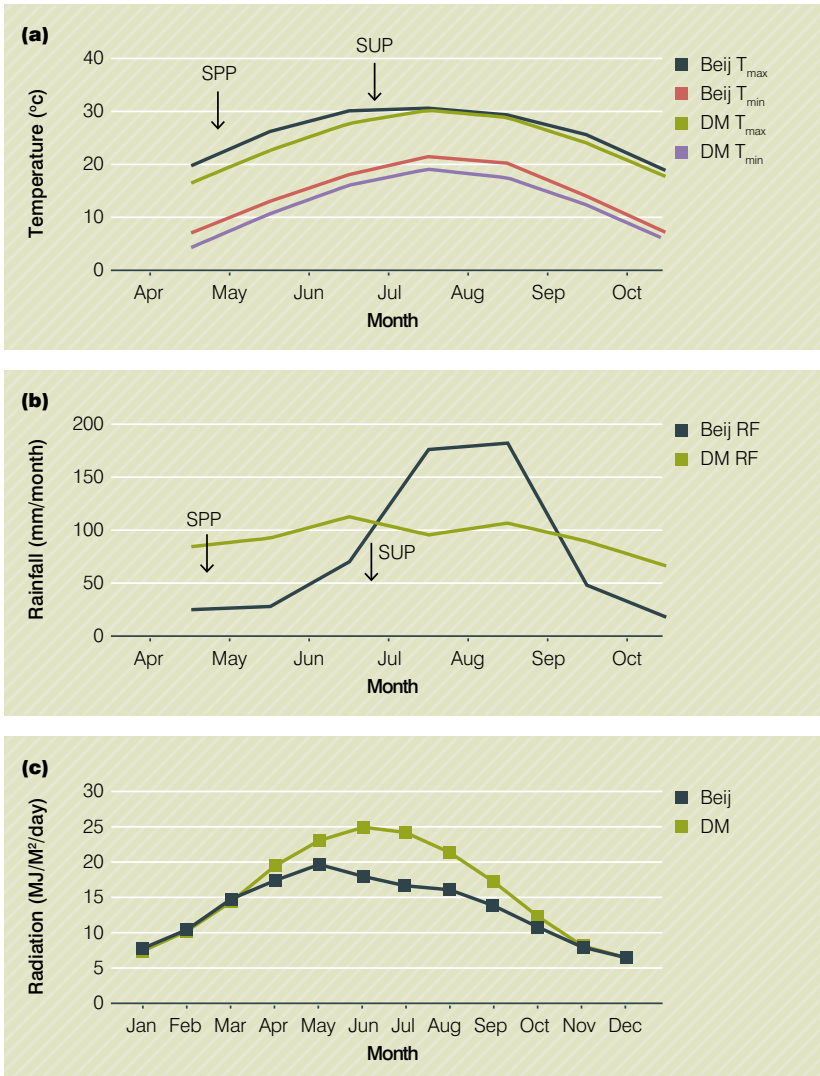
Chen et al. (2011) used the Hybrid-Maize simulation model from Nebraska, USA, to guide nitrogen management. Through 66 field trials, Chen and colleagues verified that PY levels of 13 t/ha can be obtained for spring and summer maize. The field trial PY levels were 90% greater and used 8% less nitrogen fertiliser than yields obtained under current farmer practices, and also used only one-third of the level of nitrogen applied to conventional high-yielding plots, which averaged 15 t/ha.

A surprising finding by simulation was the benefit of planting longer duration hybrids in summer (vs. spring planting). In this way, higher summer temperatures and drought prior to the onset of the rains (see box figure) no longer coincide with flowering, and grain-filling occurs during cooler autumn conditions. However, Chen et al. (2011) apparently did not consider increased risk of early frost during grain-filling and the cost to succeeding wheat crops when late maize harvests delay wheat planting. Maize planting delays of this magnitude (from spring to summer) are usually associated with losses of up to 50% of PY at similar latitudes in the USA (Lauer et al. 1999).

The box figure clearly shows that despite similar latitudes, there are climatic differences between key maize locations in the Corn Belt of USA and the NCP of China—especially in patterns of monthly rainfall and solar radiation, reflecting the monsoonal aspects of the NCP summer—and therefore the results of simulation modelling need to be interpreted cautiously.

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Comparison of (a) monthly means for maximum (T_{max}) and minimum (T_{min}) daily temperatures, (b) monthly rainfall and (c) daily solar radiation during the crop season for Beijing (Beij), North China Plain (39.9 °N) and Des Moines (DM), Iowa, Corn Belt, USA (41.6 °N). SPP = spring planting date, Beijing and Des Moines; SUP = summer planting date, Beijing. Source: World Meteorological Organization (2012)

Farm yield constraints for maize in northern China and closing the yield gap

A broad survey of farmer practices throughout China in 2001–02 (Meng et al. 2006) identified that yield gaps were due to:

- drought—inadequate irrigation water and/or declining watertables
- labour shortages
- lack of head smut resistance
- lodging
- low soil fertility—arising through delayed or insufficient fertiliser application, and/or reduced use of organic fertiliser (manure or compost)
- poor seed quality
- poor weed control.

Drought was consistently identified as the key abiotic constraint, followed by early frost in north-eastern China. In all regions, other issues included quality of inputs (i.e. fertiliser, pesticides and seeds) and the lack of extension information for crop management. Other surveys, such as that reported by Liang et al. (2011) for a part of the province of Hebei in the NCP, suggest that yield gaps in summer maize relate to:

- delayed planting
- unbalanced and inadequate fertilisation (though the average of 200 kg N/ha on summer maize appears excessive)
- low plant density
- premature harvest
- challenges of managing very small fields.

Notwithstanding the above survey results, it is now widely recognised that excessive amounts of nitrogen—fuelled by cheap and plentiful chemical supplies—were applied to maize in China in the 1990s and early 2000s. As a result large amounts of nitrogen were leached below the root zone of maize crops (Zhao et al. 2006). In a survey of farmer practices across the three temperate maize regions above, Chen et al. (2011) reported average nitrogen application rates of 257 kg N/ha, well above the average of 160 kg N/ha used in Iowa, USA.

With such high nitrogen rates, it is not surprising that recovery of nitrogen by crops is less than 30% of that applied (Ju et al. 2009). Nitrogen use efficiency (NUE) values for high-yielding maize in China can be as low as 21 kg grain produced per kilogram of nitrogen applied (Chen et al. 2011) and the national average is only 29 kg grain/kg N (Table 11.1). This low NUE is in stark contrast to the US average of 60 kg grain/kg N (Table 11.1). Excess nitrogen application has resulted in a significant degree of soil acidification (Guo et al. 2010) while leaching of excess nitrogen has contributed to eutrophication of several large lakes in China.

Many of the FY constraints listed above can be overcome with improved agronomic practice. Chen et al. (2011) applied integrated crop and soil management to 66 sites distributed across the temperate maize area of China (Box 5.3), whereby amounts and timing of nitrogen application were better matched to crop needs. The study reported no obvious water stress and an average PY of 13 t/ha for an unspecified mix of spring and summer maize sites; this is almost double farmer yields from a nitrogen input of 237 kg N/ha. Needless to say, NUE was improved greatly, reaching 57 kg grain/kg N compared to just 21 kg grain/kg N achieved in the farmer survey. This confirms earlier results of Zhao et al. (2006) who showed little yield loss when nitrogen, applied over 8 years to a winter wheat – summer maize rotation, was substantially reduced from 300 kg/ha/yr to ~90 kg/ha/yr.

Plant densities for maize in China are still relatively low, although during the 1990s densities increased to ~55,000 plants/ha for spring maize, and to 56,000–65,000 plants/ha for summer maize (H. Wang et al. 2009; Liang et al. 2011). Lower densities partly reflect the legacy of intercropping and hand harvesting—and perhaps, also partly, limited water supply (in some places) and lodging risk. These densities are probably optimal for the current suite of hybrids, and where adequate farm labour remains available.

Lack of water is a special constraint in Chinese temperate maize systems, particularly the northern NCP and non-irrigated parts of north-western China (MME8). Water requirement for the irrigated wheat–maize system in northern NCP is 870 mm per year, whereas annual rainfall is <570 mm (Zhang et al. 2006). Thus water constraints are increasing because of dependency on groundwater, with groundwater levels falling rapidly (see also Section 11.5). In addition, competing industrial demands for water are increasing rapidly (H. Wang et al. 2009). As irrigation water becomes scarcer, some researchers are contemplating replacing wheat–maize with spring maize alone and delaying maize planting sufficiently to reduce risk of early dry spells and/or heat at silking.

Improved hybrids and better agronomy may have helped improve WUE. For example, X. Zhang et al. (2011) reported that between 1980 and 2010, improved hybrids and better management raised WUE by 73% for summer maize at a site in the NCP (see Figure 11.1). Potential evapotranspiration also increased, but only from 366 mm to 403 mm. Plastic inter-row mulching is one practice shown to improve spring maize yield in MME8. In north-western China (dry, rainfed, high elevation and Loess soils) in 2002, ~22% of maize was grown with plastic inter-row mulching (Fan et al. 2005). For maize, plastic—which is usually applied in autumn to 80–90% of the ground surface—captures and directs precipitation to future planting furrows, reduces soil evaporation and weed growth, and warms the soil in spring. Consequently, large yield increases can be obtained especially when the extra soil moisture obviates stress at critical stages (Fan et al. 2005; Zhou et al. 2009).

Studies of plastic inter-row mulching report that WUE averaged 31 kg grain per mm rainfall over 12 consecutive years in the high semi-arid Loess Plateau of Gansu

(<400 mm annual rainfall) (T. Fan, pers. comm. 2011). There, plastic inter-row mulching dramatically and reliability improved maize production while results in a wetter, double-crop maize–wheat system were less spectacular. In a 6-year study conducted in the province of Shaanxi (to the south-west of the NCP), Zhou et al. (2011) showed that WUE increased by only 27% while wheat straw mulch alone increased WUE by 22%. The long-term prospects of plastic inter-row mulching are unclear and depend on more research.

Meanwhile, zero-till—which has not yet been widely adopted in China—could facilitate straw retention. Combined with raised beds and controlled traffic (wheels in furrows only) zero-till offers further scope for improved WUE and yield. Managing quantities of crop residue—which can annually exceed 17 t/ha in double-cropped areas of the NCP—requires skill, and probably further research (Liang et al. 2011). Residue retention associated with zero-till cools the soil in spring which, depending on the exact location, can negate the advantage of better water storage with residue (X. Wang et al. 2011). Finally, reduced tillage may also help avoid a recently identified constraint—the presence of soil hardpans (at ~20 cm from the soil surface) that restrict maize root depth (S. Zhang, pers. comm. 2011). The cause, it seems, is extensive use of two-wheel tractors and rotary cultivators.

Physiology of potential yield progress for maize in China

Y. Li et al. (2011) studied morphological changes in Chinese hybrids released since 1960. They reported the following changes:

- increased height and later maturity
- larger tassels and ears
- more upright leaves
- fewer barren plants
- more grains per ear
- greater weight per grain.

These changes have been confirmed by Ci et al. (2012) who also found no significant changes in anthesis-to-silking interval (ASI) or HI. By comparison, US hybrids had not changed in maturity, and were slightly shorter, with smaller tassels and fewer grains per ear (Duvick 2005a). Several key traits such as staygreen and stalk lodging were not reported in the above Chinese studies, though in a similar study of six Chinese hybrids from vintage series, Ding et al. (2005) noted that foliar senescence of older hybrids during grain-filling was more rapid than in recent hybrids. The light saturated rate of photosynthesis of the newer hybrids was not always higher than that of the older ones, but declined less rapidly with time.

These unique changes in Chinese hybrids toward taller and slightly later plants may reflect less selection pressure under high density and moisture stress, and a greater emphasis on individual plant performance in a farming system where most maize is still hand harvested.

Conclusion for maize in China

The annual rate of 0.7% FY improvement in maize yields in China since 1990 has been disappointing. While input use is high, FY at 5.4 t/ha remains low relative to reasonably comparable temperate environments in the USA and Europe. Low FY can be attributed to:

- policy changes leading to a loss of production incentives
- numerous gaps in crop agronomy and poor extension services
- apparently modest breeding gains at high plant density
- 40% of maize planted in the summer, rather than spring.

The estimates given for PY are approximately twice that of FY, leaving a yield gap of 100%, and thus gap-closing agronomy could be an effective strategy for improving maize FY over coming decades. Field studies and modelling by Chen et al. (2011) and Liang et al. (2011) have shown that careful crop management can increase yield substantially, but this requires changes that may be too complex for smallholder farmers. Also, there is probably less opportunity for yield gain when these changes are incorporated into multiple cropping systems that produce around half of China's maize. Water is becoming increasingly scarce in the NCP, so that WUE is a special target for improved crop management.

The modest increases in PY achieved recently in China suggest great benefit could be obtained from an infusion of stress-tolerant, elite temperate germplasm from the USA and Europe, together with appropriate modern selection strategies. There appears to be good scope for achieving higher PY in China by further exploitation of the genotype-by-density interaction. This should also lead to better drought tolerance, as seen elsewhere, and facilitate breeding of varieties suited to machine harvesting (an inevitable and imminent development).

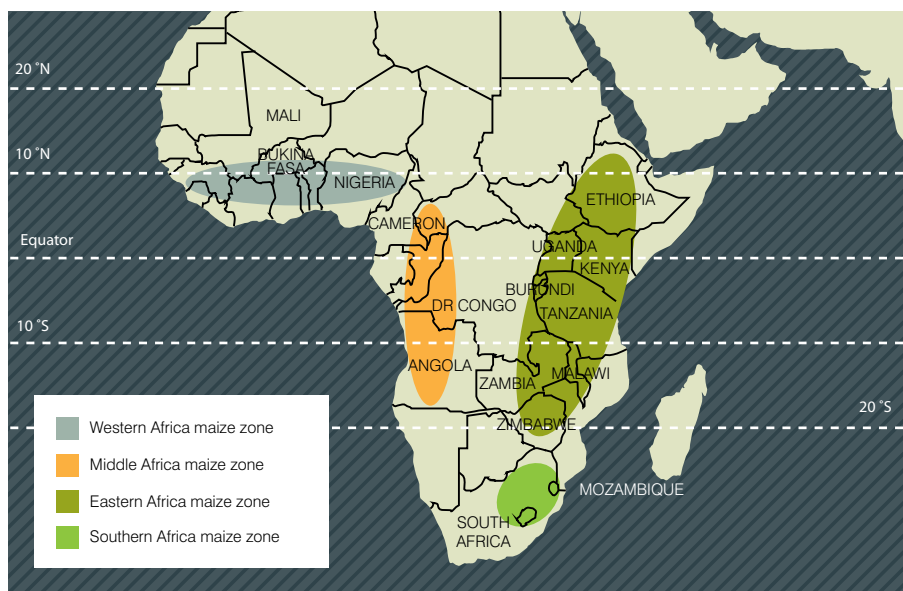
There is no GE maize grown commercially in China, although several minor GE food crops (papaya, tomato and capsicum) are grown (James 2012). This reflects a notable hesitancy of the Chinese Government to release GE versions of staple crops, even when the crop is primarily for feed (as with maize). However, in 2009 China did approve the extensive testing of phytase maize, which has a novel trait that allows pigs to digest more of the maize grain's phosphorus, at the same time reducing phosphorus pollution from animal waste (James 2012). China has over 500 M pigs.

5.4 MME1–6—Maize, a staple food crop in Sub-Saharan Africa

Introduction to maize in Sub-Saharan Africa

Sub-Saharan Africa (SSA) is that part of the continent south of the Sahara Desert, producing 53 Mt of maize annually in 2008–10 (Table 5.1). It is, however, a very diverse region divided by the Food and Agriculture Organization (FAO) into four subregions whose major maize producing countries are listed in Table 5.5 (see also Map 5.4). Maize is a staple food for many areas in eastern and southern Africa, and, while less important in western and middle Africa, it also remains a strategically important food source for those subregions. At present, maize area is increasing in eastern (2.0% p.a.) and middle Africa (1.9% p.a.), steady in western Africa and declining in South Africa (–3.4% p.a.).

Kenya provides a focus for this section because it offers the best documented maize production system in eastern Africa. However, examples are also drawn from several other countries in SSA. Of these, South Africa is the largest maize producer—and dominates production statistics (Table 5.5)—but because it is distinct by its being dominated by a large farm sector it has been excluded from much of the discussion.



Map 5.4 Major maize-growing regions of Sub-Saharan Africa. Note: Zoning is according to FAO; for countries within each zone see Table 5.5.

Table 5.5 Annual production, harvested area and farm yield (FY) data for maize in 2008–10 in selected countries in Sub-Saharan Africa, and change in FY from 1991 to 2010, together with fertiliser applications to cropland

Country or region	Average 2008–10		Farm yield (FY)			Nutrients applied ^a (kg/ha/yr)	
	Production (Mt)	Area (Mha)	Average 2008–10 (t/ha)	Gain per year 1991–2010			
				(kg/ha)	(% of 2008–10)		
Kenya	2.8	1.9	1.5	ns –9	–0.6	13	27
Malawi	3.2	1.6	2.0	*47	2.4	23	29
Tanzania	4.5	3.3	1.3	ns –5	–0.4	48	5
Eastern Africa ^b	21.9	14.3	1.5	ns 13	0.8	10	10
Nigeria	7.5	3.8	2.0	***46	2.3	15	3
Ghana	1.7	0.9	1.8	***16	0.9	8	5
Western Africa ^c	14.7	8.3	1.8	***33	1.9	13	3
Cameroon	1.6	0.8	2.0	**31	1.6	19	8
DR Congo ^d	1.2	1.5	0.8	nd	nd	nd	1
Middle Africa ^e	4.0	4.0	1.0	***12	1.2	10	3
South Africa ^f	12.5	2.7	4.7	***142	3.0	23	116

*** $P < 0.01$, ** $0.01 < P < 0.05$, * $0.05 < P < 0.10$, ns = $P > 0.10$

- a Ratio of nutrients applied (elemental nitrogen, phosphorus and potassium) to total cultivated area
- b Eastern Africa incorporates Burundi, Ethiopia, Kenya, Madagascar, Malawi, Mozambique, Rwanda, Somalia, Uganda, Tanzania, Zambia and Zimbabwe, each growing >0.1 Mt of maize annually
- c Western Africa incorporates Benin, Burkina Faso, Côte d'Ivoire, Ghana, Guinea, Liberia, Mali, Nigeria, Senegal and Togo, each growing >0.1 Mt of maize annually
- d nd = no reliable long-term data
- e Middle Africa incorporates Angola, Cameroon, Chad, Central African Republic, Democratic Republic of Congo (DR Congo), each growing >0.1 Mt of maize annually
- f South Africa produces 98% of the maize in southern Africa; the other members of this region are Botswana, Lesotho, Namibia and Swaziland

Source: FAOSTAT (2013)

Smale et al. (2011) recently provided a broad overview of maize and the evolving policy framework in SSA, a subject that receives much critical attention for significant reasons including:

- declining food supply per capita
- rapid regional rate of population increase
- low maize yields that average 25–50% of global yields
- slow FY progress especially in key eastern countries (such as Kenya and Tanzania).

Kenya, Malawi and Tanzania together produce ~50% of eastern African maize (Table 5.5). Maize is the dominant food crop there and occupies 56% of cropped area. Almost 75% of Kenya's maize is grown in mid-altitude and highland zones between 1,100 and 2,900 masl (Hassan 1998), where the lower fringes are constantly subjected to drought. Maize-growing ecologies in Tanzania and Malawi follow a similar pattern to Kenya. The common mega-environments represented are MME1 (highland tropical), MME2 (wet upper mid-altitude subtropical), MME3 (wet lower mid-altitude subtropical) and MME4 (dry mid-altitude subtropical) (Table 5.2).

In the mid-altitude zones of these three countries an estimated 40% of area receives >600 mm annual rainfall and 60% qualifies as dry (Bänziger et al. 2006). SSA, and especially eastern and southern Africa, clearly experience more yield loss in maize due to lack of water than any other major growing region around the world (Heisey and Edmeades 1999). The variability in seasonal rainfall results in a high inter-annual coefficient of variation of yields, reaching 48% in Tanzania in eastern African, compared with lower values elsewhere (Table 5.5).

FY progress in SSA has been generally disappointing. As a whole, eastern Africa shows no significant yield progress; neither do Tanzania and Kenya (Table 5.5). An exception to this is Malawi, where, despite challenging climatic conditions, mean FY has increased by 47 kg/ha/yr, or 2.4 % of the 2008–10 FY of 2.0 t/ha (Table 5.5). FY has increased in Malawi in recent years largely because of rapid uptake of subsidised seed and fertiliser. The rate nutrients are applied per hectare of arable land in Malawi is five times greater than Tanzania, and a bit less than 10 times greater than the average for middle Africa (Table 5.5).

Western Africa is dominated by lowland tropical MME5 (wet) and MME6 (dry), and shows significant yield increase of 33 kg/ha/yr, or 1.9% p.a. of the 2008–10 FY of 1.8 t/ha (Table 5.5). Nigeria is the dominant western African producer and the host country for the International Institute for Tropical Agriculture (IITA), which works on maize improvement at a regional level.

Causes of low maize yields in Sub-Saharan Africa

Surveys of expert opinion regarding maize yield constraints in SSA (Gibbon et al. 2007) have identified several major factors leading to low yields (Figure 5.3). The main

agronomic factors responsible for yield reduction are soil constraints (44% of losses), weeds (19%) including *Striga* spp., and drought (18%). The widespread practice of intercropping further reduces maize yields, although the practice offers an opportunity to boost overall farm output, and adds needed diversity to farmers' fields.

Cropland soil fertility is low in much of SSA. While annual application of elemental nitrogen, phosphorus and potassium (NPK) fertiliser to arable and permanent crops is greatest in South Africa, Kenya and Malawi (Table 5.5), it remains well below world average (50 kg NPK/ha) and far short of the Asian average (157 kg NPK/ha). Low output is, of course, the primary consequence of low-input farming systems, but (importantly) a subsequent effect is the ongoing net loss of soil nutrients, and this is the case for many SSA farming systems (see Box 5.4). It is therefore not surprising that a study of yield gaps in SSA has shown that a smaller gap is associated with good market access because it facilitates higher use of fertiliser (van Dijk et al. 2012).

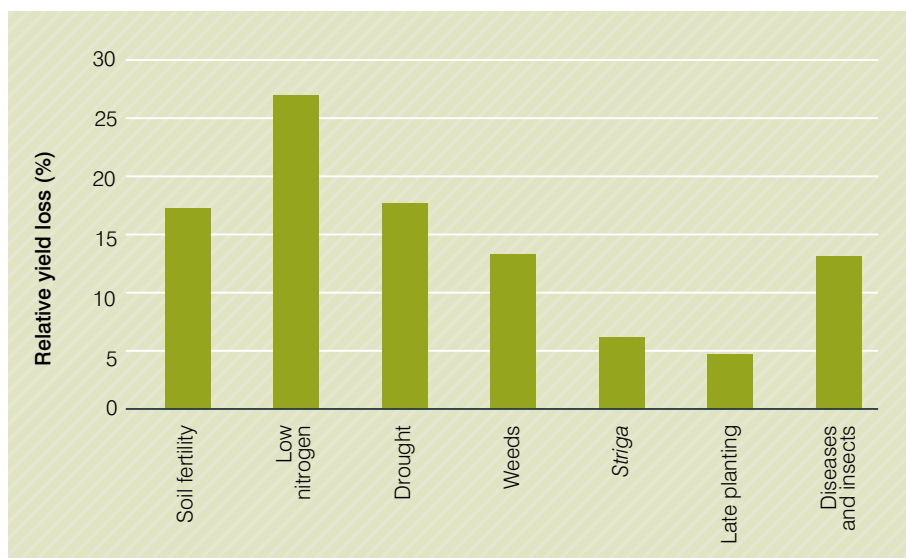


Figure 5.3 Relative yield losses from agronomic causes in maize crops in Sub-Saharan Africa. Soil fertility includes low soil organic matter, deficiencies in zinc, phosphorus and potassium, and soil acidity, but not low nitrogen status. Source: based on Gibbon et al. (2007)

Three other constraints—drought, weeds and scarce use of improved varieties—directly affect yield and (hence) rates of fertiliser application and efficiency. For example, in eastern Kenya and southern Zimbabwe, under the driest growing conditions, water stress causes a crop failure for 1 in every 3 years, and the declining levels of soil organic matter further reduce soil water-holding capacity.

Box 5.4 Africa's negative soil nutrient balance

Because fertiliser application rates are low in Sub-Saharan Africa (SSA), annual net losses of major soil nutrients—elemental nitrogen, phosphorus and potassium (NPK)—may reach >4 Mt. These losses equal 30–60 kg NPK/ha/yr on 45% of cropped land, and exceed 60 kg NPK/ha/yr on a further 40% (Henao and Baanante 2006; Craswell and Vlek 2013). Low rates of NPK addition have been accompanied by a sharp reduction in the length of the traditional fallow periods between crops when some nutrient recovery can be expected. Furthermore, there has been a steady loss of soil organic carbon because low-yielding crops return very small amounts of residue, and what remains is often burned or grazed. This results in severe soil degradation.

Key factors affecting low usage of fertiliser in SSA are high farm-gate prices (reflecting low traded volumes), poor infrastructure and an inadequate distribution network. Use of fertiliser is further limited by the perceived high risk (associated with both production and price) of uneconomic returns due to drought, untimely availability of inputs and/or weak markets. Farm-gate fertiliser prices are often double those in other developing regions, and 4–6 times those seen in developed countries (Morris et al. 2007). However, cost-effectiveness for fertiliser is 6–10 times greater than the cost of food-aid maize delivered to the farm gate (Sanchez et al. 2009).

Biological responses to added nitrogen and phosphorus for maize in SSA are generally similar to those reported elsewhere. Responses to microdosing have been especially promising, giving values for nitrogen use efficiency (NUE) of 15–45 kg grain/kg N even under quite dry conditions (Twomlow et al. 2010). Because base-level soil fertility in SSA is so low, responses to fertiliser will often extend to higher levels of application—a contrast to South America and Asia, where responses plateau at comparably lower application rates. However, lower than expected (or even nil) responses to fertiliser have also been reported in some areas with low yields; this is usually where soil carbon levels have fallen to below 0.5% (Nziguheba et al. 2010). In such instances, NUE values were as low as 5 kg grain/kg N (Zingore et al. 2007), because other aspects of the degradation syndrome limit responses.

For example, low responses to NPK can also indicate undiagnosed micronutrient deficiencies, because these elements are often strongly associated with the soil organic matter fraction, or soil pathogens (N. Sanginga, pers. comm. 2012). Recent research has highlighted the possibility for organic fertilisers to restore carbon inputs to the soil, but more realistically a substantial increase in use of inorganic fertiliser is also urgently needed to boost soil carbon through added biomass (Tittonell et al. 2008b; Chivenge et al. 2011). While the degraded fertility of SSA soils can be restored, it will be a difficult and expensive process.

Weeds are a major source of yield loss. Farmers commonly respond to low soil fertility by planting a large area. However, this tactic often exceeds weed management capacity, given that limited use of herbicide makes weeding very labour intensive. Of special significance is the parasitic weed, *Striga*, which reduces maize yields in fields with low fertility, both in the mid altitudes of eastern Africa and in the savannas of western Africa. Its incidence is closely linked to a decline in soil fertility, so addition of nitrogen fertiliser will often allow crops to overcome the effects of the parasite (Ransom et al. 2007).

The third constraint—lack of adoption of improved varieties and hybrids—varies greatly in SSA. In eastern Africa, estimated use of improved germplasm over the total area sown in 2006–07 was 72% for Kenya, 22% for Malawi and 18% for Tanzania (Langyintuo et al. 2010). Despite all the other constraints, there is useful scope for yield increases in the region through greater deployment of improved varieties (see below). The major constraint to adoption of improved germplasm is the unavailability of seed for well-tested hybrids and OPVs adapted to the agroecologies of SSA. Availability reflects both weakness of the seed sector and inadequacy of the testing and release mechanisms that are a characteristic of many countries in SSA.

Maize breeding in Sub-Saharan Africa

Maize breeding has a relatively long history in SSA. Maize came to coastal Africa from the Americas about 500 years ago, and was quickly adopted, especially in southern and eastern parts of the continent. Concerted breeding efforts were launched in a number of countries, leading to release in 1960 of the world's first commercial single-cross hybrid, SR52, in Zimbabwe. A further key development was discovery in Kenya of two natural heterotic groups (see Box 5.1) formed by: (1) a local, large, white-grained synthetic cultivar, Kitale II; and (2) a landrace, Ecuador 573, which was introduced from South America to Kenya in 1959. This heterotic pattern still forms the basis of most Kenyan commercial maize breeding programs.

Today maize breeding is jointly undertaken by national research programs, international agricultural research centres and the commercial sector. Much of the improved lowland tropical maize germplasm used in SSA (and suited to MME5 and MME6) originates from IITA in Nigeria. CIMMYT conducts breeding programs in Kenya, Zimbabwe and Ethiopia, and supplies much of the mid-altitude tropical germplasm suited to MME1–4. Hybrids comprise more than 90% of all improved maize seed currently sold (Langyintuo et al. 2010), although planting of F2 hybrid seed (the first progeny of hybrid seed) by farmers can reach 50% in drought-prone areas.

Multinational and regional seed companies are active in eastern Africa, especially in Kenya and Malawi. Maize breeding programs in Kenya are the strongest of any country in eastern Africa, in particular that of the parastatal Kenya Seed Company, which markets its hybrids in neighbouring countries. Headquartered in Zimbabwe,

the regional seed company SeedCo operates in 13 African countries, and is probably the largest private sector seed producer in SSA. In Tanzania, weak infrastructure and a difficult commercial environment have slowed development of the private seed sector, and seed availability for stress-tolerant hybrids and OPVs continues to constrain production. Release procedures, once slow and cumbersome, have improved throughout this region in recent years.

In western Africa the private seed sector is in its infancy though growing rapidly. Improved seed is still largely the domain of parastatals and government institutions, except in Nigeria where hybrids marketed by private companies are being steadily adopted.

An increasing (and very appropriate) emphasis in breeding led by CIMMYT and IITA—and supported by the Bill and Melinda Gates Foundation—has been to improve tolerance to drought and low nitrogen of hybrids and OPVs adapted to the broad agroecologies of SSA. Improvement in heat tolerance may also be critically important in the future. In a large recent study of trends in yields of ~1,000 maize variety trials across SSA, Lobell et al. (2011a) estimated that yield fell by 1% for every day spent above 30 °C, and that this increased to 1.7% per day if the crop was under drought. Fortunately, good genetic material for drought and heat tolerance is available for maize, and selection using new genomics tools could provide varieties at a pace that will match or exceed the changing thermal and rainfall environment (Cairns et al. 2012). However, the recent recognition that drought and heat tolerance are genetically independent in maize (at least in the eastern African environment) will inevitably slow this breeding progress (Cairns et al. 2013).

The projected introduction of hybrids that have been genetically engineered for improved drought and insect resistance—made available on a royalty-free basis to Kenya, Uganda, Tanzania and Mozambique through the Water Efficient Maize for Africa (WEMA) Project that links Monsanto, CIMMYT and the Bill and Melinda Gates Foundation—could provide an exciting technology choice for SSA's resource-poor farmers. GE varieties (for both insect and herbicide resistance) have already been deployed commercially in South Africa over the past decade, and there is a considerable and increasing demand for such products, with no evidence of risk to human health as they have entered the food chain. As in the USA, development of insect resistance to *Bacillus thuringiensis* (*Bt*) toxins in South African maize threatens earlier gains from this technology and requires careful management.

Potential yield for maize in Sub-Saharan Africa

We might easily question whether low maize FY in SSA reflects low PY for the region. Where soils have been severely degraded by loss of soil organic carbon, erosion, acidification and/or compaction, PY results are less than might expected based on the temperature and rainfall regime. In general, however, PY of maize in SSA adheres to the estimates of Muchow et al. (1990) shown in Table 5.2.

More than 40 years ago, yields > 12 t/ha were reported for the hybrid cultivar SR52 grown under good rainfall at 1,600 masl near Harare, Zimbabwe (Allison 1969). Since then, PY values of 5–14 t/ha have commonly been reported for individual trials in the higher rainfall areas at 1,200–1,800 masl in eastern Africa. Considering the results of hundreds of recent variety trials in this zone conducted under optimal conditions (Dhliwayo et al. 2009; MIG 2011; Weber et al. 2012; S. Mugo, pers. comm. 2011; A. Tarakegne, pers. comm. 2011), a weighted mean PY for 2006 hybrid varieties is calculated to be **6.1 t/ha** (early-maturing) **and 7.1 t/ha** (later maturing). This is a conservative estimate since PY of individual hybrids or specific environments can exceed these values in any trial by 50–75%. It is useful to note that Singh et al. (2009) report simulated PY (under no water or nitrogen limitations) in the range 6.1–7.3 t/ha for early-maturing varieties in eastern mid-altitude Kenya.

The PY values reported in the lowland tropics of coastal areas of eastern and western Africa (MME5) are about 25% lower than the values above, at **4.4 t/ha** (for early-maturing varieties) **and 5.3 t/ha** (late varieties) (Badu-Apraku et al. 2011; A. Menkir, pers. comm. 2011) but these results refer to OPVs. It is likely that hybrids grown in these areas approach the PY values of mid-elevation eastern Africa (Dhliwayo et al. 2009).

Water-limited PY (PY_w) is difficult to estimate since maize is grown across a spectrum of water stresses within MME4 and MME6. However, PY_w is thought to range from 20% to 80% of PY.

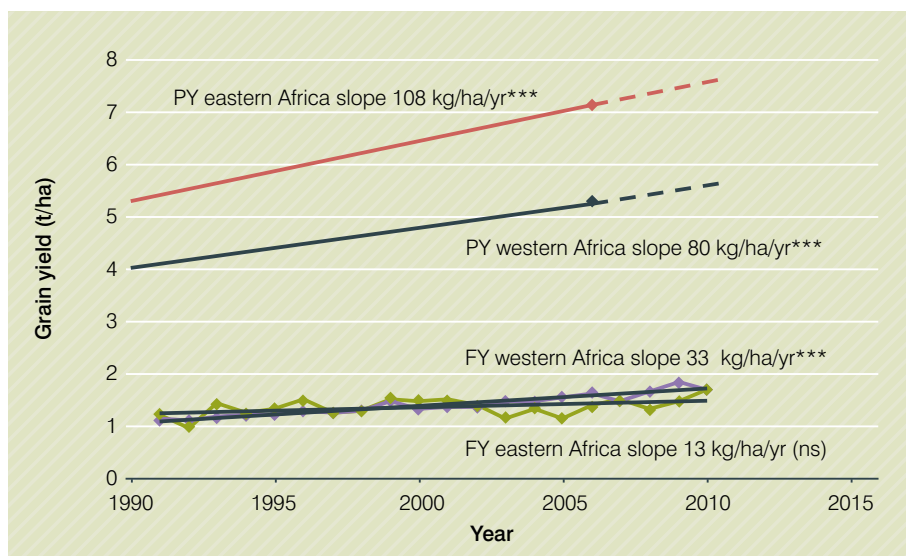
Under prevailing circumstances in Africa, a more universal situation is nitrogen-limited yield caused by chronic soil infertility, regardless of water supply. Although absolute crop failures almost never occur under low fertility, FY is commonly reduced to ~40% of PY. In one recent report, based on 137 variety trials conducted in southern Africa, random stresses (thought to be mainly water and fertility factors) reduced average FY of hybrid trials to 1.8 t/ha, which was just 30% of PY (Weber et al. 2012). Thus breeding for 'potential yield' under limited soil nitrogen can be a worthwhile activity (see below).

Published estimates of increases in PY due to breeding programs in SSA are scarce, and estimates rely mainly on those generated internally within projects such as the Drought Tolerant Maize for Africa (DTMA) Project—a collaboration between CIMMYT, IITA and African national maize programs. Under DTMA, a PY of 128 kg/ha/yr (1.4% p.a.) has been estimated from regional hybrid yields from 9 years of regional trial means for early-maturing germplasm evaluated under optimal conditions (A. Tarakegne, pers. comm. 2011). A second less rigorous estimate by DTMA staff over a shorter period in similar germplasm suggest improvements of ~2.4% p.a. (C. Magorokosho, pers. comm. 2011).

In germplasm for lowlands in western Africa, Kamara et al. (2004) reported PY increases of 0.4% p.a. in early OPVs suited to the Sudan savanna vegetation zone and released over the 1970–99 period. Omoigui et al. (2006) reported a gain of 1.4% p.a. from recurrent selection in late-maturing germplasm. Although these are scattered assessments, together they point to a strong rate of **annual PY progress estimated**

here to average $\sim 1.5\%$ p.a. relative to the above estimated 2006 PY of ~ 7.1 t/ha in the mid-altitude zones of eastern Africa, and 5.3 t/ha in western Africa, giving PY progress of 108 and 80 kg/ha/yr, respectively.

These PY values and trends are shown in Figure 5.4 in relation to reported FY values. It is clear that the yield gap in SSA is huge, and apparently widening. For example, in 1990 the yield gap in eastern Africa was 294% of FY and by 2007–09 may have increased to 422% of FY. Yield gaps of 600% of FY were estimated from simulations of PY_w under high-input technologies in drought-prone eastern Kenya (Singh et al. 2009). In western Africa, on the other hand, the gap may have remained relatively constant, changing from 200% of FY in 1990 to 218% of FY in 2007–09.



ns = $P > 0.10$, *** $P < 0.01$

Figure 5.4 Farm yield (FY) for maize in Africa plotted against year, and potential yield (PY) plotted against year of release, from 1991 to 2010. PY progress is based on a 1.5% p.a. increase determined in 2006 vintage hybrids in eastern African mid-altitude zones and western Africa lowland tropics (see text). Source: FY from FAOSTAT (2013)

Closing the maize yield gap in Sub-Saharan Africa

The data shown in Figure 5.4 make it clear that gap closing is a significantly greater priority for SSA than increasing PY. Similarly the data endorse the current breeding strategy, which targets gap closing through improving traits for tolerance to low fertility, drought and *Striga*. While genetic improvements in maize will go some way to improving

yields under low nitrogen, or stabilising yield under variable water stress, genetic improvement will certainly not eliminate the need for adequate crop management.

Unfortunately, a number of current risk management practices of small-scale farmers effectively reduce maize yields at the farm level. For example, intercropping is widely practised in SSA and may account for 25% of the yield gap between FY and simulated or experiment station yields (Kibaara et al. 2008). As the popularity of commercial maize has risen, however, the prevalence of intercropping has declined, but it will remain an important risk avoidance strategy for small-scale farmers in SSA in the foreseeable future and cannot be overlooked.

Four important interventions can both stabilise and increase maize yields—three agronomic and one genetic. **Management of soil fertility is clearly the first major step** in closing the yield gap; for example Keating et al. (2010) describe the soil fertility constraint as 'overwhelming'. Judicious use of small amounts of inorganic fertiliser, along with organic sources of nutrients, has the greatest likelihood of success (Tittonell et al. 2008a,b; Keating et al. 2010; Twomlow et al. 2010). This depends on making fertiliser available on farms at the optimal time for application—something that does not occur often in SSA.

The order of importance of limiting nutrients is often nitrogen, followed by phosphorus and zinc, then potassium followed by sulfur, and finally micronutrients. Zinc deficiencies are widespread in heavily cropped western African savanna soils, where soil organic carbon commonly falls below 0.5%. Organic interventions usually revolve around rotations with legumes, although the economics and practicality of doing so at the farm level are too often countered by the need to provide an edible legume grain for home consumption and forage for animals.

A recent large farmer participatory study in Malawi (eastern Africa) showed increased yield stability and profitability when modest fertiliser use (35 kg N/ha) on maize was coupled with either semi-perennial pigeon pea as an intercrop, or either pigeon pea or *Mucuna pruriens* in a two-season rotation (Snapp et al. 2010). These rotations doubled returns to maize, with good weed suppressing legumes providing 60–80 kg N/ha through nitrogen fixation. These rotations were also preferred by farmers, although the presence of bitter tannins in *Mucuna* seed mean it is rarely used for food.

Several other studies (on less extensive scales) have shown similar benefits to farmer income from improved crop nutrition in countries considered by the Millennium Villages Project (principally Kenya, Tanzania, Ethiopia, Malawi, Nigeria and Ghana; Sanchez et al. 2009; Nziguheba et al. 2010) or the Sasakawa Global 2000 (SG2000) Project (Ethiopia and Mozambique; Howard et al. 2003). In both projects an assured supply of fertiliser was made available to small-scale farmers, implying some level of subsidy. However, some soils are now so degraded that rehabilitation will be more complex and slower (Tittonell et al. 2008b).

One well-publicised but complex alternative to standard soil fertility treatment is adopting agroforestry, or 'fertiliser trees'. Box 11.3 (see Chapter 11) discusses one

such tree, *Faidherbia albida*, which is grown to fix nitrogen and recycle nutrients through leaf litter while competing only minimally with the understory of maize in nutrient-poor situations (Garrity et al. 2010).

Improvements in crop water supply and erosion control through better rainfall infiltration, reduced run-off and reduced evaporation with **conservation agriculture (CA)** provide a second major agronomic step toward closing the yield gap by tackling another major group of production constraints. Conservation agriculture is being promoted through a number of large projects in eastern Africa, but is not without its critics. For example, Giller et al. (2009) point out that—in the absence of herbicides—weeds may overwhelm plots and require additional labour to control, and that the alternative use of crop residue for fodder often conflicts with mulching requirements of conservation agriculture. It is certainly difficult to envisage production of sufficient biomass for both mulch and forage without adequate fertility and water (Valbuena et al. 2012). Nonetheless, conservation agriculture has widespread potential, in part because direct planting without cultivation is a traditional practice in the forest areas of SSA, and also because the practice notably improves crop water supply and saves labour.

Since the benefits of conservation agriculture to soil properties develop slowly and are long lasting, its greatest benefits will be achieved where systems of land tenure are stable. Although not a panacea, adoption of conservation agriculture will make major contributions in some countries and agroecologies (Giller et al. 2011). The standard package of such practices will need to be adapted to local circumstances through participatory farmer research, with which must come (Erenstein et al. 2012):

- control of cattle grazing in the fallow (free-grazing cattle currently remove most crop residue)
- development of new systems to support construction of small-scale farm machinery suited for conservation agriculture
- reliable supply of key inputs (such as herbicides and hand sprayers).

Water harvesting at a micro level (e.g. pitting and stone barriers) is also a useful practice in dry areas and is practised in parts of western Africa.

A third important agronomic intervention in gap closing must be **improved control of weeds**, moving away from laborious hand hoeing. Technologies such as herbicide (imazapyr)-resistant maize sold as herbicide-coated seed show excellent promise of controlling *Striga hermonthica* in the field (Kanampiu et al. 2007) without affecting intercrops (provided precautions are taken during sowing); however, commercialisation of this technology has been slow. Furthermore there is evidence that application of nitrogen suppresses compounds produced by maize roots that promote germination of *Striga* (Jamil et al. 2012), suggesting that improved soil fertility and *Striga* control go hand-in-hand.

While basic agronomic practices such as higher densities and better crop nutrition go some way to suppressing weed growth, adequate control (especially under zero-till)

will ultimately depend on judicious use of herbicides. Kanampiu et al. (2007) note that when glyphosate is used as a seed coat, glyphosate-resistant maize may deliver below-ground control of *Striga*. Application of glyphosate-resistant GE maize in SSA is surely merited, not only for *Striga* control, but also because weed control is labour intensive so is generally a major constraint on maize area and yield.

The fourth important intervention has already been mentioned: the **improvement of stress tolerance in maize varieties**. Given that improved varieties are superior even with low inputs (Edmeades et al. 1991), and especially under drought (Campos et al. 2004; Duvick 2005a; see Section 5.2 on the US Corn Belt), this step offers a key means to closing yield gaps. Since 1996, through several pilot projects, there has been a concerted effort in Africa to improve the performance of varieties under drought and low nitrogen. More recently, work has progressed through projects supported by the Bill and Melinda Gates Foundation, DTMA, WEMA and Improved Maize for African Soils (IMAS). IMAS is a collaboration among CIMMYT, national research programs and Pioneer Hi-Bred focused on developing tolerance of elite maize hybrids to low-nitrogen conditions in Kenya and South Africa using conventional selection and GE traits made available by Pioneer.

For example, benefits of stress-tolerant varieties, determined using multilocation evaluations for a range of water and nitrogen input levels, demonstrated that stress-tolerant varieties out-yielded current commercial control varieties by ~40% at trial yield levels of 1 t/ha, and by 2.5% at 10 t/ha (Bänziger et al. 2006). Preliminary assessments of improved varieties under managed-stress environments (drought and low nitrogen), conducted as an adjunct to multi-environment trials, showed PY increases of ~1.4% p.a. for unstressed conditions and 2.5% p.a. for low-nitrogen conditions, but almost no PY_w increase under managed water-limited conditions (A. Tarakegne, pers. comm. 2011). Subsequently Weber et al. (2012) reported on selection for performance in the CIMMYT African maize program under the random abiotic stresses faced by southern African farmers. Selection was best performed indirectly under optimal or managed low-nitrogen conditions than under the random abiotic stress conditions, or indirectly under managed drought. Lack of PY progress under water limitation may reflect low repeatability of the managed drought sites perhaps because of the timing of the drought or because the trials were run in the dry off-season. This result contrasts with the experience in the USA (Section 5.2) and at CIMMYT in Mexico. Weber et al. (2012) confirmed that good progress for performance under low nitrogen can be made by direct selection in such conditions.

Hybrids with improved stress tolerance are increasingly being released by public and private seed companies. The impact from this germplasm will, however, depend on the **strength of the seed sector** (both for seed development and extension) and adequacy of rural roads and markets (Langyintuo et al. 2010). Across countries within shared agroecologies, harmonisation of testing procedures and release policies is already underway. There is slow but steady progress in the development of laws and regulations surrounding use of GE maize. These initiatives, coupled with 'innovation platforms' (concentration of suppliers of extension and inputs in specific areas) should

significantly shorten times needed for impact (Juma 2010; Smale et al. 2011). As noted earlier, smart subsidies to encourage use of improved seed and fertilisers have been tested in Malawi, resulting in considerable uptake of new stress-tolerant varieties and hybrids, and notable increases in production.

Maize **losses during storage** are especially severe in SSA. A recent multi-agency study on postharvest losses in eastern and southern Africa indicated that 17% of total maize harvest is lost, mainly to insect pests in storage in the lowland humid areas. At higher, cooler elevations, this figure falls to 11% (World Bank 2011). Countering these losses is clearly an area meriting further research and development, even as low-cost hermetically sealed containers are being made more available.

Conclusions for maize in Sub-Saharan Africa

Maize is a staple food crop in SSA, yet outside of pockets in South Africa and a few other countries, maize is underperforming in a dramatic manner. Yield gaps are in excess of 100% of FY; in many cases they are 200–400% of FY. Inadequate crop nutrition is the major constraint to maize production, followed by lack of use of drought ameliorative measures, poor weed control and lack of adoption of available germplasm improved for stress tolerance.

Reasons for inadequate crop nutrition in SSA are complex, and are often associated with very low levels of soil organic carbon, implying multiple deficiencies and physical soil problems. Inadequate crop nutrition will not be resolved at the farm level until costs per unit fertiliser nutrients are reduced through better infrastructure, and uncertainty surrounding crop returns is reduced. This will be achieved through more efficient markets and adoption of stable hybrids from better seed quality. Meanwhile, the need for restoring soil organic carbon and correcting other issues related to low soil fertility—such as spread and impact of *Striga*—are growing in importance, as is weed control in general, and will continue to require significant research investment.

Soil fertility in SSA is often so low that—in contrast to rainfed cropping elsewhere in the world, where risk of drought would normally constrain nitrogen uptake (and therefore application)—crops in SSA will usually respond to nitrogen and/or phosphorus even under drought conditions (provided that there are no other constraints). However, drought effects in drought-prone MMEs of SSA are amplified by poor management of soil and water resources (e.g. poor water infiltration, accompanied by run-off and soil erosion in the absence of conservation agriculture) and inadequate weed control during the fallow season.

New breeding materials—from Mexico, Asia, Europe and the USA—will carry across traits for high PY as they are introgressed into African germplasm. Improvement of abiotic stress tolerance in maize hybrids is progressing well, although deployment of resulting hybrids must be accompanied by improved agronomic practices to maximise returns on available nutrients and water. Significant opposition to the introduction of GE maize has arisen in countries such as Zambia, but much of this can be traced to

attitudes imported from outside the region, rather than to any hard data. Solving these problems of food supply in Africa will require every tool available, including genetic engineering.

Investment in research and development in African agriculture is pitiful, except in a handful of countries. Despite 20% increase in agricultural research and development in SSA during the last decade, Beintema and Stads (2011) conclude that national investment levels in the lower socioeconomic countries have fallen so low as to leave them 'dangerously dependent on often volatile, external funding sources' (see also Section 13.2 on investment in research and development). New investment needs a long-term vision, and must be tailored to meet the needs of the private sector and limitations faced by economically disadvantaged farmers. If this can be achieved, it is highly probable that the 100 million farmers of smallholdings in SSA will respond to market signals to purchase more inputs and deploy them in a timely and appropriate manner. In doing so, it will then be possible for farmers to reduce the yield gap (see also Chapter 8 'Yield gap closing').

5.5 Maize in Brazil and Argentina

Introduction to maize in Brazil and Argentina

Many centuries ago maize migrated south and east to Argentina and Brazil from its centre of origin in Mesoamerica. It is only in the past 50 years, however, that it has become a large commercial crop there. Brazil is now the third largest maize producer in the world, producing 55 Mt annually, while Argentina, producing 19 Mt annually, ranks sixth behind Mexico (Table 5.1). Argentina is the second largest exporter of maize after the USA, selling 70% of its harvest abroad, and Brazil is the third largest.

There are various maize production environments in Brazil and Argentina (Map 5.5a). North-eastern Brazil is categorised into lowland tropical mega-environments MME5 (wet) and MME6 (dry), while higher elevation areas—700–1100 masl—of central and southern Brazil, and northern Argentina, belong largely to MME3 (wet lower mid-altitude subtropical). Further south, below about latitude 30 °S, in the southernmost Brazilian state of Rio Grande do Sul, and in much of the rolling pampas of central and eastern Argentina at latitudes 32–35 °S, the MMEs are temperate (mostly humid (MME7) in the east and drier (MME8) in the west) where temperate hybrids perform well (Carcová et al. 2000; Luque et al. 2006).

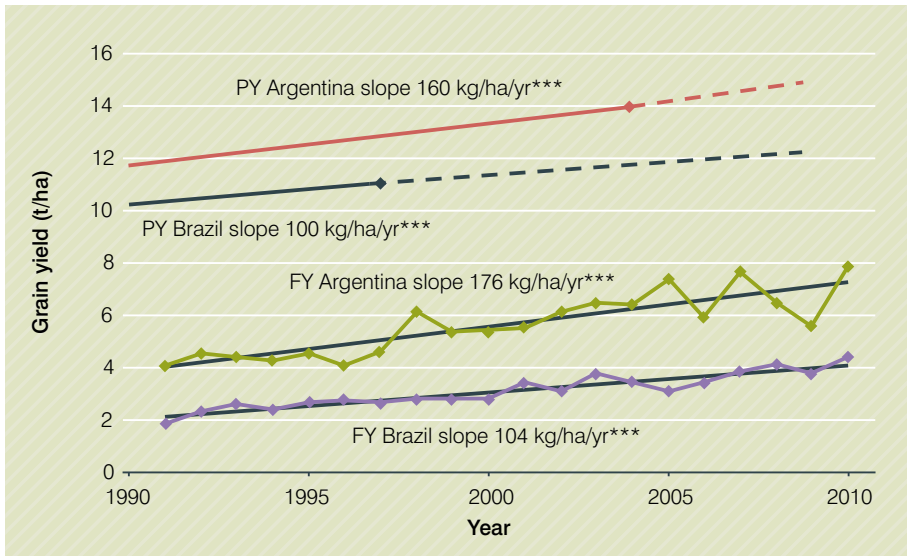
The dominant MMEs for both Argentina and Brazil have humid conditions: MME3 dominates in Brazil, north of about latitude 30 °S, while MME7 dominates to the south in Argentina. Thus moisture supply for maize grown in Argentina and Brazil is generally good, although serious droughts can occur with notable yield reductions—for example, the 2008–09 drought in Argentina (Figure 5.5).



5



Map 5.5 (a) South America showing countries with >1 Mt p.a. maize production (2008–10) and major maize regions in Brazil, Argentina and Paraguay and (b) extent of the Brazilian Cerrado region and key states of Brazil



*** $P < 0.01$

Figure 5.5 Maize farm yield (FY) plotted against year, and estimated potential yield (PY) plotted against year of release, for Brazil and Argentina from 1991 to 2010. Source: FY from FAOSTAT (2013)

In the temperate and winter-dry subtropical parts of northern Argentina, maize is typically a single summer crop. However, production systems become more complex as moisture increases moving north-eastwards into Brazil. Double cropping of winter-summer crops is possible in the wetter northern pampas of Argentina and is common in the southern Brazilian states—Rio Grande do Sul, Santa Catarina and Paraná (Map 5.5b)—where annual rainfall of $> 1,500$ mm is evenly distributed throughout the year. A typical 2-year rotation in these states is wheat followed by soybean, then winter green manure followed by maize.

A significant portion of Brazil's maize, largely MME3, is grown north of Paraná in the Cerrado region (Map 5.5b; Box 5.5), where the winter season is dry but relatively short. Soybean is the main summer season crop, harvested in February–March, and it is wet enough for this to be followed by a *safrinha* season maize crop, which catches the last month or two of the wet season. This maize crop is often called a winter crop but in reality it grows mainly during late summer–autumn. The *safrinha* crop—which has become increasingly popular since 1980—flowers in April and is harvested in June–July, so it can be subject to late drought; meanwhile cool temperatures and early frosts during grain-filling in June can be a constraint in the southern parts of the Cerrado.

It is estimated that 50% of maize production in Brazil now occurs in the *safrinha* season on 50% of the planted area (R. Rissi, pers. comm. 2012), and its rapid expansion has

been accompanied by a 30% reduction in area planted to the summer maize crop in the region. Hybrids and growing practices have been quickly adapted to requirements of the new second season *safinha* crop in the Cerrado. However, the potential yield is probably less than that of summer maize due to dryness during grain-filling. Nevertheless, the soybean–maize double-crop is a very productive system and now common in the Cerrado.

Box 5.5 Brazil's Cerrado region

The term 'cerrado' refers to savanna-type vegetation. The Cerrado region, as now defined in Brazil, covers a vast area (207 Mha) lying in a north-east to south-west band across central Brazil (Map 5.5b). The Cerrado ranges from scrubby savanna in the south to transitional rainforest in the north, adjacent to the Amazonas region. The rolling landscape is generally 500–1,100 masl and annual rainfall is >1,000 mm, with a dry winter season lasting 3–6 months. The major Cerrado cropping state is Mato Grosso.

Many soils of the Cerrado—and further south in the states of Paraná and Rio Grande do Sul—are deep red Oxisols, which are physically excellent but strongly acidic to depth with high levels of free aluminium. When, some 50 years ago, it was shown that heavy liming and phosphorus applications greatly improved the productivity of these soils, cropping began to expand rapidly into the Cerrado. Today clearing continues in the Cerrado under strict regulations regarding the set aside of native vegetation, particularly along stream lines. By 2006, ~80 Mha of the Cerrado had been cleared and a ~14 Mha is cropped (giving 20 Mha of crop, producing over 50 Mt of grain). The remaining cleared area is classified largely as pasture in various stages of degradation. Major crops are soybean, maize, cotton, rice and beans (*Phaseolus vulgaris*), sometimes grown under pivot irrigation in the dry season, while the region also has over 100 million head of cattle. Landholdings are generally large to very large. However, a major constraint is the lack of good transport connections to the major Atlantic export ports.

The Cerrado is reasonably well served by public and private agricultural research, including the Brazilian Agricultural Research Corporation, Embrapa, and national and international breeding companies. Direct seeding of crops predominates, particularly in order to reduce the erosion risk and conserve moisture, but maintaining good groundcover remains a challenge, especially immediately following soybean. Other issues include crop nutrition, herbicide-resistant weeds and minimising environmental impacts of agricultural chemicals, especially nitrate losses from fields.

Maize farm yield changes in Brazil and Argentina

Average maize FY in Brazil is only ~60% of that in Argentina. Over the past 20 years, it has increased at 104 and 171 kg/ha/yr in Brazil and Argentina, respectively, rates equal to **2.6% p.a. and 2.4% of their respective estimated FYs in 2010 of 4.0 t/ha and 7.2 t/ha** (Figure 5.5). Maize area has increased at rates of 0.2% p.a. (Brazil) and 0.6% p.a. (Argentina) but these rates were not significant ($P > 0.10$, Table 5.1); generally maize cropping remains within areas where annual rainfall is >750 mm.

The above rates of FY progress are outstanding, especially given that the vast majority of maize crops are rainfed. Magrin et al. (2005) estimated that a significant increase in summer rainfall across the Argentine pampas for the period 1971–99 compared with 1950–70 should have lifted maize yields by ~18%. There is, however, no evidence (at least in the Argentine pampas) of significant rainfall trends in the 20 years since 1990 for which yields are shown in Figure 5.5 (G. Magrin, pers. comm. 2012).

The big boost to FY since 1990 is likely to have arisen from adoption of new hybrids and of conservation agriculture and zero-till—techniques that have reduced the impact of dry periods in these rainfed systems. The maize (and soybean) fields of Argentina and Brazil were the origin of the conservation agriculture revolution where it is often termed ‘direct seeding’ (see Section 8.5 on this success story).

The techniques emerged in Argentina and southern Brazil in the late 1980s, and by 2009 had spread across 26 Mha of arable land in Brazil (Derpsch et al. 2010) and 22 Mha in Argentina (Trigo et al. 2009a)—see Figure 8.2. By 2012, direct seeding will occur on an estimated 70% of cropped land in Brazil (Trecenti 2012).

Genetic engineering technology is also now widespread, especially in Argentina. A recent study of GE crops under production over 15 years in Argentina showed an accumulated benefit of \$US5 billion due to *Bt* insect-resistant maize and glyphosate-resistant maize; ~70% of this economic benefit was acquired by the growers (Trigo 2011). *Bt* maize in Argentina is allowing farmers to plant maize later when the weather favours higher yield, something precluded by the prevalence of maize borer attack more common before *Bt* (M. Otegui, pers. comm. 2012).

Sale of GE maize seed in Brazil became legal in 2006 and uptake—particularly of herbicide resistance—has been extremely rapid, especially in the south and (more recently) the Cerrado. It is expected that 54% of the summer crop in 2011–12 will be genetically engineered, and up to 75% for the winter *safrinha* crop (Celeres 2011).

Maize potential yield and progress in the well-watered temperate and subtropical regions

This section focuses on progress in the humid temperate MME7 in the south and humid subtropical MME3 further north. Rates of PY increase through breeding for these regions are similar to those reported in the USA. This is to be expected, given

the infusion of US germplasm into Brazilian and Argentine breeding programs over the past 30 years (I. Colonna, pers. comm. 2009). Double-cross hybrids were first released in Brazil in 1939, second only to the USA (Venkovsky and Ramalho 2006), and hybrids now account for >90% of all maize planted there.

Estimates of PY increase from breeding in Brazil and Argentina have usually involved small samples of vintage hybrids. In Brazil, Sangoi et al. (2001) evaluated four hybrids released between 1960 and 2000 that showed a gain of 65 kg/ha/yr at 200 kg applied nitrogen per hectare, but only 34 kg/ha/yr at 150 kg N/ha. Bispo (2007) tested hybrids released in 1987–2005 at two densities in four environments and reported very highly significant gains of 65 kg/ha/yr or 1.0% p.a. of the 2005 PY. Venkovsky and Ramalho (2006) reviewed maize improvement from 1974 to 2004 and estimated gain at 66 kg/ha/yr, while an analysis of changes in yields in farmer contests from 1977–99 showed winning yields rising at 275 kg/ha/yr. In Argentina evaluation of hybrids covering the past three decades up to the mid 1990s gave PY increases of 170–190 kg/ha/yr (Echarte et al. 2000; Eyherabide and Damilano 2001; Luque et al. 2006). More relevant results come from regional research trials of elite hybrids by Pioneer for 1990–2009 that showed a very highly significant gain of 181 kg/ha/yr (I. Colonna, pers. comm. 2009). Overall, for the purposes of determining PY here, it is estimated that the **mean annual rates of increase in PY are ~100 kg/ha/yr for Brazil and ~160 kg/ha/yr for Argentina** (Figure 5.5).

PY generally increases from north to south, and with elevation (as suggested in Table 5.2). Values of 5 t/ha were reported for irrigated *safriinha* maize grown in MME3 (wet lower mid-altitude subtropical) in central Brazil (Soler et al. 2007), but these values appear low. In another example, de Souza et al. (2008) measured PY values for tropical hybrids that averaged 10.1 t/ha and reached as high as 15 t/ha (for trials conducted at 720 masl; small plots; single year). At elevations of ~900 masl in southern Brazil, PY appears to be 8 t/ha on acid soils (limed to a depth of 17 cm) (Ernani et al. 2002) and ~10 t/ha on a less acidic soil (Sangoi et al. 2001, 2002). Also, Serpa et al. (2012) reported PY values of 13–14 t/ha with early sowing of recent hybrids in Rio Grande do Sul (MME7), while yield contests ranged from 13.4–16.8 t/ha in the 1998–99 season (Venkovsky and Ramalho 2006).

PY in the humid temperate zone (MME7) of Argentina resembles that of the US Corn Belt. In a planting date study over 2 years—under irrigation and ample nitrogen—Otegui et al. (1995) reported an average PY of 13.8 t/ha. By comparison, PY values of 14–15 t/ha have been observed in elite hybrid research plots (Rozas et al. 2004; Luque et al. 2006; Cirilo et al. 2009). PY values from Pioneer research trials of elite commercial hybrids have averaged 12 t/ha in recent years (I. Colonna, pers. comm. 2009).

Thus **PY was ~11 t/ha for much of Brazil** (for hybrids released ~1997), **and 14 t/ha for temperate Argentina** (for hybrids released ~2004) (Figure 5.5). Reasons for differences in PY between Brazil and Argentina include latitude, since tropical climates have a lower PY than temperate ones. Moreover, the potential for *safriinha* crops is thought to be lower than main season crops and this reduces the national estimate of

PY for Brazil. Water-limited PY (PY_w) is not treated here, but is considered to be ~60% of our PY estimates, based on the decrease in Argentine yields in dry years (for example, the 2008–09 drought seen for FY in Figure 5.5). Hidden drought, caused by shallow rooting on soils with acid subsoils, may also reduce FY in areas of Brazil where rainfall appears to be adequate.

Rates of PY increase—100 kg/ha/yr (Brazil) and 160 kg/ha/yr (Argentina)—determined earlier are anchored, respectively, to the above PY values and release dates in Figure 5.5. PY in 2010 had to be estimated by extrapolation as 12 t/ha for Brazil and 15 t/ha for Argentina. The estimates for PY increase represents rates—relative to estimated PY in **2010—of 0.8% p.a. for Brazil, and 1.1% p.a. for Argentina.** This also indicates that in 2010, the **yield gap was 200% of FY in Brazil and 103% of FY in Argentina.**

Farm yield constraints for maize in Brazil and Argentina and closing the yield gap

Although the yield gap is closing rapidly (in relative terms) in both countries—i.e. gains in FY are occurring at 2.5% p.a. while gains in PY are occurring at only ~1% p.a.—the gap is still surprisingly large, probably due (in part) to drought stresses that have not been accounted for in setting PY in Figure 5.5. On this basis it seems appropriate that any gap closing strategy should emphasise high-quality agronomic research and breeding for increased tolerance to water shortage.

Because maize is especially sensitive to water shortage around flowering, significant gap-closing possibilities are offered by **supplemental sprinkler irrigation**, even in moderate to high rainfall regions of both countries. For example, Bergamaschi et al. (2006) reported average maize yields of 10 t/ha under irrigation in Rio Grande do Sul, compared to adjacent rainfed yields of ~6 t/ha (range 1.5–10 t/ha).

Irrigation of maize is still limited but is increasing. Total irrigated area in Brazil was 3 Mha in 2006, but on-farm storages and shallow aquifers offer potential to irrigate 16 Mha (Bermamaschi and Dalmago 2006). A switch to irrigation will boost the amount of straw present for zero-till (especially in the subhumid Brazilian Cerrado), so that modifications in machinery and management will be required to maximise its benefits.

Acid soils continue to constrain production and yields in much of Brazil, especially under drought where rooting depth is constrained by high subsoil aluminium levels. Deep liming is difficult, but provides an important part of the solution. In addition, soil microfauna may play a useful role in gradually transporting alkaline material deeper into the soil. High levels of acid-soil tolerance have been developed in maize hybrids suited to the Orinoco Basin of Colombia (L. Narro, pers. comm. 2011) and is a target for maize breeding in Brazil. Drought tolerance will be increasingly required in response to the growing demand for hybrids suited to *safrinha* plantings, especially where rooting depth is constrained by soil acidity.

There is continuing evolution in **conservation agriculture**. As intensification of cropping has increased, especially in *safrinha* areas of Brazil, management of zero-till becomes more challenging. One example is the emergence of herbicide-resistant weeds. A second is the development of maize hybrids specifically adapted to zero-till and to the main vs. *safrinha* seasons. Since soybean is the dominant crop in these areas, maize is increasingly grown in 50-cm rows, and this affects how hybrids are being tested prior to release. Grey leaf spot, often associated with conservation agriculture, is becoming a major maize disease in Brazil (W. Trevisan, pers. comm. 2012). As cropping intensifies there is a growing need for research on balanced crop nutrition. Sulfur deficiencies are emerging in the main grain growing areas of Argentina as natural fertility of pampas soils is depleted (Prystupa et al. 2006).

Conservation agriculture for maize needs to be complemented with **rotation and cover crops** (*Brachiaria* spp. or pigeon pea), especially in warmer areas (such as the Cerrado) to provide groundcover, mulch and forage between successive maize crops (Baldé et al. 2011). Even the common, continuous soybean–maize system of the Cerrado would likely benefit from inclusion of a pasture phase (plus cattle) in the rotation. Such development has potential to become a uniquely diverse and sustainable farming system for the subtropics.

The relatively recent appearance of a new cropping enterprise system, the *pools de siembra* (sowing pools), is a unique feature of cropping (including maize) in Argentina. This system is leading to large-scale cropping corporations that have lately spread their influence northwards into parts of Uruguay, Paraguay and the Cerrado of Brazil. Large-scale farms—which offer precision farming techniques, modern mechanisation and the latest hybrids and agronomic methods—point toward a continuing rapid increase in FY and further narrowing of the yield gap in the future. The effect of emerging large-scale farms is also relevant to soybean cropping in Argentina and Brazil (see Chapter 6 ‘Soybean’). The *pools de siembra* system and its influence are described in more detail in Chapter 8 ‘Yield gap closing’.

Physiology of yield gains in maize

Argentinian researchers have contributed strongly to maize physiology (see Section 2.6 for background crop physiology). They have shown that improvements in yield and plant density tolerance achieved through breeding have arisen through greater partition of DM to developing ears in the critical period from 1 week before silking to 3 weeks after (Andrade et al. 2000). Selection for high density tolerance has also reduced the threshold supply of assimilate needed for successful grain set and has increased stress tolerance (Echarte et al. 2000; 2004).

In addition, RUE during the critical period showed a significant annual increase of 0.026 g/MJ/yr (or 1.5% p.a.) across a vintage set of hybrids (Luque et al. 2006), suggesting a modest increase in maximum photosynthetic rate (P_{\max}). Breeding also appears to have increased water use efficiency (WUE): grain number per unit of

evapotranspiration (grains/m²/mmET) increased from 386 grains/m²/mmET for a variety released in 1975, to 853 grains/m²/mm ET for a variety released in 1993 (Cárcova et al. 2000).

However, since all of these physiological studies involve hybrids released more than 10–15 years ago, they may not adequately represent current advances.

Conclusions for maize in Brazil and Argentina

Increases in production and yields in maize regions of Brazil and Argentina have been impressive over the past 20 years—especially in Argentina—and there appear to be no major constraints to continued yield increase over the next few decades.

Driven by farmer innovation and private sector investment, the region has led the way in adopting and adapting conservation agriculture, a process facilitated since around 2000 by the availability of herbicide-resistant hybrids. Considered in conjunction with rapid uptake of these GE hybrids, and establishment of the basic maize–soybean rotation, it is reasonable to say that current practices point to sustainable gains in productivity.

As elsewhere, vigilant management against pest resistance to *Bt*, compliance regarding refuges, and monitoring and managing herbicide resistance of weeds will be essential. Targeted breeding for greater tolerance to abiotic stress (drought, and soil acidity in Brazil) in hybrids for the region will also increase WUE and—along with expansion in supplemental sprinkler irrigation—will help to reduce year-to-year variation in yield.

5.6 Maize cameos—Europe and Bangladesh

Europe and Bangladesh both show maize production and yield trends that are worth noting. Europe, defined to include all land west of the Ural Mountains, produces 10% of global maize (Table 5.1) from a belt lying between latitudes 37 °N and 52 °N, but the rate of yield progress in western Europe has decreased in recent years. By comparison, Bangladesh provides an example of rapid maize expansion and dramatic yield increases.

Maize in Europe

France, Italy, Serbia, Hungary, Romania, Ukraine and the Russian Federation each produce more than 5 Mt of maize, with France reaching 15 Mt and Italy 9 Mt. Over this geographic range (see Map 3.7 for reference), the MMEs of Europe thus include wet temperate MME7 (irrigated southern Europe and rainfed western Europe) and dry temperate MME8 (mainly eastern Europe, extending to the Volga River).

Variation in maize FY in Europe is mainly associated with latitude, length of the frost-free growing period and proximity to the ocean in the west. The highest yields are achieved in western European countries—under well-watered, intensively managed, cool climate conditions—but also in the irrigated sunny south. Estimated mean FY values of >9 t/ha are seen in Austria, France, Germany, Greece, Italy and Spain (FAOSTAT 2013), with highest maize yields achieved in Belgium, which produces 12.4 t/ha (but only over a tiny area of 64,000 ha). Moving eastwards across Europe, mean FY values generally fall steadily, averaging ~6 t/ha in Hungary and less than 5 t/ha in Romania, the Russian Federation and Ukraine.

European FY and its rate of increase have lagged behind those for the USA, but with differences across the continent. Although the climate in eastern parts of Europe is less favourable for maize—and despite political upheavals in these areas—the highest rates of FY increase are being recorded there. By comparison, rate of FY progress in western Europe (where several yield constraints are faced) appears to be slowing in recent years. Table 5.6 shows FY and rates of FY increase for five representative countries of Europe.

Table 5.6 Estimated maize farm yield (FY) in 2010 and rate of increase from 1991 to 2010 for selected European countries, and for Bangladesh from 1999 to 2008

Country	Estimated FY 2010 (t/ha)	Rate of change in FY (kg/ha/yr)	Rate of change relative to FY 2008 or 2010 (% p.a.)
France	9.2	***72	0.8
Italy	9.4	ns 43	0.5
Spain	10.0	***191	1.9
Hungary	6.6	*102	1.5
Ukraine	4.6	***128	2.8
Bangladesh ^a	6.0	***520	8.7

ns = $P > 0.10$, * $0.05 < P < 0.10$, *** $P < 0.01$

a Changes measured between 1999 and 2008

Source: FAOSTAT (2013)

Italy and France are representative major maize producers (24 Mt combined) of western Europe, where FY progress has slowed markedly. Italy shows no significant progress in the past 20 years, and France's progress, although significant over the past 20 years is not in the past 15 years. This may be attributed in part to a drying and warming trend during the cropping season over recent decades (Supit et al. 2010). Others, however, have identified that rejection of GE maize—a policy common to almost all European Union countries—is isolating the region from technology development that has helped drive exceptional progress in the US Corn Belt.

Experience in Spain supports this contention. There, where most maize is irrigated and 30% of the crop is GE for the *Bt* trait (James 2012), the rate of FY progress during the same period has been rapid at 1.9% p.a. of estimated 2010 FY of 10 t/ha (Table 5.6). In addition to changing climate and rejection of gene technology, the third constraint faced by western Europe is the growing regulation for use of agricultural chemicals. This constraint is commonly accepted as slowing European wheat yield progress (see Section 3.8).

The higher rate of FY progress in eastern Europe, compared with France and Italy, reflects recovery from political upheaval, a low starting FY, and emergence of large-scale high-technology farms (Deininger and Byerlee 2011) that use improved agronomic practices and higher yielding maize germplasm from western Europe and the USA (although not yet GE maize).

Recent estimates of breeding progress are not readily available for Europe, but it can be expected that the contribution of breeding to yield increases in western Europe would be similar to that estimated for the USA (~70–90 kg/ha/yr). Similarly, there are no recent published estimates of PY in Europe, but PY is thought to be ~14t/ha in western and southern Europe, and ~12 t/ha in eastern Europe. Thus for western Europe, these data suggest a relative annual rate of PY increase of 0.5–0.6% p.a. and a yield gap of ~50% of FY. For eastern Europe, the yield gap is ~150% of FY, but is tending to close with time.

Maize in Bangladesh

Bangladesh deserves special mention as the scene of very rapid expansion of maize production under irrigation during the winter (known as the *Rabi* season in South Asia). This expansion has been driven by local demand for poultry products and hence poultry feed (Ali et al. 2008). Although winter maize can take >140 days to mature, net returns from maize—which produced average yields of 6 t/ha in 2008—are significantly larger than from competing winter crops (wheat or *Boro* rice) and, compared with wheat and rice, maize requires less water.

Before 1999, maize planting in Bangladesh was negligible. During the 10 years following 1999, however, maize area simultaneously expanded to 0.20 Mha while FY increased dramatically at a rate of 8.7% p.a. of the estimated 2008 FY of 6 t/ha (Table 5.6). This situation changed again in 2009, when bird flu dramatically reduced poultry numbers and demand for maize, and halted area expansion and yield progress—probably temporarily.

The hybrids adapted to Bangladesh's MME3 conditions (wet lower mid-altitude subtropical)³⁹ initially came from India, but local public-sector hybrids are now also

³⁹ Altitude in Bangladesh is close to sea level, but the cool season temperatures match those of summer in other mid-altitude regions.

available. PY levels of 11–13 t/ha have been reached in experiments; in fact, modelled PY values exceed 16 t/ha (Timsina et al. 2010). These PY values indicate that the yield gap is still ~100%. Ali et al. (2008) argue that gap closing will depend primarily on efforts to balance irrigation and drainage, while optimising crop nutrition.

Given rising demand for poultry products in India, the remarkable expansion of winter maize seen in Bangladesh is likely to be repeated in nearby eastern Indian Indo-Gangetic Plain states (e.g. West Bengal and Bihar; see Map 4.4), where slightly cooler winters are experiencing gradual temperature rise.

5.7 Summary of global maize

5

Farm yields, potential yields, yield gaps and changes with time for world maize

Table 5.7 summarises maize yield statistics from sample countries and/or regions of all key maize-growing areas considered in Chapter 5. At 5.6 t/ha, average FY shown in Table 5.7 is greater than the world average of 5.1 t/ha (Table 5.1), which reflects a slight (and unsurprising) bias toward high-yielding maize-growing regions.

Maize yield gap averaged 104%, but this figure offers little meaning given the range of values (36–400%). It should be also noted that—in contrast to all other cases—Iowa (USA) and Italy had relatively low gaps. The average rate of 1.7% p.a. FY increase shown in Table 5.7 is near to the world average of 1.5% p.a. shown in Table 5.1.

Rates of PY increase were more difficult to determine, but values did not vary much with an average of 1.1% p.a.—a rate of progress that is notably better than average rates for wheat and rice. Averages for FY and PY increase suggest that yield gaps are closing, except for China and eastern Africa.

Yield gaps in Table 5.7 can be compared with examples from the 1990s listed in the extensive review by Lobell et al. (2009). That review cited nine tropical and subtropical maize cases from around the world, for which FY results ranged from 16% to 46% of PY, with an average of 33%. In addition, the review provided two reports for maize in Nebraska (USA) which, using simulation modelled PY values by authors, estimate rainfed FY at 65% of PY_w and irrigated FY at 75% of PY. These yield gap estimates, when expressed relative to FY as done here, are 200% (average tropics and subtropics), 54% (Nebraska, rainfed) and 33% (Nebraska, irrigated). Considering that Nebraska is adjacent to Iowa, these numbers are comparable to those in Table 5.7, as is the more recent number of 36% for rainfed maize in the US Corn Belt (van Wart et al. 2013b). Globally, yield gaps especially in the developing world are generally larger for maize than for wheat (Chapter 3) and rice (Chapter 4).

Table 5.7 Summary of global maize farm yields (FY), potential yields (PY) and yield gaps in 2010, and current respective annual rates of change over the past 20 years

MME ^a	Region	Estimated yield (t/ha) and yield gap (%)			Rate of change (% p.a.)		
		FY ^b	PY ^d	Yield gap ^c	FY ^e	PY ^e	Yield gap ^f
7	Iowa, USA	11.4	15	36	1.8	0.8	-1.0
7 + 8	China	5.3	10.4	96	0.7	0.8	0.1
2, 3, 4	Eastern Africa	1.4	7.1	400	0.8	1.5	0.7
5 + 6	Western Africa	1.7	5.3	200	1.9	1.5	-0.4
3, 4, 7	Brazil	4.0	12	200	2.6	0.8	-1.8
7 + 8	Argentina	7.4	15	100	2.4	1.1	-1.3
7	Italy	9.5	14	47	0.5	na	na
8	Ukraine	4.4	12	170	2.8	na	na
Average	<i>n</i> = 8	5.6	na	104	1.69	1.08	-0.61

- a For maize mega-environment (MME) definitions see Table 5.2
- b FY for 2010 is predicted from linear trends over past 20 years
- c Yield gap is $[(PY-FY)/FY]$, expressed as a percentage
- d Mean of high-yield research plots in most cases
- e Rates of increase all significant ($P < 0.05$), except FY in eastern Africa and Italy where $P > 0.1$; na = not available
- f Yield gap change is annual increase in PY (%) minus annual increase in FY (%); unlikely to be affected by CO₂ increase because maize is a C₄ plant.

Estimated maize yield and yield change by maize mega-environment

Information from Tables 5.2 and 5.7 has been coupled with expert opinion to provide the estimates of FY and PY, and their rates of change, for each MME. They are presented in Table 5.8. As was done for wheat and rice, the order of the columns in Table 5.8 differs from the presentation in Table 5.7 to highlight that PY and yield gap together contribute to FY. The FY levels for MMEs have been estimated to match the global 2008–10 FY of 5.2 t/ha (Table 5.1). In the same way, annual rates of FY increase have been estimated to match the global rate of 1.5% p.a. (Table 5.1).

Table 5.8 Estimates of farm yield (FY), yield gap and potential yield (PY) for maize in 2008–10, and rate of change over the past 20 years across maize mega-environments (MMEs)

MME	Weighting factor (fraction of total)		Estimated yield (t/ha) and yield gap (%) for 2008–10 ^a			Estimated rate of change relative to 2008–10 values (% p.a.)		
	Area	Production	FY	Yield gap	PY	FY	Yield gap ^b	PY
1	0.03	0.02	3.5	214	11	1.2	-0.5	0.7
2	0.03	0.03	4.0	225	13	1.4	-0.2	1.2
3	0.05	0.03	3.0	233	10	1.6	-0.2	1.4
4	0.08	0.02	2.0	300	8	1.6	-0.2	1.4
5	0.15	0.075	2.5	260	9	2.0	-0.8	1.2
6	0.14	0.03	1.0	400	5	2.0	-0.6	1.4
7	0.35	0.625	9.5	47	14	1.4	-0.7	0.7
8	0.17	0.17	5.0	80	9	1.6	-0.8	0.8
World average	1.00	1.00	5.2 ^c	98 ^d	10.3 ^c	1.5 ^d	-0.7 ^d	0.8 ^d

a Estimates apply to 2008–10, when world maize area was 162 Mha and production was 833 Mt.

b Gap increase is annual increase in PY (%) minus annual increase in FY (%)

c Weighted by area of the MME

d Weighted by production of the MME

Source: area fractions from Table 5.2; other parameters estimated and calculated by authors (see text).

The result is properly weighted averages for PY and rate of PY increase, although limited by the few environments that were sampled. The values presented should be considered with this in mind. There was considerable variation within the two dominant mega-environments (temperate MME7 and MME8), particularly between the USA and China, but it is reasonably clear that annual rate of PY progress in these key production areas has fallen below 1% p.a. relative to the 2008–10 PY values (Table 5.8).

The analysis in Table 5.8, using averages weighted for MME production, reveals that global progress in FY is derived fairly equally from increases in PY (0.8% p.a.) and from gap closing (0.7% p.a.). Yield gap closing is evident in all MMEs because (on the relative scale) FY is increasing more rapidly than PY. Globally the gap between FY and PY averages 98% of FY but varies greatly among mega-environments; substantial gaps in the tropics and subtropics are balanced by smaller gaps in temperate regions. It is also possible to calculate that in terms of lost global production, gaps between FY and attainable yield (given by a yield gap of 30% relative to FY) are roughly similar in the tropics (33%), subtropics (36%) and temperate areas (31%). Also more production is lost through these yield gaps in humid (61%) than dry environments (39%).

In MME7—the very large temperate mega-environment that includes the US Corn Belt—FY may be getting closest to attainable yield such that it is anticipated that FY increases will slow, unless breakthroughs increase PY progress (as discussed in Chapter 9 ‘Increasing yield potential’). In all other MMEs there appear to be faster PY increases on a percentage basis, perhaps reflecting gradual introgression of temperate germplasm into tropical hybrids, often by multinational seed companies. However, the real scope for FY progress in these mega-environments (most of which lie in Sub-Saharan Africa) must be in closing the currently huge yield gaps; this issue is discussed again in Chapter 8 ‘Yield gap closing’.

Physiological patterns for potential yield increase in world maize

Most physiological studies on yield progress in maize have been conducted in temperate environments (USA, Canada, China and Argentina). However, CIMMYT worked on tropical material in central Mexico and (later) in eastern Africa, primarily under managed drought.

The picture emerging from PY progress in temperate hybrids is clear enough and dominated by the unique positive interaction with planting density. This higher density tolerance of modern hybrids is associated with greater partition of assimilate to the growing cobs and consequent production of more grains per unit of cob weight, such that PY progress is largely related to increase in grain number per unit area (GN).

There is some evidence for greater RUE and crop growth rate around silking—but none for greater intrinsic maximum photosynthetic rate (P_{max})—and stronger evidence for increases in these measures after silking, associated with delayed senescence of the canopy (staygreen) and possibly a stronger sink. The net effect of this and the higher plant densities is greater total DM production, rather than greater HI, which is already high (>0.5), another unique feature of modern temperate maize.

Many physiological aspects of modern maize hybrids show greater resistance to various stresses besides higher density stress, in particular water shortage. This appears to contribute to greater PY_w .

Some physiological aspects of progress in temperate maize have also been seen in PY and PY_w progress obtained when tropical materials have been selected at low latitudes under managed drought stress by CIMMYT. The main changes have been in maintaining HI, both under high plant density and under droughts that coincide with flowering, but HI levels have yet to reach the high levels seen in temperate hybrids. Key traits that have been widely used during selection in low-latitude conditions are reduced barrenness and more rapid silk growth (reduced anthesis-to-silking interval), leading to improved GN when under stress (Edmeades et al. 2006). Selection under low soil nitrogen has also given useful progress.

Soybean

6



Key points

- World soybean production in 2008–10 was 240 Mt, having more than doubled over the past 20 years. Growth in production remains very strong at 3.2% per annum (p.a.), resulting from a strong rate of harvested area increase (2.6% p.a.) supported by a moderate rate of yield progress (1.0% p.a.). The 2008–10 average global yield was 2.4 t/ha.
- Case studies presented in this chapter—from North America (mainly the USA), Argentina and Brazil, and north-eastern China—have explored farm yield (FY), potential yield (PY) and yield gap, and their respective rates of change over the past 20–30 years.
- Based on these cases, the current rate of soybean FY increase was significant ($P < 0.05$ or better) in all cases, with a range from 0.9% p.a. to 1.7% p.a. relative to FY around 2010.
- Likewise, the current rate of soybean PY increase was also significant ($P < 0.05$ or better) in all cases, ranging from 0.4% p.a. to 1.1% p.a. (relative to PY around 2010), with an average rate of 0.7% p.a.
- Yield gaps were almost identical (~30% of FY) in each soybean case studied. Gaps appear to be closing at a moderately rapid rate in Argentina and north-eastern China (average change about -1% p.a.).
- Genetically engineered (GE) herbicide-tolerant varieties now occupy 81% of the world soybean area, but are presently grown only in North and South America.
- Advances in soybean agronomy (better seed management, narrower rows, earlier planting and/or zero-till combined with herbicide tolerance) in the hands of medium to large-scale farmers have helped close yield gaps in the Americas.
- Future FY progress may slow to match the modest rate of PY increase, especially because more attention to management of biotic constraints will likely be needed in the current intensive soybean cropping systems, which notably lack diversity.
- Increase in PY in soybean has been associated with both greater dry matter (DM) and harvest index (HI); there is some evidence that photosynthetic rate (P_{\max}) has also increased.

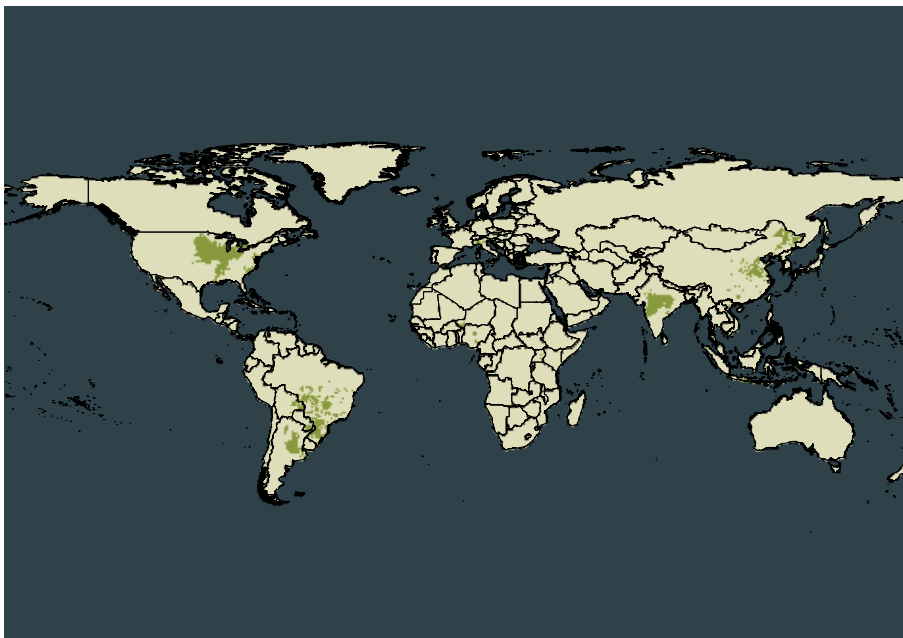
Soybean



6.1 Global soybean progress

Soybean (*Glycine max*) is a legume that produces seed containing ~20% oil and ~40% protein, and these traits make it a nutritionally rich food and feed crop. As recently as a century ago, this unique crop was largely unknown outside of China (Hartman et al. 2011), but today the majority of global soybean production comes from the United States of America (USA), Brazil and Argentina (Table 6.1). Despite potential for Sub-Saharan Africa to grow soybean as a nitrogen-fixing crop to produce high quality food, there is currently only a very small area (1.2 Mha) of soybean grown there (Map 6.1).

6



Map 6.1 Global distribution of soybean area circa 2000. Source: Harvest Choice project, International Food Policy Research Institute; data from You et al. (2009a)

The expansion of soybean production has been driven by a booming world market in vegetable oils and animal feed. Currently >60% of soybean is exported as grain, cake (meal) and oil, with the biggest annual exports (2008–10) from the USA (48 Mt), Brazil (41 Mt) and Argentina (38 Mt). The first two countries largely export soybean as a grain while Argentina exports soybean as cake (or meal) following oil extraction. The biggest net soybean grain importers are China (47 Mt), the European Union (~15 Mt) and Japan (~4 Mt).

Table 6.1 Annual soybean production, harvested area and yield in 2008–10, and annual rates of change from 1991 to 2010 (relative to 2008–10 average)

Country	Average 2008–10			Rate of change ^b (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^a (t/ha)	Area	Yield
World	239.8	99.3	2.41	2.6	1.0
USA	87.6	31.0	2.85	1.2	0.9
Brazil	62.0	22.1	2.80	3.7	1.6
Argentina	43.3	17.1	2.53	4.5	1.3 ^c
China	15.2	8.9	1.70	0.8	ns 0.4
India	10.9	9.6	1.13	3.4	1.0
Paraguay	5.9	2.6	2.29	4.6	-1.5
Canada	3.7	1.4	2.76	2.8	ns 0.2

a What FAOSTAT calls 'yield' this book calls 'farm yield' (FY); see Chapter 2.

b All slopes highly significant ($P < 0.05$) or better, except ns = not significant ($P > 0.10$)

c This value includes the severe drought year of 2008–09 (FY 1.8 t/ha), which if excluded brings yield increase up to 1.6% p.a., and 2008–10 average yield to 2.94 t/ha, similar to Brazil.

Source: FAOSTAT (2013)

Soybean area in South American countries and India has increased remarkably over the past 20 years at annual rates above 3% (Table 6.1). Although expansion in the USA and China has not been as large, area increases in both these countries remain notable when compared with lower changes in cereal area. Soybean has largely expanded onto pasture lands in South America and fallow lands in India, while in the USA and China (and to some extent Argentina), expansion has occurred primarily at the expense of wheat.

Soybean farm yield (FY; see Chapter 2 on definitions) in major producing countries has increased even as area has expanded. Table 6.1 shows notable annual rates of FY increase for Brazil and Argentina (1.6% and 1.3%, respectively). Both these countries are slowly catching up to the high US FY of 2.85 t/ha because of a lower rate of US FY

progress (1.0% p.a.). In fact these three countries reached similar FY levels of 2.9 t/ha in 2010 (FAOSTAT 2013). While there is no evidence to suggest that area increase in Brazil and Argentina occurred because of incursion onto more (or less) productive land, it is likely that the significant decrease in FY in Paraguay (Table 6.1) may be attributed to the very rapid expansion of the crop there.

Soybean is a crop for warm, humid growing conditions. There has been no elaboration of mega-environments for soybean, but latitude is recognised as the major environmental determinant for breeding purposes, especially in North and South America, as soybean is a short day plant. Latitude also controls whether soybean is grown as a sole crop following winter fallow—as occurs in the USA, Canada, parts of Argentina and China above latitude 35–40°—or as a double crop, with wheat or maize, as in Brazil and parts of Argentina (<35–40° latitude). In these temperate and subtropical regions, soybean is usually planted in late spring to grow through summer and flower as days shorten after the solstice. In the tropics, where days are shorter, soybean can be grown at any time and is quick to flower. For example, in tropical Asia, it is readily slotted into intensive rice rotations.

On average, water supply is close to (or above) potential evapotranspiration in all growing regions so, for discussion here, potential yield (PY; see Chapter 2) can be taken as water-unlimited yield. In practice, because soybean is quite susceptible to lack of water, significant yield variation in many situations may, however, be explained by rainfall and the plant-available water-holding capacity of the soil.

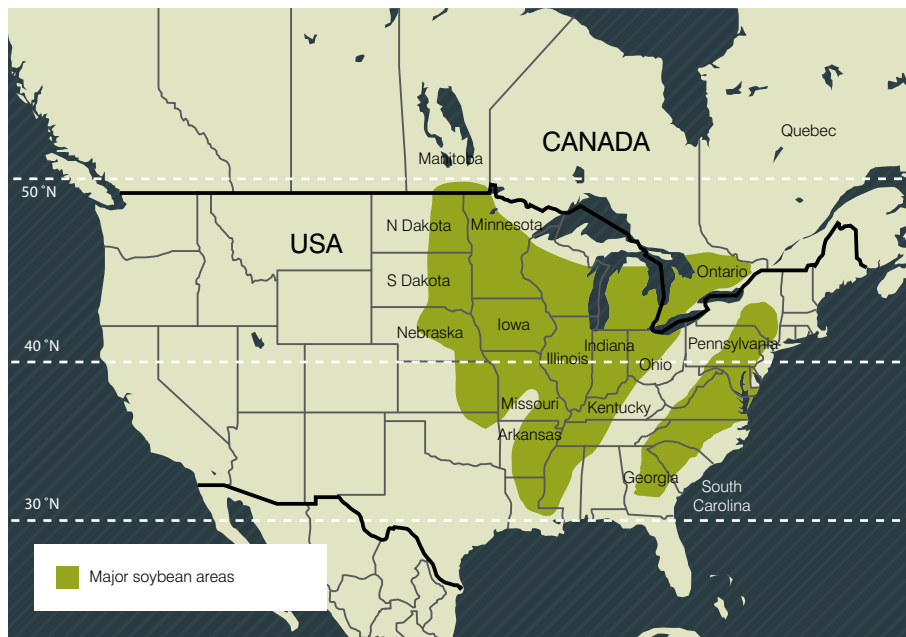
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6.2 Soybean in North America

Introduction

In the USA soybean is concentrated in the Mid West (from the states of Kansas to Ohio, and North Dakota to Missouri, see Section 5.2 'US Corn Belt'), with smaller amounts of production in the Mississippi Valley (Kentucky to Mississippi), and along the east coast (Pennsylvania to Georgia), while Canada grows soybean largely in the provinces of Ontario and Quebec (Map 6.2). Iowa and Illinois alone grow 25% of North America's soybean. Traditionally, varietal adaptation has largely been a matter of matching crop growth duration to the summer growing season. This comes from having appropriate photoperiod sensitivity for the latitude, resulting in narrow latitudinal adaptation (Evans 1993). For this reason, early-maturity varieties—i.e. early-maturity groups MG0, MG00 and MG000 (as defined by US soybean breeders)—are grown in northern areas (>45 °N) which have the longest days, and longer cycle maturity groups (MGVI–MGVIII) are grown in southern areas (<35 °N). The highest productivity occurs between latitudes 35 °N and 45 °N.

Soybean is usually grown as a sole crop in 2-year rotations with maize, but some double cropping with wheat occurs in southern USA. The crop is mostly rainfed but there are significant areas of irrigated soybean in the west, especially in the states of Nebraska and Arkansas. In rainfed areas, water shortage can be a significant constraint, especially on poor water-holding soils (Egli 2008a; Sinclair et al. 2010). This response does not contradict the notion that evapotranspiration of rainfed soybean will usually be reasonably close to potential—rather, it highlights the sensitivity of soybean to lack of water.



Map 6.2 Major soybean regions of North America. Source: Map constructed using data from the IFPRI/SPAM world map

Progress in soybean farm yield in the USA

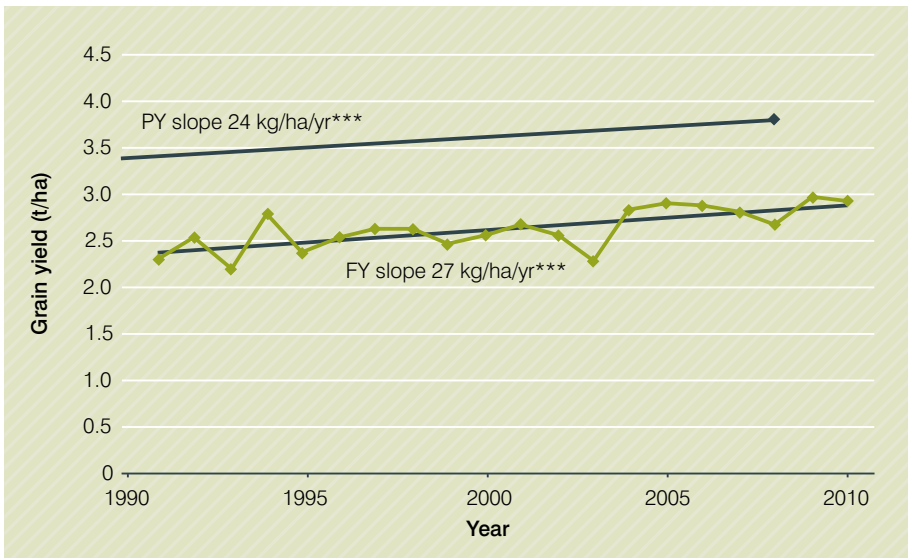
The history of US soybean production is a remarkable story of genetic and agronomic achievement. FY progress over the past 20 years (Table 6.1) has been strongly linear (Figure 6.1) at **a rate of 0.9% p.a. of the estimated 2010 FY of 2.9 t/ha**. Observed FY progress has been positive and linear since 1924 (Specht et al. 1999) when US soybean was still an infant grain crop and FY only 0.7 t/ha.

Several investigations have evaluated recent FY progress in US soybean. Twine and Kucharik (2009) have claimed from simulation modelling that 20–25% of the progress

in US rainfed soybean yields between 1982 and 2002 can be explained by a positive trend in temperature and in precipitation over the period, the former permitting earlier planting. However, the relationship of simulated yield to year was statistically weak ($P = 0.30$) and needs corroboration.

A comparison of yield progress in rainfed and irrigated crops in Nebraska (Specht et al. 1999) has been continued over recent years. During 1972–2008, FY progress for rainfed soybean was 23 kg/ha/yr (or 0.9% p.a. of the 2008 estimated FY of 2.7 t/ha). For the same period, FY progress for irrigated soybean was greater at 36 kg/ha/yr (or 1.0% p.a. of the 2008 estimated FY of 3.7 t/ha) (J. Specht, pers. comm. 2012).

In a comparable analysis among US counties, most of which showed significant FY increase between 1972 and 2003, Egli (2008a) established that although absolute rates of FY progress were greatest in irrigated counties in Nebraska, relative rates of FY progress were similar (1% p.a.) between irrigated and rainfed counties. He also found little evidence that the linear rate of FY progress was slowing anywhere, although across Kentucky the relative rate of FY progress seemed to decline with an increase in proportion of soybean–wheat double cropping. Data from Nebraska and Arkansas suggest a 30–40% response in FY to irrigation. Further north and east, in the top five (and predominantly rainfed) soybean-growing states—Iowa, Illinois, Minnesota, Indiana and Missouri—lack of water is likely to be less important, but not negligible.



*** $P < 0.01$

Figure 6.1 Average farm yield (FY) for soybean in the USA, plotted against year, and estimated potential yield (PY), plotted against year of release, from 1991 to 2010. Source: FAOSTAT (2013) for FY

Progress in soybean potential yield in the USA

Seven studies report PY progress in North America. Unfortunately a shared feature is that none has included the most recent varieties, and this limits the conclusions that may be drawn.

Voldeng et al. (1997) grew early-maturity (MG0, MG00 and MG000) releases from 1934 to 1992 in Ontario, Canada. When corrected for maturity variation (i.e. later varieties tended to yield more) the most relevant subset (1976–92) revealed a rate of PY progress of 0.6% p.a. relative to the 1992 PY ~3.2 t/ha. Morrison et al. (2000), also in Ontario, analysed a different subset (best releases 1934–92) and estimated PY progress of 13 kg/ha/yr (or 0.4% p.a. of the 1992 PY of 3.4 t/ha).

In northern USA, Wilcox (2001) worked with multilocation 1951–99 results of the Uniform Soybean Tests (Northern Region) for publicly developed elite lines. The results revealed significant PY progress in all maturity groups, whether looking at elite lines or released control varieties. The most nationally representative rate of PY progress is probably the 38 kg/ha/yr average of the highest yielding maturity groups (MGII and MGIII) over the 1981–99 test period. Since 1999 yield for these groups averaged 3.75 t/ha, relative PY progress becomes 1.0% p.a. This period reported a small decrease in test row spacing over this period (from ~70 to 50 cm), so the PY increase may also contain a small positive interaction between breeding and agronomy. This estimate of progress compares well with an analysis of privately bred varieties (MGII and MGIII) in the same region (Specht et al. 1999), which estimated the contribution of breeding alone to PY progress to be 25–30 kg/ha/yr, or an average rate of 0.7% p.a. of the 1999 PY of 3.75 t/ha.

In the southern USA, breeding progress for late maturity varieties (MGV and MGVI) has been established in two studies. PY of varieties released during 1954–89 increased at ~0.6% p.a. of the 1989 PY of 2.6 t/ha (Ustun et al. 2001), while for releases during the longer period, 1954–99, PY progress occurred at a rate of 0.9% p.a. of the 1999 PY of 3.5 t/ha (Kahlon et al. 2011).

Finally, De Bruin and Pedersen (2008) reported yield vs. release date for sites in Iowa with a range of soybean cyst nematode (SCN) infestations. Where nematode levels were low, PY progress over the release period 1938–2004 was 30 kg/ha/yr (or 0.6% p.a. of the 2004 PY of 4.8 t/ha). The analysis also revealed that resistance to SCN in modern varieties (later than 1997) carried no yield penalty when SCN was low, and contributed an advantage of ~0.8 t/ha (or 27%) when SCN levels were high.

These seven estimates of **progress in PY average a very highly significant 0.7% p.a.** and the gains appear to derive mostly from breeding plus a likely small contribution from the positive interaction of more recent varieties and narrower rows. Although the results are drawn from studies that were limited to varieties released prior to the late 1990s, early results from a comprehensive interstate vintage trial show no sign of decrease in rate of PY progress in varieties released as late as 2008 (J. Specht, pers. comm. 2012).

It is difficult to estimate current PY for a region as large and diverse as the USA. The average yield was 3.9 t/ha for the best three varieties in state yield tests from Iowa, Indiana and Illinois conducted during 2007–09. This is close to the estimated PY of 3.7 t/ha in 2008 obtained if the value 3.41 t/ha in 1999 from Wilcox (2001)—calculated from the mean yield of top varieties across all maturity groups (MG00–MGV)—is projected forward using the above estimated rate of progress of 0.7% p.a. or 24 kg/ha/yr. Since it is a 9-year prediction, 0.2% p.a. is added for the effect of increasing CO₂ (see Section 2.4 on confounding factors in FY change). Rowntree et al. (2013) found that, under the normal planting date, the PY of 2007 and 2008 releases was about 4 t/ha. Thus Figure 6.1 uses **an average PY for 2008 of 3.8 t/ha**. A possible complicating effect of SCN and its changing incidence and impact cannot be ruled out; De Bruin and Pederson (2008) achieved trial yields of 4.8 t/ha for a 2004 release when SCN levels were low, but that was for only one site in Iowa over 2 years.

The 2009 PY estimate establishes a **yield gap in 2009 of 31%** of the then-estimated US FY (2.9 t/ha). By including PY progress in Figure 6.1, it becomes evident that PY and FY have risen almost in parallel over the past 20 years, meaning that the absolute yield gap has remained remarkably stable.

Agronomic innovations in soybean in the USA

Agronomic changes that have accompanied recent FY and PY progress in soybean in the USA include (Egli 2008b):

- conservation tillage practices
- earlier planting
- improved weed control
- narrower rows (now 38 cm)
- reduced harvest losses.

The glyphosate-resistance trait released in 1996 and which facilitated some agronomic changes (conservation tillage, earlier planting and narrow rows) was found in 93% of plantings in the USA in 2012 (James 2012). This trait has also reduced crop losses due to toxicity of other herbicides used before the advent of glyphosate tolerance (Owen et al. 2010).

Based on United States Department of Agriculture (USDA) crop progress reports for 1981–2005, Sacks and Kucharik (2011) estimated that time of soybean planting has advanced by 12 days across the USA, while date of crop maturity has changed very little. This is attributed to new technologies, especially those enabling earlier maize planting (see Section 5.2 'US Corn Belt') which precedes soybean planting on most farms. Yield would be expected to benefit from earlier planting, especially with modern fungicidal seed treatment for better performance in cool soils (Bastidas et al. 2008). Precision seeding has also expanded in the USA, which (along with better seed quality)

has meant better plant stands contributing to increased yield (J. Specht, pers. comm. 2012). Generally nitrogen fertiliser is not used on soybean—except when very high yields are sought (Salvagiotti et al. 2008)—and inoculation is not needed in traditional US soybean areas.

Obviously some PY increase has arisen through positive interaction with agronomic change, such as narrower rows and earlier planting. A clear interaction (Cooper 2003) can be observed using extremely narrow rows (17 cm) for maximum yield in semi-dwarf determinate varieties (those in which the stem apex terminates in a flower). Under favourable moisture conditions, determinate varieties outyielded older indeterminate varieties and delivered an average yield of ~5 t/ha. Current varieties, however, remain generally indeterminate because breeders have notably shortened the stature and improved lodging resistance in indeterminate varieties (Wilcox 2001). Such varieties now perform satisfactorily when planted in narrow (38 cm) rows. At the same time, reduced harvest losses can be partly explained by steady improvement in genetic resistance to lodging, which usually accompanies reduced stature.

There is some evidence of increased incidence of soybean diseases and infestations of soybean nematodes and insects in intensive soybean–maize rotations (Nafziger 2004). Host-plant resistance traits are extensively used in soybean breeding, but these traits have slowed the breeding effort for yield gain, and have not yet been fully effective across all biotic stresses. GE-resistance may be achievable (Hartman et al. 2011) but this has yet to be deployed. Crop rotation is essential for managing levels of SCN, with a non-host crop planted at least every alternate crop in the sequence. Asian soybean rust reached North America in 2004; it can be problematic (especially in the south) but fungicides and resistance breeding should maintain control (Hartman et al. 2011). In some locations, glyphosate-tolerant weed biotypes are becoming common, and unfortunately farmer awareness of this serious challenge to the system remains poor (Owen et al. 2010). These growing problems will command more attention as they challenge past yield gains, while Egli (2008b) suggests that future yield increases from new agronomy are unlikely to occur in soybean.

Physiology of yield progress in soybean

North America has contributed strongly to knowledge of soybean physiology ever since pioneering work on photoperiod sensitivity in the 1920s at the USDA in Beltsville, Maryland, was used to produce varieties to fit the duration of growing season at each latitude in the USA.

More recent physiological studies, summarised by Specht et al. (1999), revealed that the route to higher yield has arisen through increased production of dry matter (DM) during seed filling, rather than increased harvest index (HI). In addition, modern varieties have better lodging resistance and are more tolerant of high plant density stress. In contrast, detailed studies in Canada on early-maturity group varieties by Morrison et al. (1999) established that HI increased with year of release while DM did

not change. Specht et al. (1999) went on to show that yield progress resulted from higher grain number per square metre (GN) and higher seed oil percentage without change in seed weight—although seed protein decreased as oil increased, which is a general observation in North America (Rowntree et al. 2013)—and greater lodging resistance (Morrison et al. 2000). A dominant role of GN in yield progress in US varieties was confirmed by Kahlon et al. (2011).

It is useful to consider more detailed work on photosynthesis and nitrogen fixation to better understand yield progress in soybean. Of particular interest is the work of Morrison et al. (1999), which identified a significant increase in leaf photosynthetic rate (P_{\max} , averaged across vegetative and reproductive stages) with year of release (0.5% p.a.; $P < 0.01$) and with yield ($P < 0.05$). Stomatal conductance and chlorophyll concentration were also positively correlated with yield (both $P < 0.05$), while leaf area index (LAI) decreased with year of release ($P < 0.05$) and specific leaf weight tended to increase.

In another study, Morrison et al. (2000) cited earlier US work that corroborated their observed increase in leaf photosynthesis. However, some of these studies focused on seed filling when sink feedback or staygreen may be controlling factors, rather than on intrinsic photosynthetic activity. More modern soybean varieties appear to be able to fix more nitrogen and accumulate more nitrogen during seed filling (Specht et al. 1999), but breeding progress for yield did not appear to be affected by the source of nitrogen supply (fertiliser nitrogen vs. nitrogen fixation), or of incident radiation (Kumudini et al. 2008).

The abovementioned studies relate to higher latitudes; lower latitudes have longer growing seasons and hence offer more flexible planting dates and variety durations. For example, for early summer irrigated plantings in Australia (latitude 34 °S), DM and yield initially increase with days to flowering, with yield levelling off for varieties with >50 days to flowering (or >120 days to maturity) (Gaynor et al. 2011a,b). Egli (2011) reported similar results in the USA. The components of this response are positive DM and negative HI relationships with crop growth duration.

At even shorter days (earlier spring plantings, latitudes below 34°), soybean tends to flower too quickly, and the simply inherited long juvenile trait has been useful in slowing time to flowering in such situations. For example, long juvenile varieties produce superior yields from early spring plantings in the southern USA (Shipe et al. 1997), in the tropics (James and Lawn 2011) and in Brazil (see below).

Apart from the use of knowledge of day length sensitivity in soybean breeding, the above physiological changes have been observed retrospectively. However, Cooper (1981) deliberately pursued a soybean ideotype for higher yield—a determinate semi-dwarf habit planted in narrow rows, with the results reported above. More recently T. R. Sinclair tackled prospective physiological breeding, targeting (among other things) tolerance to periods of water shortage through observed genetic variability. For example, Sinclair et al. (2010) described variation in nitrogen-fixation sensitivity to soil

water shortage, and variation in stomatal sensitivity to vapour pressure deficit (slow wilting trait). Using simulation modelling, these authors predicted likely significant yield benefits of these traits across the USA, but breeding has yet to deliver on this.

6.3 Soybean—a new crop in the new lands of South America

Soybean production began gradually in southern Brazil, eastern Paraguay and northern Argentina about 40 years ago. However, only since the 1990s has planted area expanded rapidly—northwards in Brazil, and westwards and southwards in Argentina. The result has been more than a doubling of soybean area in Brazil and a tripling in Argentina and Paraguay, while rapid rates of expansion continue (Table 6.1). Currently, the 43 Mha of soybean in this region, including adjacent areas in Uruguay and lowland Bolivia, which make up the remaining 1.2 Mha (Map 6.3), exceeds soybean area in the USA by more than 40%.



Map 6.3 Major soybean regions of South America. Source: Map constructed using data from the IFPRI/SPAM world map

Initially soybean expanded onto pasture lands, but there has also been significant clearing of savannas in northern Argentina (the Chaco region), eastern Paraguay and Brazil's Cerrado region (see Map 5.5b). Savanna clearing in the Cerrado is south of the legally protected Amazon rainforest and much soybean there is also planted on degraded pasture land (see Box 5.5).

At around **1.5% p.a., the rate of FY increase** in Argentina and Brazil has been high (Table 6.1), driven by adoption of new varieties and agronomic technologies, and supported by novel land management arrangements (see Chapter 8 'Yield gap closing') and, in most instances, reasonable policy environments. Although a significant jump in summer rainfall occurred around 1970 in Argentina and adjacent parts of this region (e.g. Magrin et al. 2005), there has been no clear rainfall trend favouring FY, at least since 1990 in the Argentinian pampas.

Rural transformation between 1991 and 2008—driven by soybean industry expansion in a well-integrated value chain—was truly remarkable in Argentina (Regunaga 2010), a country of moderate to large soybean farms. Expansion was facilitated with positive policy measures in the early 1990s, but with a sharp reversal in 2008 when a 35% export tax was introduced, reducing incentives for further investment. Innovative models for transfer of farmer technology have also played a role in FY increase in Argentina.

The soybean revolution in Brazil since the mid 1990s has been no less spectacular. The same new technologies as used in Argentina were a vital component of Brazil's progress, combined with an especially strong public research sector. Initially farmer cooperatives in southern Brazil played an important role, but expansion into the Cerrado has been the result of enterprising farmers with an appetite for risk, and an initially relaxed policy environment for land clearing in that vast region.

Despite intensive public (and now private sector) **soybean breeding** and release of many varieties, there appear to be few specific studies of PY progress. Initially, varieties flowed into Argentina and southern Brazil from the USA, but one widely cited study (Salado-Navarro et al. 1993) reported that while 1945–83 Florida varieties showed yield progress in Florida, USA, no yield gains were observed when the same varieties were grown in favourable sites at similar latitudes in Argentina. More recently, the Argentinian Association of Soybean Breeders (known as PROSOJA) conducted a vintage experiment at 10 representative locations in Argentina (27–34 °S) over 4 years (2002–05) with 45 varieties released between 1982 and 2000 (Santos et al. 2006). PY increased significantly with year of release (14 kg/ha/yr, $P < 0.01$), and **rate of PY progress was 0.4% p.a.** relative to an **estimated PY of 3.5 t/ha** for 2000 releases. A forward prediction of this rate of progress suggests that **PY for 2010 would be 3.6 t/ha**. With a **2010 FY** estimated from the trendline at **2.7 t/ha**, **the yield gap for Argentina appears to be only 33% of FY.**

There is insufficient information on breeding advance in Brazil to establish a rate of PY progress or to provide the current PY and yield gap for such a large growing region. However, in the Brazilian state of Rio Grande do Sul (Map 5.5b), Lange and Federizzi

(2009) measured PY progress across breeders' advanced lines in unprotected multi-environment trials between 1980 and 1999. PY progress for this major region (~28 °S) was reported as 23 kg/ha/yr, averaged across early, medium and late maturity groups (although early-maturity groups showed little progress), equating to progress of 0.7% p.a. of the 1999 PY of 3.1 t/ha. Further north in Brazil—especially under short days at latitudes <20 °S—even the latest US maturity groups flowered too early. Therefore, in the search for higher yield, local breeders achieved later flowering from various genetic sources, including the long juvenile trait mentioned earlier (Spehar et al. 1998; Toledo et al. 1998).

Zero-till (known as '**direct seeding**' in the region)—along with retention of crop residue—has been an agronomic revolution in the South American soybean region (see also Chapter 8 'Yield gap closing'). The practice started in the late 1970s in order to control water erosion, long before glyphosate-resistant (Roundup®-Ready) cultivars became available. Zero-till is especially prominent in soybean because the relatively wide row spacing (compared with wheat) is suited to planting into heavy residue of the prior crop. The zero-till revolution was boosted by the 1996 arrival of **genetically engineered glyphosate-resistant varieties** to Argentina. Since then, such varieties have been almost completely adopted in Argentina (100%), Paraguay (95%) and Brazil (88%) (James 2012), as has the practice of zero-till. Trigo (2011) estimated that the glyphosate-resistant trait in soybean contributed US\$65 billion to the Argentinian economy between 1996 and 2010.

Since introduction of zero-till, soil erosion has been substantially reduced and moisture supply to crops has increased. This, along with better weed control from herbicide-resistant varieties, has undoubtedly contributed notably to FY progress in the region. Additional agronomic advances for soybean have been achieved through liming of acid soils (common throughout Brazil) and widespread use of phosphorus fertiliser.

Crop rotations have become intensive and are reasonably diverse in Brazil but now less so in Argentina. Soybean usually follows cereals, because soybean residue alone is insufficient to protect soil from erosion. North of latitude 30 °S, double-cropped soybean is common where moisture is sufficient (annual rainfall >1,000 mm). Soybean–wheat rotations are found where winters are cooler (e.g. northern parts of central Argentina and southern Brazil). Further north, soybean–maize rotations are common in the Brazilian Cerrado. In the southern parts of the Argentinian soybean region, early planted sole-crop soybean (*soja de primera*) competes with later planted, lower yielding soybean following wheat (*soja de segunda*).

In some double-cropping situations there are benefits from shorter duration soybean, and this may limit progress in overall soybean FY. In addition, high soybean frequency in many regional cropping systems—and reliance on glyphosate-resistant varieties—may demand greater rotational diversity, with weed resistance to glyphosate a major risk to be managed. In this regard, the continuing presence of livestock (especially cattle) in soybean areas of Argentina and Brazil creates unique opportunities for diversification through crop–pasture integration. Finally, the arrival of soybean rust in

the region in 2001 has prompted the use of fungicides on current varieties in Brazil and has posed a new challenge for breeders—as will other diseases and pests as soybean loses its status as a new crop.

6.4 North-eastern China—the old home of soybean

North-eastern China (40 °N–50 °N) is a geographical region comprising three provinces: Liaoning, Jilin and Heilongjiang (see Map 4.3). Soybean has been cultivated there for 5,000 years (H. Zheng et al. 2011), and the region now plants about one-half of China's soybean crop, with more than 80% in Heilongjiang, predominately on the black soils (Mollisols) (Liu et al. 2008). In contrast to the rest of China, big state farms, and larger private ones (25 ha), are common in the north-east. As in the rest of China, soybean area (currently ~4.5 Mha; J. Jin, pers. comm. 2012) has been increasing, largely at expense of wheat area. Moreover **FY for north-eastern China has progressed at a rate of 38 kg/ha/yr ($P < 0.01$), or 1.7% p.a.** of the estimated 2008 FY of 2.3 t/ha (data from Liu et al. 2008 and J. Jin, pers. comm. 2012); this is much greater than for China as a whole (0.4% p.a.).

There is good evidence of recent strong warming in Heilongjiang. H. Zheng et al. (2011) reported increases in minimum (0.116 °C/yr) and maximum (0.105 °C/yr) temperatures from 1987 to 2004 for the soybean-growing season (1 May – 30 September). These authors applied the first difference method (which is discussed in Section 3.2) to show that while yield will increase (~0.38 t/ha/ °C) with rising minimum temperature in this cool environment, yield will decrease (~0.30 t/ha/ °C) with rising maximum temperature. In other words, the effects of rising minimum and maximum temperatures more or less cancel each other, leaving an estimated net yield increase of just ~5 kg/ha/yr due to warming. H. Zheng et al. (2011) appeared unaware of this balance of effects, and instead emphasised benefits of warming that included earlier seed filling. Further, these authors did not specify if sowing date was allowed to advance with warming—a key question of adaptation for such studies—so the influence of recent climate warming on soybean FY in north-eastern China remains uncertain.

In a three-year vintage trial for 1951–2006 releases (maturity groups MG0 and MG00), J. Jin et al. (2010) found **PY to increase linearly at 12 kg/ha/yr, or 0.4% p.a. of the 2006 estimated PY of 2.5 t/ha.** This PY is only slightly greater than the north-eastern China FY of 2.3 t/ha. While this progress measure is valid, it is possible that the very northern location (latitude 47 °N) used by J. Jin et al. (2010) is approaching the low-temperature limit for soybean. Other reports suggest that PY in recent releases is ~3 t/ha (cited in Liu et al. 2008). Even this value suggests only a modest **yield gap of 30% of FY.**

The steep climb in FY in north-eastern China that is closing the yield gap reflects attention to **crop agronomy**. For example, agronomic changes have included higher plant density, moderate nitrogen and high phosphorus fertilisation, and tillage arrangements (such as ridge planting) that warm the soil in the spring (Liu et al. 2008). Replacement of traditional diverse crop rotations with continuous maize–soybean (one crop per year)—and even continuous soybean cropping—is, however, placing the system under disease threat (for example, from cyst nematode, *Phytophthora* rootrot and *Sclerotinia* stem rot).

Research on **soybean physiology** is strong in Heilongjiang province. There is at least one good study of breeding progress that associates gains in PY with greater GN, greater DM, greater HI, shorter plants and less lodging (J. Jin et al. 2010). Recent varieties had lower LAI and notably higher maximum photosynthetic rate (P_{max}) at the start of the seed stage (known as 'R5' by soybean scientists). Across the vintage series, increases were observed in leaf nitrogen concentration, leaf nitrogen per unit area, nodule weight per plant and total nitrogen uptake (Jin et al. 2011).

6.5 Summary of global soybean

Soybean yields in North and South America are only about one-third of those of maize in the same cropping system. Part of this difference is explained by energy requirements of nitrogen fixation and seed constituents. Soybean contains 20% oil and 40% protein vs. 5% oil and 10% protein in maize. Energetically speaking, 1 t of soybean produced from crops relying on nitrogen fixation is equivalent to about 1.9 t of maize using mineral nitrogen (Connor et al. 2011). The rest of the yield difference presumably results from the lower intrinsic photosynthesis of C_3 soybean vs. C_4 maize (see Section 2.6 on weather and soil parameters as determinants of yield), and the shorter duration of the soybean crop, but comparative yield is further reduced in commerce because soybean yield is usually reported at 8% moisture and maize at ~15% moisture. For these reasons, FY levels are here considered respectable in major production and export regions of North and South America, and also in north-eastern China where the short-season environment is an added constraint.

Soybean results are summarised in Table 6.2. The three cases presented show higher average FY progress than the world average (1.0% p.a. in Table 6.1), because cases from lower performing regions such as the rest of China and in India were not available. The reported soybean yield gap is not large, and most FY progress has been driven by advances in agronomy, especially from the benefits of zero-till in the Americas, facilitated by the advent of glyphosate-resistant varieties in 1996. Modest PY progress (0.4–0.7% p.a.), largely due to breeding, has been achieved in all locations.

In addition to the abovementioned studies, it is also interesting to note breeding progress made in tropical Nigeria, where all soybean varieties now carry a promiscuous

trait for effective nitrogen fixation in African soils (without seed inoculation). The International Institute for Tropical Agriculture (IITA), Nigeria, conducted vintage trials (at 9–11 °N) with 1980–96 varieties and reported PY progress of 23 kg/ha/yr, or 1.1% p.a. of the 1996 PY of 2.0 t/ha (Tefera et al. 2010).

Table 6.2 Summary for soybean farm yield (FY), potential yield (PY) and yield gap in 2009 or 2010, and rate of change over the past 20 years

Country or region	Estimated yield in 2009 or 2010 (t/ha) and yield gap (%)			Estimated rate of change relative to current values ^a (% p.a.)		
	FY	PY	Yield gap	FY	PY	Yield gap
USA	2.9	3.8	31	0.9	0.7	–0.2
Argentina	2.7	3.6	33	1.3	0.4	–0.9
North-eastern China	2.3	3.0	30	1.7	0.4	–1.3
Average (<i>n</i> = 3)	2.6	3.5	31	1.3	0.5	–0.8

a All slopes significant at $P < 0.05$

Source: Estimates from preceding sections of this chapter

For soybean, the modest PY progress from breeding should continue, but as with cereals, no yield-positive agronomic breakthroughs appear on the horizon. Moreover, breeders and agronomists will be occupied maintaining current yield levels, especially given the high frequency of soybean in current cropping systems and the wide range of weeds, pests and diseases affecting soybean. Given these challenges—and that soybean yield gaps are already quite small—the rate of FY progress is likely to slow in the immediate future from the high levels reported in this chapter. Area expansion, especially in South America, is likely to continue, driven by strong demand and prices.

The physiology of soybean is different from that of cereals and so comparisons of DM production, yield and HI should be made with caution. Modern soybean varieties are generally indeterminate but have a relatively short vegetative period (as defined in Table 2.1). Soybean grain yield is reduced by the high energy demands of high oil and protein content, and DM production is also reduced by the metabolic costs of nitrogen fixation, although recent research in other legumes challenges this view (see Section 11.3 ‘Nutrient use efficiency’).

While PY progress in soybean is sometimes associated with either or both of greater DM (and longer crop growth duration) and greater HI, these relationships probably depend on latitude (Lawn and James 2011), with DM assuming more importance at low latitudes where soybean development tends to be accelerated. More in parallel with cereals, increased PY in soybean seems to be always associated with greater GN (seeds/m²) and, in studies in Canada and China, with greater P_{\max} activity before and during pod growth.

Finally, because studies in soybean do not usually account for the substantial leaf fall as crops approach maturity, reported values of final DM (and consequently of HI) are difficult to interpret in a physiological sense. When DM was corrected for leaf loss, Morrison et al. (2000) reported HI to reach only 0.33 in the best variety (from 1990), while J. Jin et al. (2010) measured HI as 0.48 for 2004 varieties. Reported values of >0.5 HI are probably biased upwards by leaf loss and should be treated with caution. As with comparisons of yield, the comparison of HI between cereals and soybean should be corrected upwards, given that soybean seed has a 60% higher energy content on a dry weight basis (see Section 11.4).



Other crops

7



Key points

- This chapter briefly deals with 20 lesser crops for which harvest calorie value (relative to that of wheat) ranges from 23% in sugarcane, to a low 4% in millet, sunflower and sweetpotato, to even less for individual pulses.
- These crops are valuable for diversifying cropping systems and diet, and some (e.g. cassava, millet, cowpea, pigeon pea and/or sweetpotato) provide staple foods in marginal areas of developing countries.
- Over the past 20 years, some of these crops (barley, sugar beet, peas, lupins and sweetpotato) have shown notable decrease in harvested area. In contrast, some other crops (rapeseed, otherwise known as canola, and oil palm) have shown strong area growth. There have also been cases of notable geographic shifts, such as potato moving to Asia, and sunflower moving to regions of the former Union of Soviet Socialist Republics (USSR).
- The current rate of average global farm yield (FY) progress is high (>1.5% per annum (p.a.)) for canola, oil palm, sugar beet and cowpea. By contrast, sorghum and peas, respectively, show low and/or negative rates of FY progress, partly associated with a shift to less favourable environments.
- Studies of PY increase have been scarce, but across 13 examples the average current rate of potential yield (PY) increase is 1.25% p.a. (range 0.5–1.8% p.a.), with cassava and sugar beet showing the best progress. Progress in PY appears to be largely due to breeding efforts.
- Some of the high PY progress attained through breeding probably resulted from earlier neglect of the crop (such as occurred with millet, cassava and narrow-leaf lupin); other progress has likely been hindered by strict quality requirements (e.g. potato) and/or biotic stresses (e.g. potato and pulses).
- Yield gaps were modest (<50% of FY) in developed countries, but often large (>100%) in developing ones; however, FY values for sugarcane were surprisingly high in most developing countries.

Other crops

7.1 Introduction

In addition to the four major grain crops already discussed—wheat, rice, maize and soybean (Chapters 3–6)—many other grains are important for feeding humankind (see Table 1.2). However, limited availability of both data and space has permitted only brief reference in this book to some of these crops in situations where:

- the crop is of high importance (such as in developing countries)
- the crop contains unique features
- documentation of yield improvement is adequate.

Unfortunately, data on potential yield (PY; see Chapter 2 on definitions) and PY progress of such crops are very limited. The crops are presented in order of harvested area as shown in Table 1.2—some coarse grains (barley, sorghum and millet), pulses, rapeseed (including canola), other oilseeds (peanut and sunflower), sugar crops, cassava, oil palm, potato and sweetpotato. In all the tables in this chapter, data are presented for major producing countries in order of current production, followed by harvested area, yield and rate of increase in area and yield; rate of production increase is sometimes referred to in the text.

7.2 Coarse grains other than maize

Table 7.1 shows, in order of importance, 2008–10 annual average world production of barley (*Hordeum vulgare*), sorghum (*Sorghum bicolor*) and millet, mainly pearl millet (*Pennisitum glaucum*), which combine to 235 Mt. Unfortunately, sorghum and millet statistics for Africa, where sorghum and millet are especially important, are not as reliable as those from elsewhere. The area of finger millet (*Eleusine coracana*), a significant crop in eastern Africa and India, in each case occupying more than 1 Mha, is included in millet statistics (FAOSTAT 2013). It differs from sorghum and pearl millet in that it is often grown in areas with adequate rainfall.

These three crops are known to perform relatively well under dry rainfed conditions. Barley is a C₃ plant (see Section 2.6) and adapted to temperate zones, while sorghum and millet are C₄ plants and adapted to tropical and subtropical areas. Since these crops are also typically found in marginal areas in developing countries, the forage value of crop residue is of considerable value, especially in dry years. As food grains, millet is the most important and barley the least.

Barley

For barley, world area is falling sharply (–2.3% p.a.) while yield is rising at only 0.9% p.a. (Table 7.1), such that world production is contracting (0.9% p.a.). Most major producing countries show a similar picture (Table 7.1), including a huge 8.7% p.a. decline in area in the USA. Only Australia recorded a substantial area increase (2.5% p.a.). The crop is used mostly for animal forage, and grain is used for both feed and malt production; very little is used directly as food. Global trade is moderate, with annual exports dominated by France (5 Mt), Ukraine (5 Mt), Australia (3 Mt) and Canada (2 Mt).

Barley, like wheat, has varieties of spring and winter habit, although winter barley is more susceptible to winter kill than is winter wheat. For this reason, western European countries in Table 7.1 grow more spring barley than the higher yielding (but more risky) winter barley. The earliness of spring barleys permits successful growth at higher latitudes and altitudes, and in drier winter-rainfall regions, where seasons are shorter than for common wheat environments. Thus at higher latitude, the Russian Federation grows largely spring barley, while in dry regions at lower latitude, Australia and Morocco plant spring barley in autumn–winter.

Morocco is included in Table 7.1 as one of the driest growing environments for barley, but also because it represents an important crop in a developing country. Harvested area and yield remain static in Morocco, but with high variation in yield (coefficient of variation 48%), reflecting recurrent droughts in a marginal environment. Australia also shows no significant farm yield (FY) progress. In contrast, major barley producing countries of western Europe normally enjoy sufficient rainfall for barley to reach PY, but FY progress is only moderate (0.3 to 0.7% p.a.).

PY progress data are available for barley in the United Kingdom (UK) (Mackay et al. 2010; Bingham et al. 2012) where varieties are grown in a ratio of about one-third winter and two-thirds spring barley. In protected trials, variety yield increased relative to year of release between 1982 and 2007 at a rate of 71 kg/ha/yr for winter barley and 60 kg/ha/yr for spring barley (Mackay et al. 2010). As was also the case with wheat (see Section 3.8), the effect of year (reflecting changes in both agronomy and climate) was not significant over this period, so the PY progress is achieved entirely from breeding. Recent data from trials of the UK Home Grown Cereal Authority (HGCA 2011) reveal that in 2010, PY was ~9 t/ha for winter barley (with a 4% advantage for feed over malting varieties) and 7.5 t/ha for spring barley, so that **relative rates of PY progress were both 0.8% p.a.** This is identical to the breeding progress with spring barley in the

Table 7.1 Annual barley, sorghum and millet grain production, harvested area and yield in 2008–10, and annual rates of change from 1991 to 2010 for the world, principal producing countries and other countries of interest

Country	Average 2008–10			Rate of change ^b (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^a (t/ha)	Area	Yield ^a
Barley					
World	143.4	52.3	2.73	–2.3	0.9
Russian Federation	16.5	7.4	2.15	–5.9	1.5
France	11.7	1.8	6.66	ns 0.4	0.6
Germany	11.6	1.8	6.31	–1.6	0.7
Ukraine	11.0	4.5	2.45	0.9	ns –1.0
Canada	9.6	2.9	3.27	–2.4	ns 0.3
Australia	7.7	4.5	1.72	2.5	ns –0.5
United Kingdom	6.0	1.0	5.83	–1.9	0.3
USA	4.7	1.3	3.76	–8.7	0.9
Morocco	2.6	2.1	1.23	ns –0.4	ns 0.8
Sorghum					
World	60.3	42.3	1.42	ns 0.2	ns 0.1
USA	10.2	2.4	4.31	–4.8	ns 0.2
India	7.3	7.7	0.95	–3.5	ns 0.4
Nigeria	7.2	5.8	1.26	ns 0.8	1.0
Mexico	6.6	1.8	3.71	1.3	0.8
Sudan	3.6	6.3	0.56	ns 1.0	ns 0.3
Australia	2.7	0.7	3.54	1.9	1.9
Ethiopia	2.7	1.6	1.69	3.6	1.4
Millet					
World	31.5	35.4	0.89	–0.3	1.2
India	11.1	11.3	0.99	–1.3	1.9
Nigeria	6.4	4.4	1.44	ns –0.6	2.4
Niger	3.3	6.8	0.49	1.7	1.5
Mali	1.4	1.5	0.92	1.9	1.2
Burkina Faso	1.1	1.4	0.80	0.7	1.4

a What FAOSTAT calls 'yield' this book calls 'farm yield' (FY); see Chapter 2.

b Relative to 2008–10 average; all slopes significant at $P < 0.05$ or better, except Ukraine barley area ($0.05 < P < 0.10$) and where ns = $P > 0.10$

Source: FAOSTAT (2013)

Netherlands (Rijk et al. 2013). Bingham et al. (2012) studied leading western European spring barley varieties released between 1931 and 2005 in protected vintage trials in Scotland and measured an annual relative rate of PY increase equivalent to 0.6% p.a. of the 2005 PY. Despite the constraint that maintaining brewing quality imposes on spring barley breeders, it seems yield progress as good as that with wheat is being achieved (see Chapter 3).

Taking UK farm yield (FY) as 5.83 t/ha from Table 7.1, and assuming one-third winter barley and two-thirds spring barley (as previously mentioned), estimated PY becomes 8.0 t/ha for 2010. **Yield gap, at 37% of FY**, is very close to that for UK winter wheat (34% of wheat FY; Table 3.6). This is to be expected since the same conditions apply to barley as to wheat growing in the UK.

Sorghum

World sorghum area and yield, and hence production, are all static but the aggregate data shown in Table 7.1 hide area decline and static yields outside of Africa—including the USA, the major producer. Sorghum is mostly used as feed, but in Africa (and to some extent, in India) it is a traditional food crop and the straw is valued as forage. World trade is small; the USA is the major exporter (5 Mt p.a.). Ethiopia—the centre of origin for sorghum—is included in the analysis because it shows strong increases in both sorghum area and yield.

The USA grows 100% hybrid sorghum, which competes with maize in the Great Plains region (see Map 3.5). Despite its reputation for drought resistance, sorghum yielded about 33% less than maize under moderately dry rainfed conditions (with sorghum yields around 5 t/ha) and under irrigated conditions (Mason et al. 2008). Also, this maize–sorghum difference appears to be increasing since yields have shown little breeding progress (0.2% p.a., $P > 0.10$), at least for releases between 1956 and 1999 (Mason et al. 2008). Rainfed agronomy may be improving with conservation tillage, earlier sowing, modified row spacing and increased nitrogen fertiliser (Assefa and Staggenborg 2010). However, these practices also benefit maize, which displaces sorghum from more favoured environments in the eastern Great Plains. The net effect appears to be loss of sorghum area and stagnant sorghum yield (Table 7.1). Absence of clear yield improvement in US sorghum hybrids, compared with dramatic increases in maize (see Section 5.2), may also be the result of different levels of investment in breeding.

India grows sorghum (90% rainfed) during the monsoon (*Kharif*) and in the post-monsoon (*Rabi*) seasons, the latter often serving as a dual-purpose crop for forage and grain. Although *Rabi* sorghum is slowly becoming relatively more important, most research has concentrated on *Kharif* sorghum. There is widespread adoption of modern varieties (>90%), including >70% adoption of hybrids (Deb and Bantilan 2003).

The hybrid story is an excellent example of a successful public–private partnership (Pray and Nagarajan 2009). Generally this has involved the International Crops

Research Institute for the Semi-Arid Tropics (ICRISAT)—the source of sorghum inbreds, located in Hyderabad, India—and the Indian public institutions and private breeding companies that produce the hybrids and seed for growers. By analysing data across districts, Ramaswami et al. (2002) found a significant positive relationship between average sorghum yield and the percentage of private hybrids grown. These authors pointed to this relationship as a strong vindication of policy reforms in India in the early 1990s, and similarly of the private–public partnership model that facilitated private plant breeding.

ICRISAT continues to incorporate many biotic and abiotic stress-resistant traits into sorghum inbreds (Kumar et al. 2011) but there is no clear record of water-limited potential yield (PY_w) progress, which may have slowed in the past two decades. Indian national yield, which is very low relative to experimental yields and is not increasing significantly, may also reflect replacement of sorghum by other crops in the more favoured areas, as well as a rise in proportion of generally lower yielding *Rabi* sorghum.

Sorghum production appears to be increasing, notably in Nigeria and Ethiopia, (Table 7.1), as both area and yield increase, the latter from a very low yield base, but is stagnant in Sudan. Yield increase is probably linked to release and spread of higher yielding, mostly open-pollinated varieties, although seed availability is reported as the greatest constraint to adoption (Camara et al. 2006). A major factor in the expansion of sorghum production in Nigeria is the increasing demand for sorghum malt by the brewing industry. Sorghum is also very responsive to microdosing with nitrogen and phosphorus fertilisers (Tabo et al. 2006). However, access to fertiliser, credit and knowledge continue to limit adoption of fertilisation.

Some idea of yield possibilities for sorghum can be gained by comparing western African results (average yield 1 t/ha, increasing 1.1% p.a.) with those from eastern Australia, where sorghum is also grown under semi-arid conditions with similar growing season rainfall. Remarkable recent FY progress (1.9% p.a.) and current FY level (3.5 t/ha, or ~8 kg/ha/mm crop evapotranspiration) in eastern Australia reflect (Stephens et al. 2011):

- controlled traffic
- fertilisation rates more accurately adjusted to crop needs
- improved agronomy (including zero-till)
- improved sorghum hybrids
- wider row spacing (to better meter stored soil water supply).

Stephens et al. (2011) argue there is still a **yield gap of 100% (of FY) to PY_w in the Australian situation**, so clearly yield gap in Africa, with FY generally less than 1.5 t/ha, would be at least double this value (>200%). In addition, Africa faces at least four unique proximate yield constraints—chronic low soil fertility, bird damage, widespread incidence of the parasitic weed *Striga* and limited use of hybrids, despite a level of hybrid vigour that provides about 40% yield increase over OPVs.

Millet

Millet is an important traditional food crop in the semi-arid tropics of north-western India and the Sahelian region of western Africa, to which the four African countries in Table 7.1 belong. In contrast to the other coarse grains, world millet production is increasing at a rate of 0.8% p.a. Area decreases (except in Africa, but globally averaging -0.3% p.a.) have been countered by very good FY increase rates of 1.2–2.4% p.a. from the major producers (Table 7.1), although coming off a very low yield base. International trade in millet is very minor.

Pearl millet is an important traditional food crop in its growing region in India and western Africa, with a chemical composition similar to wheat; millet straw is valued as forage. Finger millet, a relatively unimproved crop, is emerging in eastern Africa as an important health food especially for urban dwellers and newly weaned children. Its straw is valued as forage and as thatch.

Like sorghum, millet is a warm-season crop, renowned for drought resistance that is partly linked to rapid development (drought escape) and high tillering capability. For a crop grown under marginal conditions (>90% rainfed), FY progress in India is remarkable and partly due to adoption of hybrids from the 1960s that later incorporated resistance to the dominant disease, downy mildew. After establishment in 1972, ICRISAT was heavily involved in millet improvement following the same model of private–public partnership used for sorghum. Currently, Indian farmers grow about 85% improved varieties, including 50% hybrids (Pray and Nagarajan 2009). These improved varieties likely explain most of the yield increase because agronomic inputs (e.g. chemicals and water) for millet are usually minimal. Millet area is declining as Indian people eat less millet, partly because of price policies favouring wheat and rice consumption.

ICRISAT has also been involved in releasing and promoting improved millet varieties (OPVs) in the Sahelian part of western Africa, in particular Mali (growing of hybrid millet is still minimal in the region). Adoption of OPVs has been slower than in India but nonetheless, a steady increase in adoption (Camara et al. 2006) is likely to be one driver of the apparently strong yield gains in this region (Table 7.1). It is interesting that millet-growing regions in Niger and Burkina Faso have been the sites of several widespread, novel yield-enhancing agronomic innovations—farmer managed tree regeneration in Niger (see Box 11.3 on agroforestry) and soil pitting (*zai*) and stone contour bunding in Burkina Faso (Reij et al. 2010).

There appear to be no clear data on breeding progress for PY_w in millet, either in India or western Africa, but if national yield progress figures in Table 7.1 are any indication, some progress must be present. The level of PY_w is also unknown, but yield gaps are likely to be very high. As with sorghum, chronic low soil fertility, incidence of *Striga* and drought are the major constraints to millet production in Sub-Saharan Africa.

7.3 Pulses

Pulses considered here comprise:

- five temperate grain legumes—peas,⁴⁰ chickpea, broad (or faba) bean, lentil and lupins
- three warm area legumes—beans,⁴⁰ cowpea and pigeon pea.

Irrigation of these crops is minimal. Lentil, chickpea, cowpea and pigeon pea are particularly suited to dry conditions.

Total annual global pulse production is 65 Mt (Table 7.2), with bean (*Phaseolus vulgaris*) by far the most important, followed by pea (*Pisum sativum*) and chickpea (*Cicer arietinum*). Table 7.2 also shows that average FY for pulses globally is about 1 t/ha, with only low to moderate increases in global production, area and yield over the past 20 years. Nevertheless, pulses are the fifth largest source of edible protein (Table 1.2) and are of particular importance to many poor countries.

Table 7.2 Annual global pulse production, harvested area and yield in 2008–10, and annual rate of change from 1991 to 2010

Pulse crop	World production		Principal producers		World area		World yield ^a	
	(Mt)	Change ^b (% p.a.)	First	Second	(Mha)	Change ^b (% p.a.)	(t/ha)	Change ^b (% p.a.)
All pulses	65.0	0.9	India	Canada	73.2	0.4	0.89	0.6
Beans	21.6	1.4	India	Brazil	27.3	0.5	0.80	1.0
Peas	10.1	-2.0	Canada	Russian Federation	6.4	-1.0	1.59	-0.9
Chickpea	10.0	1.2	India	Pakistan	11.5	ns 0.3	0.87	1.0
Cowpea	5.9	3.3	Nigeria	Niger	11.0	1.8	0.54	2.1
Faba bean	4.2	1.5	China	Ethiopia	2.5	0.8	1.70	0.8
Pigeon pea	3.9	1.7	India	Myanmar ^c	4.8	0.8	0.81	1.0
Lentil	3.8	1.8	Canada	India	3.8	0.9	1.00	1.1
Lupins	1.0	-3.6	Australia	Poland	0.8	-4.8	1.29	ns 0.5

a What FAOSTAT calls 'yield' this book calls 'farm yield' (FY); see Chapter 2.

b Expressed as a percentage of the 2008–10 mean value; all slopes significant at $P < 0.05$, except ns when $P > 0.10$

c Myanmar grows a suite of other warm-season pulses including mungbean (*Vigna radiata*) and black gram (*Vigna mungo*), which may be included in the pigeon pea or bean statistics.

Source: FAOSTAT (2013)

⁴⁰ Peas here refers to dry peas, and beans to dry beans, as in FAOSTAT (2013), in order to distinguish them from green peas and beans, respectively, which are considered vegetable crops.

Beans

Brazil, where beans are an important staple food, is the largest producer. In 2008–10, Brazil produced 3.4 Mt, and although crop area has been declining at a rate of –1.9% p.a. (relative to the 2008–10 average), over the past 20 years there has been a strong increase in FY of 2.3% p.a. Active public breeding programs in Brazil have reported overall progress of up to 1.9% p.a. (Chiorato et al. 2010). However, without analysis of the fractions due to breeding for PY improvement, better disease resistance, and increase in proportion of irrigated beans in the dry winter season, it is difficult to know the true PY increase.

India is apparently the second largest producer of bean (also 3.4 Mt) and Myanmar follows closely with 3.2 Mt, but in both cases what is called 'bean' is not always (or even often) *Phaseolus vulgaris*, but rather a suite of other minor warm-season pulses including mungbean (*Vigna radiata*) and black gram (*Vigna mungo*). Even so, both the total stagnation of harvested area and yield in India and the strong increases in both area (4.3% p.a.) and FY (2.6% p.a.), relative to 2008–10 values, in Myanmar are noteworthy.

Peas

Peas have decreased globally in both area and yield (Table 7.2), while production has shifted from humid Europe to the semi-arid western prairies of Canada where harvested area has increased at a rate of 4.7% p.a. over the past 20 years. FY for Canadian pea is steady at 2.2 t/ha and annual production in 2008–10 reached 3.3 Mt. By comparison, France is now a small producer, but a more favourable climate sustains a higher FY of 3.8 t/ha (2008–10).

Expansion of peas in Canada is a notable success story of research, development and extension by the Saskatchewan Pulse Growers, funded by farmer levies and public sector sources (Gray 2011). Veeman and Gray (2010) calculated a pea variety index—a PY index, based on varieties grown and their relative yield advantages from trials (see Section 2.2)—for the pea-growing region, and determined that PY of varieties in farmers' fields increased at a rate of 1.4% p.a. during the 20 years to 2006. This result contrasts with the lack of FY progress over the same period, which the authors suggest may be related to the very rapid area increase (bringing learning problems and probably replacing summer fallow) and to disease pressures on-farm.

Chickpea

Turkey was a traditional chickpea producer, but has now almost ceased production with only 0.5 Mt grown annually in 2008–10, as harvested area decreased at a rate of –4.5% p.a. over the past 20 years. India by comparison, at 6.7 Mt, was the biggest chickpea producer, but has not increased harvested area; FY averaged only 0.86 t/ha 2008–10, with a moderate rate of 0.7% p.a. progress, and **the yield gap is ~110% of**

FY according to Waddington et al. (2010). ICRISAT works on chickpea and has claimed breeding breakthroughs on earliness, and (recently) more extensive and deeper rooting varieties; some of the FY progress in India may derive from the early varieties released 20 years ago.

Cowpea

The minor pulse crop, cowpea (*Vigna unguiculata*), originated in western Africa and continues to be mostly produced there with substantial increases in production (Table 7.2). Harvested area in western Africa (for countries see Table 5.5) has increased at a rate of 1.7% p.a., and FY at a rate of 2.2% p.a., over the past 20 years, but the 2008–10 average FY was still only 0.51 t/ha. However, one country of this region, Nigeria, has achieved a higher FY of 0.96 t/ha (average 2008–10) and this figure appears to be rising strongly (2.2% p.a.).

Cowpea breeding progress was measured across 1974–2004 releases from the International Institute of Tropical Agriculture (IITA) in a vintage trial at one savanna location in north-western Nigeria with a 4-month wet season (Kamara et al. 2011). This is considered to measure PY_w progress, which was highly significant for both determinate and semi-determinate varieties, at rates of 1.6% p.a. relative to the 2004 yield of 1.59 t/ha for the former, and 1.9% p.a. relative to the 2004 yield of 1.64 t/ha for the latter. Crop growth duration and total dry matter (DM) both increased in line with the yield increase.

The Kamara et al. (2011) rates represent excellent progress but may reflect increased disease resistance as well as greater PY_w . Even so, these 2004-release yields agree with Waddington et al. (2010), who estimated **the yield gap to be 145% of FY for western African cowpea**. As pointed out by Hall et al. (2003), low western African FY could be partly explained by the common farmer practice of intercropping cowpea in this generally stressful environment.

Faba bean

Faba bean (*Vicia faba*), also known as broad bean, is an important traditional food source in Ethiopia. Strong rates of increase have occurred over the past 20 years in both harvested area (2.5% p.a.) and FY (1.7% p.a.), although FY was only 1.3 t/ha in 2008–10. For comparison, FY in more humid China was 1.8 t/ha, and in France, with a very favourable climate, was 4.4 t/ha. There appears to be little information on PY and on FY constraints in faba bean.

Pigeon pea

Pigeon pea (*Cajanus cajan*) is a deep-rooted semi-perennial grain legume with good drought resistance. India produces 60% of world pigeon pea, often intercropped

with cereals, but has shown no increase in either harvest area or farm yield over the past 20 years of this important protein food source in marginal areas. By comparison, Myanmar has shown remarkable rates of increase in both area (4.9% p.a.) and FY (3.0% p.a.), reaching FY of 1.24 t/ha in 2008–10, to become the world's largest exporter of pigeon pea. Pigeon pea is also a new food crop of growing importance in eastern and southern Africa. ICRISAT works on pigeon pea but has reported little on progress, apart from the development, in collaboration with Indian partners, of a system to produce F_1 hybrids. The hybrids were firstly based on genetic male sterility in 1991, and more recently using cytoplasmic male sterility, which is more promising for seed production. Hybrid vigour is reported as very high (> 25%).

Lentil

Canada is now the largest producer of lentil (*Lens culinaris*), producing annually on average in 2008–10 about 1.5 Mt, almost 30% of global lentil supply. Harvested area in Canada has increased at a rate of 3.8% p.a. over the past 20 years, but FY did not change significantly, as was the case with pea in Canada; FY averaged 1.51 t/ha in 2008–10. Western Canada has moved to capture the world lentil market, in addition to the pea market.

Through increased harvest area, the second largest lentil producer, India, has slowly increased annual production to reach 0.9 Mt in 2008–10; FY has remained stagnant over the past 20 years at 0.67 t/ha. Meanwhile, as with chickpea, Turkey is no longer a major producer, with only 0.3 Mt.

Lupins

Traditionally, in Europe (e.g. Poland) *Lupinus albus* or white lupin was grown, but lupin production is now dominated by narrow-leaf lupin (*Lupinus angustifolius*), representing 60% of global production and found primarily in southern Australia. This species is interesting because it is a relatively new crop for the world, and one for which detailed analysis of breeding progress is available (Stefanova and Buirchell 2010).

Narrow-leaf lupin was domesticated and improved by Australian breeders as a grain legume for acid, sandy soils in the dry Mediterranean climate of Western Australia, to which *L. albus* was not well adapted. The first variety was released in 1967 for rotations with wheat there, and production subsequently spread to eastern Australia. Production peaked at over 1.6 Mt in the late 1990s, but area has since declined substantially, while FY has stagnated over the past 20 years. In 2008–10, Australian annual production was only 0.65 Mt with an FY of 1.19 t/ha.

Domestication initially involved selection for uniform germination, low grain alkaloid content and non-shattering pods—trait selection that was soon followed by selection for early flowering. Under best agronomy across 10 years (1997–2006), and in 14 representative locations in Western Australia, Stefanova and Buirchell (2010) showed

that from the first early variety (released in 1973) to releases from the last breeding cycle (2004), **lupin PY_w increased by 20 kg/ha/yr, or 1.4% p.a. of the 2004 PY_w of 1.4 t/ha.** Over the same testing period, FY averaged 1.1 t/ha in Western Australia, suggesting a **yield gap of only ~30% of FY.**

Further breeding progress is anticipated as the program moves to recurrent selection and shorter breeding cycles. There is no doubt that early planting—facilitated by the widespread adoption of direct seeding (see Section 3.5 on wheat in Australia)—has been important for this new crop, which grows slowly in cool winter temperatures. Adoption of lupin is still limited, however, by low yields (relative to cereals), and the challenge of developing a reliable, high-priced food market for the grain, as an alternative to the current animal feed market. The lupin experience is especially relevant for advocates of cropping diversification through development of new crops.

Experience in Australia with other temperate pulses (peas, chickpea, faba bean and lentil) has been similar to that for lupin. Apart from peas, all these pulses are relatively new crops for Australia. Like lupins, the area of peas has declined, while the newer crops, faba bean, chickpea and lentil, have increased strongly from low bases; even so Australia's annual average total pulse area of 1.5 Mha (2008–10), down 12% from 1991–93, and less than 10% of the temperate cereal area with which the pulses are rotated. Moreover, none of the five pulses show significant FY progress over the past 20 years. Compared with wheat and barley, FY remains low at ~1.0 t/ha—except faba bean at ~1.5 t/ha. This is despite considerable investment in research, development and extension, although admittedly, much less than for cereals. The slow progress with pulses in Australia reflects the challenge of lifting pulse yield in dry environments, when paradoxically the second continuing yield constraint is disease; finally, pulse export markets are considered unreliable, notwithstanding the success of Canadian exporters.

7

Conclusion for pulses

Grain legumes are rich in protein (and sometimes oil) suited for the human diet, are grown without nitrogen fertiliser and offer diversification advantages in cereal rotations. Given popular enthusiasm for the benefits from these crops, the global picture on pulse area change and yield progress is disappointing. It is noteworthy that pulse food consumption per capita declines with rise in income, so global demand increases with population growth but decreases as livelihoods improve. Pulses are also suited to animal feed, but currently this market has been captured by soybean meal.

In terms of crop improvement, pulses face not only abiotic (drought, heat and soil) problems, but also high levels of biotic stresses (weeds, insects, diseases and viruses) (Siddique et al. 2012). The poor early competitiveness shown by pulses enables weeds to prosper, and the high nitrogen level in pulse foliage favours infestation from pests and diseases. Also, legume nitrogen fixation is strongly dependent on soil phosphorus status, which is often limiting in tropical soils.

As mentioned above, FY progress of cowpea in western Africa looks promising, although the apparent high progress has been achieved from very low initial yields. Yield gaps appear low for lupins in Western Australia, and for peas and lentils in Canada, where pulses have been a success story, but yield gaps are likely to be much higher in most developing countries.

Pulse crop management is generally more difficult than for cereals, and technology transfer can be slow—especially when dealing with farmers of smallholdings (Siddique et al. 2012)—complicated by the fact that pulses are generally in need of integrated weed, disease and pest management. Siddique et al. (2012) argue that pulses are especially suited to conservation agriculture, but this notion overlooks the serious weakness of low levels of persistent crop residue following harvest. With the partial exception of pigeon pea and lupins, all pulses (and soybean) provide small amounts of residue, which furthermore is subject to rapid breakdown because of its relatively high ratio of nitrogen to carbon. For most pulses, a large proportion of fixed nitrogen is removed when grain is harvested, leaving a small net contribution to soil ranging from zero to ~60 kg N/ha.

Good pulse agronomy requires moderately high levels of farmer skill (especially in pest control) and given that these crops are primarily grown by farmers of smallholdings, it remains difficult to close yield gaps without very concerted effort by extension specialists. This is in contrast to yield progress seen for soybean—now the major grain legume (see Chapter 6)—which reflects a different situation of medium to large-scale farmers, operating in environments with generally adequate moisture and strong markets.

As recorded earlier for soybean, breeding efforts are contributing to moderate PY progress in legume crops, as has been seen with cowpea in Nigeria and narrow-leaf lupin in Australia (although the fast progress with lupin may reflect easy advances in the early post-domestication period). Singh et al. (2007) reported only ~0.4% breeding progress for PY of irrigated beans in the absence of pests and diseases in the western USA, with multiple breeding objectives (pests, diseases and grain quality) slowing breeding progress for PY. This is likely to be general for other pulses and situations discussed here. However, the likely release of genetically engineered (GE) virus-resistant bean in Brazil (James 2012) and GE pod borer-resistant cowpea in western Africa (T.J. Higgins, pers. comm.) is grounds for some optimism.

A further impediment to breeding progress is lack of critical mass in pulse breeding efforts at most locations, and also the general absence of private sector involvement. This gives international agricultural research centres, with global mandates, a key role in pulse improvement, ideally amassing the necessary sort of multidisciplinary, international collaboration, as was recently outlined for bean (*Phaseolus vulgaris*) by McClean et al. (2011). The likelihood of transgenes for improving pulse resistance to pests and viruses adds further strength to such a collaborative approach.

7.4 Rapeseed (canola)

Discussion of rapeseed here includes two *Brassica* species:

- canola (*B. napus*), which predominates global production for reasons explained below
- mustard (*B. juncea*), which is only grown in South Asia.

With about 40–45% oil and 20% protein content (the exact opposite to soybean), the rapid global expansion of canola (Table 7.3) has been driven by demands for vegetable oil and biodiesel, by breeding advances, and by the role of canola as a ‘break crop’ in wheat cropping systems. Most canola is autumn planted, and is either spring habit at low latitudes (<35°, such as India and Australia), or winter habit at intermediate latitudes (e.g. France).⁴¹ At even higher latitudes (e.g. Canada), spring canola is spring planted.

Table 7.3 Annual rapeseed^a production, harvested area and yield in 2008–10, and annual rates of change from 1991 to 2010, for the world and the five principal producing countries

Country	Average 2008–10			Rate of change ^c (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^b (t/ha)	Area	Yield ^b
World	60.2	31.5	1.91	1.8	1.7
China	12.9	7.1	1.83	0.7	2.0
Canada	12.8	6.6	1.93	2.0	1.7
India	6.5	5.9	1.11	ns –0.2	1.4
Germany	5.7	1.4	3.98	2.3	1.7
France	5.0	1.5	3.46	3.2	0.6

a This is mostly canola (*Brassica napus*) but mustard (*B. juncea*) predominates in India.

b What FAOSTAT calls ‘yield’ this book calls ‘farm yield’ (FY); see Chapter 2.

c Percentage of 2008–10 average; all slopes $P < 0.05$ or better except France yield ($0.05 < P < 0.10$) and India area ns = $P > 0.10$

Source: FAOSTAT (2013)

⁴¹ As with wheat (see Section 2.6) winter-habit canola requires a period of cold ($T_{\min} \leq 15^\circ\text{C}$) to initiate flowering, but spring-habit canola does not.

Traditional varieties of rapeseed were grown mostly as fodder crops because the seed was unsuited to human consumption. The first breeding breakthroughs, which occurred in Canada in the 1960s, changed this situation with the development of double zero *B. napus*. 'Double zero' refers to seed with zero erucic acid in the oil, and low levels of glucosinolates in the meal; both compounds seriously limited the use of these by-products. Varieties with these traits were named 'canola' by the Canadians, a name now widely used in the industry because all *B. napus* varieties for human consumption have the double zero trait.

The second breeding breakthrough occurred in the 1980s with the perfection of several genetic systems to produce hybrid seed, which would yield 5–20% more than open-pollinated varieties. These genetic systems gave the private sector a strong incentive to become involved in canola breeding, and in North America this was further reinforced with the arrival of GE herbicide-resistant canola in the 1990s.

North-western Europe is a highly favourable environment for winter canola where hybrid use had risen to ~60% of the European acreage by 2009–10 (W. Cowling, pers. comm. 2013). Germany (65% hybrid) has the highest national FY at close to 4 t/ha, and FY has increased strongly in most countries in the past 20 years. These are well-watered environments, and some limited PY data are available in recent reports from Austria and the UK.

Across official 1981–2010 trials in Austria, winter canola PY increased at a rate of 70 kg/ha/yr for OPVs and 75 kg/ha/yr for hybrid varieties (Mechtler and Hendler 2011). Hybrid PY reached 5.5 t/ha in 2010, meaning that **PY progress over the 30 years was 1.4% p.a. of the estimated 2010 PY**; OPVs were 0.3 t/ha below hybrid varieties on average. Curiously, Europe reports yield advantages of hybrids over OPVs at only 5% in trials, but 10% on farms (W. Cowling, pers. comm. 2013).

Similar results have been seen in the official national trials in the UK, where Mackay et al. (2010) measured breeding progress of 59 kg/ha/yr in protected plots between 1982 and 2007; PY reached 4.5 t/ha in 2007, **which equated to PY 1.3% p.a. progress**. As with wheat and barley in the UK, there was no significant PY progress due to improved agronomy in the study period. In both Austria and the UK, breeding also raised oil content at an annual rate of ~0.1% (absolute).

The UK is only a modest canola producer: of 0.6 Mha of crop, 37% is planted to hybrid varieties, and in 2008–10, FY averaged 3.38 t/ha. Based on the above PY, the **UK yield gap can be estimated to be 33% of FY**, and—as a rather unusual case—is increasing. This has occurred because, unlike PY, FY progress over the past 20 years at a rate of 28 kg/ha/yr (or 0.8% p.a. relative to the 2008–10 FY) has been slower than PY progress.

Canola is known for high sulfur demand. Thus, in regard to slow FY progress, Booth et al. (2005) emphasised that UK FY was particularly constrained by foliar disease and sulfur deficiency—the latter having arisen from reduced sulfur emissions from UK power

stations, which had previously (as an unintended benefit) fertilised the landscape with ample sulfur. Berry and Spink (2006) concur, but add other constraints on FY progress, such as shorter rotations, minimum tillage and excessively early sowing. Regardless of possible constraints to FY progress, a yield gap of only 33% in 2008–10 can hardly be considered large, and is similar to that for winter wheat in the UK (see Section 3.8).

Good PY progress between 2001 and 2009 (equivalent to 1.4% p.a. relative to the 2009 PY of 2.4 t/ha) and increasing oil concentration has also been reported for canola in China (D. Li et al. 2011). However, the current PY value is low, as is FY (1.83 t/ha, Table 7.3) for a predominantly autumn-sown canola grown with ample moisture, although FY progress is strong (2.0% p.a., Table 7.3). The time constraints imposed by the double crop system within which canola is grown may be the cause of the relatively low yields.

Table 7.3 reveals that good FY progress has been achieved in Canada (1.7% p.a.) and India (1.4% p.a.), both of which grow the crop under limited moisture. India, which grows largely *B. juncea*, has been running a special extension campaign to boost production. Despite the water limitations, progress for PY_w in Canada has been strong. Veeman and Gray (2010) calculated the canola variety index (see Section 2.2) for western Canada, and found that between 1986 and 2006 it rose by 36%, influenced by the development of hybrids and privatisation of breeding in the late 1980s. Over this period, **the rising index points to PY_w progress of 1.0% p.a. relative to 2006**—clearly a major factor driving the strong FY progress. There is, however, insufficient information to calculate yield gap.

Hybrid varieties appeared in the mid-1990s in Canada and by 2011 had occupied 85% of canola area (W. Cowling, pers. comm. 2013). With ~20% yield advantage over OPVs, hybrids have contributed to breeding progress in Canada; one system for producing hybrid seed is GE-based. Moreover, GE herbicide-resistant canola varieties, mostly now hybrids, occupied 96% of the Canadian planted area in 2011 (James 2011). Such varieties fit easily with newly adopted conservation agriculture and have contributed to the success of canola in drier parts of western Canada.

The above achievements demonstrate that canola breeding has been a recent worldwide success story. It is no coincidence that there is now substantial private sector involvement in this activity, including investment from leading multinational seed companies.

A crop physiological approach for canola in the UK by Berry and Spink (2006) suggested ample scope for increasing PY to 6.5 t/ha, or even 9 t/ha (in 2007 it was 4.5 t/ha). A review by Abbadi and Leckband (2011) anticipated PY progress through broadening of the genetic base, and suggested there was also much opportunity for developing varieties to deliver oil of improved nutritional quality—for example, high oleic varieties are already being grown—with no likely negative impact on PY. Canola can also play a vital role in diversifying cereal crop rotations.

7.5 Other oilseeds—peanut and sunflower

Peanut (*Arachis hypogaea*), or groundnut, is the most important oilseed after soybean and canola, followed by sunflower (*Helianthus annuus*). Peanut is a crop of reasonably humid subtropical and tropical conditions and found mostly in developing countries (Table 7.4) where it is an important source of high-energy, high-protein food, often eaten without extraction of oil. Only small quantities of peanut are traded internationally.

Sunflower is a warm-season crop in moderately humid subtropics and temperate parts of more developed countries, especially across eastern Europe, Ukraine and southern parts of the Russian Federation (Table 7.4). Sunflower seeds are mostly crushed for oil (content about 40–50%) and significant quantities of seed, oil and cake (for animal consumption) are traded internationally; the biggest exporters are Ukraine (5 Mt seed equivalent) and Argentina (2 Mt). A small but growing proportion of sunflower, known as ‘confectionary sunflower’, is grown for direct human consumption of the kernel after removing the seed coat.

Peanut

Peanut is a low-growing, warm-season legume of indeterminate habit with the unique property of geocarpy—burying its seed pods during seed filling. This habit removes the need for stems to support seeds and thus creates the potential advantage of a very high harvest index (HI). However, the habit also increases the risk of fungal infection (resulting in aflatoxin contamination and possible rejection of the grain), and introduces a need to lift the top 5–10 cm of soil during harvest.

Most peanut is grown with moderate to high in-crop rainfall, while ~20% of peanut in India is grown with irrigation during the dry season. Yield is usually quoted as in-shell (or dry pod) weight (where seed weight equals ~67% of in-shell weight) and seeds contain ~25% protein and 45–50% oil (Knauft and Wynne 1995). Peanut is largely grown in the developing world, except for the USA. Production is dominated by China and India (Table 7.4), but is nevertheless widespread through Asia, Sub-Saharan Africa and the peanut centre of origin, South America.

In China over the past 30 years, production has quadrupled as both area and yield progress have remained strong. Yield progress in China is attributed to widespread adoption (>90%) of improved varieties, use of fertilisers and of plastic film over the soil, and good pest and disease control (Bantilan et al. 2003). Yield gains in parts of India and Sub-Saharan Africa also appear to be related to the adoption of improved varieties, many of which have origins traceable to ICRISAT (Bantilan et al. 2003). Special constraints for peanut production are supply of seed of improved varieties and maintenance of seed viability in warm humid climates. These constraints may partly explain the variable progress evident in developing countries outside of China.

Table 7.4 Annual peanut^a and sunflower production, harvested area and yield in 2008–10, and rate of change from 1991 to 2010, for the world and the principal producing countries

Country	Average 2008–10			Rate of change ^c (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^b (t/ha)	Area	Yield ^b
Peanut					
World	38.7	24.4	1.58	0.6	1.4
China	14.9	4.4	3.39	1.6	1.7
India	7.0	5.9	1.21	–2.4	1.0
Nigeria	3.2	2.6	1.24	2.3	1.5
USA	2.0	0.5	3.80	–2.1	1.7
Sunflower					
World	33.4	24.4	1.37	1.4	0.5
Ukraine	6.6	4.3	1.51	3.8	1.0
Russian Federation	6.4	5.7	1.11	2.8	1.4
Argentina	3.1	2.0	1.55	–2.3	ns –0.3
China	1.8	1.0	1.89	1.3	ns 0.2
France	1.7	0.7	2.42	–3.2	0.6
USA	1.4	0.8	1.66	–2.6	ns 0.6
Hungary	1.2	0.5	2.32	1.2	1.6

a For peanut, production and yield refer to in-shell weights; for sunflower the reference is to seed yield.

b What FAOSTAT calls 'yield' this book calls farm yield (FY); see Chapter 2.

c Relative to the 2008–10 average; all slopes significant at $P < 0.10$ or better, except ns = $P > 0.10$

Source: FAOSTAT (2013)

Yield has also progressed strongly in the USA, but area has been contracting (Table 7.4). Several breeding programs operate in the USA (Isleib et al. 2001) but—neither there nor elsewhere—does published quantitative information on breeding progress or current PY for peanut appear to be available.

Sunflower

Sunflower has some unique characteristics. By virtue of its deep rooting, this warm-season crop can grow and yield under relatively dry conditions, provided that large reserves of stored soil water are available. Sunflower also has the ability to withstand

the high internal water stresses that are required to extract stored soil water. As a result of breeding selection, sunflower varieties are strongly determinate, do not branch, and produce large leaves and a single large terminal inflorescence (compound flower) or capitulum. For a C_3 plant, sunflower also has high leaf maximum photosynthetic rate (P_{max}), and because of this and the other reasons just mentioned, it has attracted much interest from crop physiologists.

Sunflower shows unusually high levels of hybrid vigour (or 'heterosis') and since the 1980s, most new sunflower varieties have been F_1 hybrids, largely from private breeding companies. Notwithstanding this, sunflower grain yield—FY, or seed yield as it is commonly termed—appears to be increasing not at all or only moderately in major producing countries (Table 7.4), except for the Ukraine and the Russian Federation, where FY increase is strong even as there are very rapid increases in harvested area. In contrast, area is decreasing in Argentina, France and the USA.

The lack of progress in FY in some countries is even more surprising when compared with changes in PY—here considered as PY_w as appropriate for the moderately dry conditions usually faced by the crop. Thus **rates of PY_w progress due to breeding** over the past 20–30 years were estimated to be:

- **1.2% p.a.** in South Africa for varieties released during 1980–2006 (Chigeza et al. 2012)
- **0.7% p.a.** in France for 1978–2003 releases (Lecoeur et al. 2011)
- **1.4% p.a.** in Austria for 1980–2010 releases (Mechtler and Hendl 2011).

Oil content has also increased in South Africa and Austria. The most detailed studies of yield progress, however, come from Argentina.

Sunflower is grown in the north, centre and south of Argentina between latitudes 26 and 39 °S. Grassini et al. (2009a) studied FY variation in 169 rainfed fields across the central region of Argentina over the period 1995–98. Seed yield was plotted against water supply, giving a linear boundary function for the highest FY values vs. water supply. The slope was 8 kg/ha/mm of water supply (stored soil water plus rainfall) with x-axis intercept of 75 mm (below which there was no yield). If the linear boundary function represents PY_w , and the average slope of all fields was about one-half of this number, this dataset suggests that **the average yield gap was ~100% of FY**. Grassini et al. (2009a) attributed the yield gap to:

- deficient or excessive rainfall at various critical stages of crop development (although by definitions used here, deficient rainfall is not a manageable constraint)
- inadequate crop nutrition
- disease
- lodging.

Rapid expansion of soybean in Argentina during the past 20 years has reduced the proportion of sunflower grown in the highest yielding central region (i.e. the western

pampas zone), and has instead pushed sunflower into generally less favourable, drier areas. This trend is the major explanation of recent stagnation in FY over the country as a whole (de la Vega and Chapman 2010).

The second explanation for FY stagnation in Argentina is that breeding progress for seed yield has not been high since the mid-1990s, although this has been offset by steady improvement in oil content (de la Vega et al. 2007), which determines the grain price. Thus for hybrids released between 1983 and 2007, **oil PY (kg/ha) has risen at a rate of about 0.6% p.a. in the central region, 0.5% p.a. in the northern region and 0.4% p.a. in the southern region** (de la Vega and Chapman 2010). During this period (and especially since 2000), breeders have made good progress in developing hybrids resistant to *Verticillium* wilt, downy mildew and *Sclerotinia* head rot, while new imidazole-resistant hybrids are facilitating adoption of zero-till, and breeding improvements have been made to oil quality (A. Hall, pers. comm. 2013)

Assuming oil content of 50% (Hall et al. 2013), the results of de la Vega and Chapman (2010) on oil yield can be converted to estimate regional 2007 PY_w (seed yield) values of 3.42 t/ha (central), 2.57 t/ha (northern) and 2.98 t/ha (southern). Sunflower area is distributed across the three regions, with the largest area (44%) found in the south, followed by the central (37%) and northern (19%) regions (Hall et al. 2013); together these numbers indicate a national PY_w of 3.1 t/ha. However, the FY values shown in Table 7.4 cannot be used to calculate seed yield gap, as these values have been somewhat depressed because 2 of the 3 years in the average were droughted. Instead, the average FY for the past decade (1.68 t/ha) is used to suggest a **seed yield gap of 85% relative to this FY**.

This yield gap analysis can be compared to the following analysis of Hall et al. (2013), who used average yield of all current commercial hybrids in trials between 2000 and 2007 to estimate PY_w (as defined here) and calculate yield gap. Estimated national PY_w was only 2.6 t/ha and yield gap only 53% of FY. It is possible that inclusion of all current hybrids did not allow for well-recognised region-by-hybrid interactions (de la Vega and Chapman 2010) and hence Hall et al. (2013) may have underestimated PY_w . Yields under irrigation quoted in Hall et al. (2013) suggest that PY in Argentina is ~50% above PY_w . This information provides an important measure of the effect of water deficit in sunflower production in Argentina.

In conclusion, sunflower is not a high-yielding oilseed (compared with canola or soybean) despite widespread use of F_1 hybrids, partly because it sees generally drier conditions. However, large potential remains for yield gap closing, not only in Argentina, but especially in the major producing countries of the Russian Federation and Ukraine. In these countries, agriculture is still recovering from the breakup of the former USSR and there are notable lags in the use of best hybrids and crop management (A. de la Vega, pers. comm. 2013) compared with the similar environment of nearby Hungary, where a more substantial FY level has been achieved (Table 7.4).

7.6 Sugarcane and sugar beet

Sugarcane (*Saccharum* spp.) is a C₄ perennial grass for warm climates. It is propagated vegetatively from stem sections (or setts). Canes are harvested close to ground level in the first (or planting) year, after which sugarcane re-sprouts from stem bases to give ratoon crops, several of which may be harvested in subsequent years.

Sugar beet (*Beta vulgaris*) is a C₃ annual or biennial broadleaf crop for temperate climates. It is propagated from seed, normally spring planted, and the storage root is harvested before the next winter. If left until the following spring, vernalisation stimulates flowering and yield suffers.

Both sugarcane and sugar beet store sugar (mostly sucrose) in non-reproductive organs. Sugarcane reaches equivalent harvest index values of ~0.4, measured as sugar relative to top dry weight (P. Jackson, pers. comm. 2012), while for sugar beet this ratio can reach >0.6, measured as sugar relative to top plus storage root dry weight (Jaggard et al. 2010). Both crops are usually grown with ample water supplies, from rainfall and/or irrigation.

Total sugar obtained globally from sugarcane is somewhat unclear (see below), but assuming 10% sugar content in cane, it is probably ~170 Mt annually of sugar in 2008–10 (Table 7.5), including that which goes directly to ethanol production in Brazil. By comparison, sugar beet production of 226 Mt (Table 7.6), with 18% sucrose (Jaggard et al. 2010), delivers only 41 Mt of sugar. Global sugarcane production has expanded over the past 20 years at a rate of 1.9% p.a. (relative to 2008–10 production), probably reflecting improved world prices and strong demand. This has in part been assisted by Brazilian policy decisions to divert a large part—an estimated 55% for 2010–11 (Valdes 2011)—of their huge sugarcane crop (685 Mt, Table 7.5) to ethanol production.

Meanwhile, in the same time frame, global sugar beet production has declined (–1.2% p.a.) with a substantial contraction in planted area, offset to some extent by yield increases (Table 7.6). Decreased sugar beet production is also a result of policy changes; in this case, many countries have reduced production quotas to allow fairer competition from sugarcane. Sugarcane can be produced at lower cost, even though sucrose yields per hectare do not differ greatly between the two crops.

Sugarcane

Sugarcane is a crop grown widely by farmers of smallholdings in Asia, but most production is from large farms and plantations in Brazil, the rest of Latin America, Sub-Saharan Africa, Australia and the USA. Both sugarcane area and FY are increasing globally (Table 7.5), especially in Brazil where this has been stimulated by the policies favouring ethanol from sugarcane (Valdes 2011). Brazil dominates world sugarcane production, although national average cane yield (79.5 t/ha) is slightly exceeded by

Australia (80.3 t/ha) with a similar climate. Under an ideal high-radiation climate, Egypt produces 118 t/ha cane yield from 135,000 ha.

Amounts of **sugar extracted from the sugarcane** shown in Table 7.5 vary considerably among countries, depending on variety and environment, and harvesting and processing methods. Average sugar content ranges from 7 to 10% of fresh cane weight in South Asia, to 11% in Thailand, and 13 to 14% in Brazil and Australia.⁴² Thus Brazil currently has an average sugar yield of 11 t/ha, Australia 12 t/ha, and Egypt, despite its superior cane yields, only 11.5 t/ha.

Notwithstanding these national differences, sugar extraction is usually a few percentage points lower in mechanically harvested cane because more leaf material is included with the cane removed. The entire Australian crop and about one-third of the Brazilian crop is harvested mechanically. Table 7.5 shows progress in cane yield at farm level; sugar yield is likely to show similar relative growth since cane sugar concentration has been relatively steady (Burnquist et al. 2010).

Table 7.5 Annual sugarcane production, harvested area and yield in 2008–10, and annual rate of change from 1991 to 2010, for the world and the five principal producing countries

Country	Average 2008–10			Rate of change ^b (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^a (t/ha)	Area	Yield ^a
World	1,705	23.9	71.3	1.3	0.8
Brazil	685	8.6	79.5	2.7	1.1
India	309	4.5	67.8	1.1	ns 0
China	118	1.7	68.3	1.7	0.6
Thailand	70	1.0	71.1	0.7	1.4
Pakistan	54	1.1	50.8	0.6	0.9
Mexico	50	0.7	71.7	1.1	ns 0
Australia	31	0.4	80.3	1.0	ns 0.1

- a Yield may refer to a planting to harvest period for a proportion of the crop greater than 12 months, and up to as long as 18 months. It is expressed here as weight of harvested cane per hectare rather than weight of sugar per hectare. Note that national cane yields always combine plant crops and ratoon crops, although the latter tends to have lower yields. This FAO 'yield' is what the book calls 'farm yield' (FY).
- b Relative to the 2008–10 average; all slopes very highly significant ($P < 0.01$), except ns = $P > 0.10$

Source: FAOSTAT (2013)

⁴² These values for sugar extraction rates were obtained from various recent USDA Foreign Agriculture Service reports *Sugar: World production supply and distribution*, available at <www.fas.usda.gov/>.

There are no recent studies **of breeding progress**. Jackson (2005) reports two studies in Australia in which the last year of variety release was 1986. In these studies, PY progress in terms of sugar per hectare was 0.7% p.a. and 1.4% p.a. of the yield of the latest releases, and entirely due to increased cane yields. Edmé et al. (2005) in Florida, USA, estimated **a rate of 0.6% p.a. PY increase for 1968–2000** sugarcane releases.

Cane mills routinely record yield and variety for all cane received for processing. Burnquist et al. (2010) used such data to conclude that varietal progress values in sugar yield in two separate breeding programs in Brazil were 0.15 t/ha/yr (releases 1989–2002) and 0.28 t/ha/yr (releases 1983–2002). Similarly, in the state of Queensland (which dominates Australian production), Burnquist et al. (2010) reported breeding progress of 0.28 t/ha/yr (1983–2006). These high numbers imply >2% PY progress annually. It is likely, however, that they are biased upward by breakdown of disease resistance in older varieties that are only slowly replaced by farmers and so remain in mill samples for some years after the breakdown. The deteriorating performance of the older varieties over time artificially bolsters the apparent rate of PY progress.

A more valid result, relating to agronomy, with the same approach based on mill records, is the estimate of Cox and Stringer (2007) that, independent of variety change, sugar **FY was declining by 0.12 t/ha/yr (–1% p.a.)** in Queensland. They attributed the decline to expansion onto marginal land, and to 'yield decline' due to long-term sugarcane monoculture's outweighing any improvements in agronomy.

'Yield decline' is a major worldwide issue in sugarcane and appears to be associated with unfavourable changes in soil biota and soil physical and chemical properties (Garside and Bell 2011). These authors have shown in Queensland that breaking sugarcane monoculture with fallow, pasture or broadleaf crops could boost yields by 27–30%—this is likely to also be the case for Brazil.

In Brazil there is also an intriguing and poorly understood benefit from sugarcane: endophytic nitrogen fixation in sugarcane stalks makes a substantial contribution (at least 50 kg N/ha/yr) to crop nutrition and productivity (e.g. Boddey et al. 2003). This is not reported, for example, in Australia.

In conclusion, it has not been possible to estimate PY or yield gap for sugarcane in Brazil or Australia, but the gap is unlikely to be large given wide adoption of modern technologies and varieties. FY in Asia is also quite high (Table 7.5), suggesting that the yield gap there is also not unusually large. From Brazilian and Australian data it appears that breeders are making about 1% p.a. PY progress, but 'yield decline' and other aspects of soil management (for example, compaction from heavy harvesting machinery) are likely to remain significant constraints to FY progress.

Sugar beet

Sugar beet statistics are shown in Table 7.6. Area decreases are universal but gains in FY are strong. Europe is the main production region; sugar beet is not a particularly

significant crop in developing countries, which represent only 18% of world production, probably because it is not suited to warm climates. However, sugar beet has interesting features of relevance to issues discussed here.

The UK has yields 30% lower than France (Table 7.6), probably due to colder springs, but **FY progress for sugar (not beet) yield has been strong at a rate of 1.6% p.a.** Mackay et al. (2010) analysed the official, optimally managed variety trials of the British Beet Research Organisation (BBRO) across the UK and found that sugar beet PY rose significantly between 1982 and 2007. Using the sugar yield (~14 t/ha) of the best varieties in 2007, this **progress in PY over the 25 years appears to be 1.6% p.a.**, the same as that for FY. Mackay et al. (2010) then partition the PY increase into a linear time trend (0.112 t/ha/yr), reflecting improved agronomy and/or a weather trend, and a linear year of release trend (0.105 t/ha/yr) attributed to breeding progress. Thus **half of the 1.6% p.a. PY progress (or 0.8% p.a.) is attributed to breeding**, and about the same amount to agronomy and/or weather. Also, given a national 2007 FY of ~9.5 t/ha sugar, **the yield gap can be estimated to be 47% of FY.**

Table 7.6 Annual sugar beet production, harvested area and yield in 2008–10, and annual rate of change from 1991 to 2010, for the world and the six principal producing countries

Country	Average 2008–10			Rate of change ^b (% p.a.)	
	Production (Mt)	Area (Mha)	Yield ^a (t/ha)	Area	Yield ^a
World	226.0	4.41	51.4	-5.2	2.1
France	32.4	0.37	88.0	-1.5	1.3
USA	26.8	0.45	60.1	-1.5	1.7
Russian Federation	25.4	0.83	30.9	-2.6	3.2
Germany	24.3	0.37	65.0	-2.7	1.4
Turkey	16.9	0.32	52.1	-2.0	1.5
UK	7.5	0.12	64.1	-3.9	1.3

a Weight of harvested roots; this FAO 'yield' is what the book calls farm yield (FY).

b As percentage of 2008–10 average; all slopes significant at $P < 0.01$

Source: FAOSTAT (2013)

Independently, Jaggard et al. (2007)—using a simulation model with fixed variety and fixed agronomy—estimated for sugar yield, over the period 1976–2004, a positive linear weather-driven trend of 0.139 t/ha/yr. During that period, mean temperature for March to October had increased by 0.45 °C per decade across central and eastern sugar beet districts of the UK. Warmer spring conditions, combined with earlier sowing—both included in the Jaggard et al. (2007) modelling—led to faster canopy closure.



The time trend of sugar yield from the Jaggard et al. (2007) analysis matches well with that calculated by Mackay et al. (2010). The similarity of results suggests that there has been **no improvement in trial agronomy since the late 1970s, but improved weather** has allowed earlier sowing. Jaggard et al. (2007) also conclude that FY progress has been constrained by a campaign to extend processing duration to achieve greater factory efficiency. This has led to some earlier harvesting (and thus, lower yields) and greater respiratory losses due to longer postharvest storage prior to processing for sugar extraction.

Subsequent to the above research, Jaggard et al. (2012) analysed breeding progress across 10 countries in Europe, comparing national trial mean sugar yields with national FY over the period 2001–10. National trial mean yield is not a perfect measure of breeding or PY progress because this measure includes possible weather trends. However, results indicate that sugar PY increased strongly at 0.25 t/ha/yr, or **1.6% p.a. of the 2010 sugar PY of 16 t/ha** (noting that sugar yield reached 20 t/ha under irrigation in Spain). Over the same period, Europe FY increased at an even greater rate **of 0.31 t/ha/yr, or 2.7% p.a. of the 2010 FY of 12 t/ha**. These numbers for Europe suggest a **yield gap of 33% of FY**. Given that part of yield gap is governed by harvesting deadlines and storage losses before processing, progress in sugar productivity from sugar beet in Europe has been even more impressive than in the UK (described above). This is confirmed very recently by Rijk et al. (2013), who report breeding progress for sugar yield in the Netherlands from trials between 1995 and 2008 of 1.2% p.a. relative to 2008 sugar PY of 14 t/ha, plus a similar rate of annual increase due to improvements in agronomy.

Despite the strong sugar beet industry in Europe and northern USA, and some impressive new technologies driving yield advance, it will be interesting to see how well this crop survives to 2050, given the general decline in area (Table 7.6). Sugar beet faces stiff competition from sugarcane and maize-derived fructose, and is challenged by difficult land management issues associated with seeding (i.e. a need for a fine seedbed) and harvesting (i.e. a need to dig the roots). Experiments in the USA with establishment of sugar beet under zero-till practices are showing promise (D. Lyon, pers. comm. 2011) and this may offer potential to reduce soil disturbance. Hybrid varieties and monogerm seed (i.e. larger embryos and seedlings for easier crop establishment) are already widely adopted, but competitiveness may be further aided by new technologies, such as is occurring with glyphosate-tolerant GE sugar beet in the USA, which in 2012 reached 97% adoption (James 2012).

One possible new breeding-by-agronomy interaction is noteworthy. It could arise in places like the UK, where yield gains may be made by shifting to autumn planting for greater spring solar radiation capture, and permitting deeper roots to improve access to water and nitrogen (Jaggard et al. 2010). This will only be possible if breeders are able to deliver varieties with strong resistance to bolting (i.e. the early floral initiation and flowering that results in reduced sugar yield), which would normally be stimulated by winter vernalisation of an autumn planting.

7.7 Cassava

Known also as yucca and manioc, cassava (*Manihot esculenta*) originates from tropical Latin America. This physiologically unique crop (Cock 1985) is a woody perennial that yields very low-protein starchy roots (~30% DM) and is largely grown as an annual of 8–12 months duration. It is grown almost entirely in the developing world, predominantly by farmers of smallholdings, and remains an important calorie source for people of lower economic status (especially in Sub-Saharan Africa). Late maturing clones are characterised by high levels of poisonous hydrocyanic acid, which must be removed from roots by soaking and boiling before consumption.

Cassava is propagated vegetatively by stem pieces, so varieties are clones, and are recognised for tolerance to high temperature, long periods of drought and poor acid soils. Crops are grown at <30° latitude and generally below 2,000 metres above sea level (masl). Although cassava is grown in moderate to high rainfall regions, yield is considered to be water-limited because it is an unirrigated upland crop and commonly grows through the hot dry season.

Annual average world production was 235 Mt of root fresh weight in 2008–10, of which 52% was grown in Sub-Saharan Africa, 33% in Asia and 14% in Latin America. The major producers are shown in Table 7.7, bearing in mind that figures (especially from Africa) may not be accurate. A small amount of cassava, largely from Thailand and Vietnam, is traded internationally for animal feed (as dried chips) and for starch, and is equivalent to 8% of world production.

World production of cassava has increased strongly (1.9% p.a.) over the past 20 years through gains in both to area and yield, although this has varied greatly among countries. Several countries (Nigeria, Ghana, Angola and Vietnam) show high increases in both area and yield (Table 7.7); others, such as the Democratic Republic of Congo and Tanzania (not shown in Table 7.7), appear to be regressing.

Cassava became a target for improvement research only relatively recently. Much of this work was initiated in the 1970s at two international research centres: International Centre for Tropical Agriculture—otherwise known as the *Centro Internacional de Agricultura Tropical* (CIAT)—in Colombia, and IITA in Nigeria. Enough published data exist from Nigeria and Thailand to permit an estimate of PY_w and yield gap.

Cassava in Nigeria

Nigeria is the biggest cassava producer and the area is expanding as cassava transitions from a subsistence crop to a traded commodity for local processing into various foods and industrial products. While FY progress is low (0.4% p.a. of the 2010 estimated FY of 11.5 t/ha, estimated over 30 years in Figure 7.1) for a country in which there is so much optimism for the crop, note that in Sub-Saharan Africa most cassava is intercropped, often with maize, thereby possibly depressing apparent cassava FY in the statistics.

Table 7.7 Annual cassava production, harvested area and yield in 2008–10, and annual rate of change from 1991 to 2010, for the world and major producing countries

Country	Average 2008–10			Rate of change ^c (% p.a.)	
	Production ^b (Mt)	Area (Mha)	Yield ^b (t/ha)	Area	Yield ^b
World	234.7	19.0	12.3	0.9	1.2
Nigeria	41.3	3.5	11.9	1.6	0.6
Thailand	25.7	1.2	20.9	–1.2	2.3
Brazil	25.2	1.8	13.9	ns 0.1	0.7
Indonesia	22.5	1.2	19.0	–0.9	2.1
DR Congo ^a	15.0	1.9	8.1	–1.8	na
Ghana	12.4	0.9	14.3	2.4	1.2
Angola	12.2	0.8	15.1	3.0	4.2
India	8.9	0.3	^d 34.2	ns 0.2	1.9
Vietnam	8.8	0.5	17.0	3.0	3.4

a Democratic Republic of the Congo

b Fresh weight of roots; this FAO 'yield' is what the book calls farm yield (FY).

c Relative to the 2008–10 average; all slopes significant at $P < 0.05$ or better; ns = $P > 0.10$

d The high yield in India arises because cassava is a specialty food, cultivated largely in the state of Kerala under favourable moisture conditions.

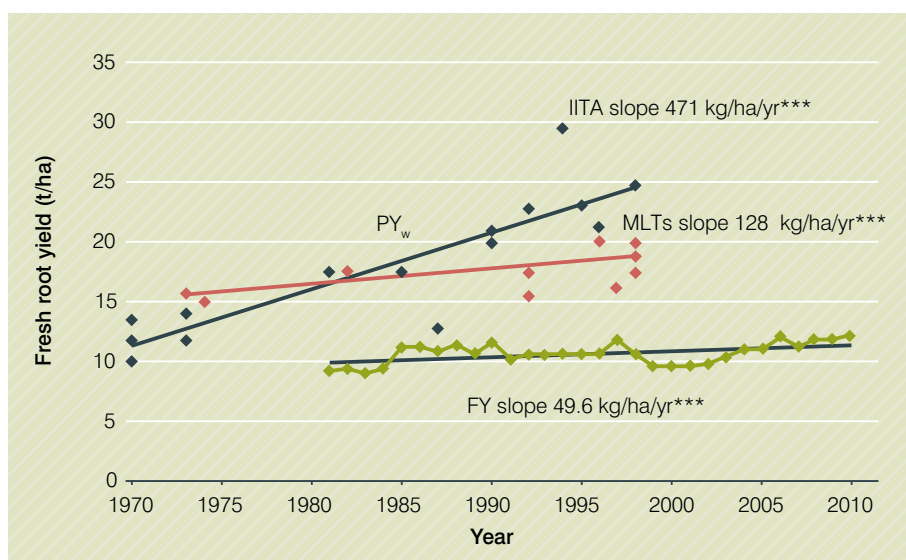
na = data not available

Source: FAOSTAT (2013)

The situation with respect to genetic improvement is complicated. Although IITA does not release varieties directly, it has undertaken genetic improvement for the past 35 years. When Okechukwu and Dixon (2008) evaluated the best five IITA clones of each decade at the IITA Ibadan location with trials held in 2003 and 2004, PY_w progress of the best clones seemed very good (Figure 7.1), reaching a rate of 1.9% p.a. of the 1998 PY of 24.5 t/ha. As trial plots were unprotected, some progress in Figure 7.1 could be attributed to the improved resistance to cassava mosaic disease (CMD) and cassava anthracnose disease, both of which are important in Nigeria. A largely different set of clones was tested across multiple location trials (MLTs) in 2003–05 in Nigeria (Dixon et al. 2008). In this case, PY_w progress (at 0.7% p.a. relative to 1998 PY_w) was less (Figure 7.1), and again more recent clones showed better CMD resistance; it is also probable that these trials did not receive optimal management.

These two sets of reported results suggest that breeders in Nigeria have made good progress on several fronts, including processing quality. From these two trial results, **average PY_w progress has occurred at a rate of 1.3% p.a. relative to an average**

1998 PY_w that was >20 t/ha (and is probably higher now), suggesting **a yield gap of >100% of FY in 1998**, a gap that is unlikely to have closed since then. Part of the yield gap is undoubtedly due to the very slow process of variety release and registration in Nigeria (Dixon et al. 2008). Another part may arise from lack of fertilisation and inadequate weed management, as was found in eastern Africa (Fermont et al. 2009). Waddington et al. (2010), using expert opinion, **estimated yield gap for cassava in Sub-Saharan Africa to be ~120%**, with yield constraints equally distributed across all categories sampled (socioeconomic, abiotic, biotic and agronomic). Despite the constraints, cassava is currently considered a ‘boom’ crop in Nigeria as production rises at more than 2% p.a. to meet the demand of small-scale operators processing cassava into a diverse range of dry foods.



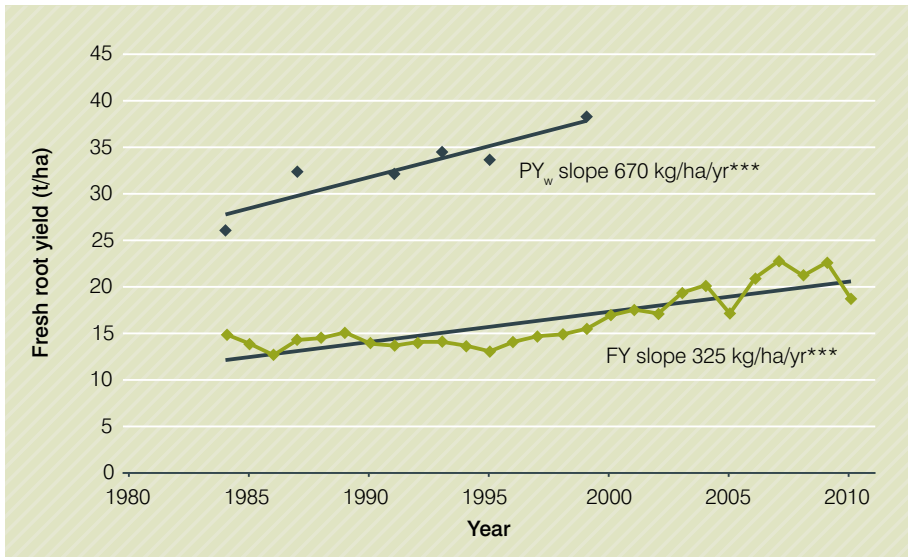
*** $P < 0.01$

Figure 7.1 Farm yield (FY) plotted against year for cassava in Nigeria, and water-limited potential yield (PY_w), plotted against year of release, from 1970 to 2010. Source: PY_w from Okechukwu and Dixon (2008) (at International Institute of Tropical Agriculture (IITA)), and Dixon et al. (2008) (from multilocational trials (MLTs)); FY from FAOSTAT (2013)

Cassava in Thailand

Cassava area peaked in Thailand in the late 1980s then gradually declined, but production has grown slowly given the strong rate of FY increase since then (Table 7.7), and cassava remains an important export crop. Conditions are relatively favourable, partly because disease and pest problems are not as severe as in Sub-Saharan Africa.

Figure 7.2 shows FY progress of 1.6% p.a. (of the 2010 estimated yield of 20 t/ha). This is less than that the rate of FY progress shown in Table 7.7 (2.3% p.a.) because a longer period is included in Figure 7.2 to match the available PY data. Either way, there has been moderately high FY progress in Thailand, especially in the past 15 years during which higher yielding varieties have been widely grown. It is not clear, however, how much FY progress has been aided by shrinkage of harvested area (−1.2% p.a.), which has probably removed cassava from more marginal, erosion-prone sloping lands.



*** $P < 0.01$

Figure 7.2 Farm yield (FY) for cassava in Thailand plotted against year, and water-limited potential yield (PY_w) plotted against year of release, from 1984 to 2010. Source: Kawano (2003) for PY_w; FAOSTAT (2011) for FY

Cassava **PY_w progress** in Thailand between 1984 and 1999—described fully in Kawano (2003) and involving improved CIAT (Colombia) parental material—**was an impressive 1.8% p.a.** of the 1999 PY_w (Figure 7.2). This progress was also accompanied by a significant increase in root DM content of ~0.3% p.a. (absolute rate of increase).

Breeding progress in Thailand is aided by the absence of major biotic constraints and reflects the high rates of yield progress obtained at CIAT during the first decade or so of scientific cassava breeding (Kawano 2003). DM and HI—calculated as dry weight of storage root weight, divided by the dry weight of tops plus roots—have improved during this period of yield progress, HI reaching about 0.6 in 1999. Breeding continues apace at CIAT, but rates of yield progress have probably slowed (Ceballos et al. 2004).

Figure 7.2 suggests a yield gap in Thailand of ~100% of FY in 1999, but recent PY_w data are lacking. Because cassava has a reputation for performing relatively well under poor fertility, farmers tend not to add fertiliser to their crop. This practice—along with poor weed control—is likely to be a major constraint to FY. Supporting the above gap estimate, Waddington et al. (2010) found **cassava yield gap to be 75% in Asia**, with multiple constraints as in Sub-Saharan Africa.

Conclusion for cassava

In the areas of adaptation for this crop—i.e. seasonally dry tropics and subtropics—the global average DM yield of ~4 t/ha cassava root is respectable compared with grain crops in the same areas (although obtained from considerably longer crop growth duration). In addition, good yield progress has been achieved after relatively few decades of genetic improvement (compared with, say, wheat).

Adoption of new varieties has been strong in Thailand, Vietnam and Nigeria. Meanwhile, scope is likely to exist for further strong PY_w increases, along with potential for better pest and disease resistance, and development of clones to better fit a growing number of end uses for cassava root. With regard to yield, recent work at IITA shows how readily cassava can be adapted to conditions on swamp lands following the wet season, to produce fresh root yields of 25 t/ha in 6 months (Okechukwu and Dixon 2009).

Physiologists point to cassava's exceptionally high tolerance to high temperature and drought (e.g. El-Sharkawy 2007) as a basis for crop improvement. While controversy surrounds the status of cassava as a C_3 - C_4 intermediate plant (as promoted by El-Sharkawy 2007), this in no way lessens the importance of cassava's unique adaptive physiological traits. However, the surprising report that cassava responds negatively to doubling of carbon dioxide (Gleadow et al. 2009) is probably confounded by growth in excessively small pots (M. El-Sharkawy, pers. comm. 2011).

Given the current practice of minimal use of inputs with cassava, great scope also exists for closing the large yield gap through better agronomy. Growing commercialisation of the crop in Sub-Saharan Africa should help close the gap by providing stimulus for farmers to invest in more inputs. Fresh cassava roots do not store well after harvest, lasting only 3–4 days before they must be consumed, dried or discarded. If shelf life of cassava can be significantly extended, this will open up a number of alternative end uses and markets. Another special challenge for cassava on sloping land is soil erosion, which results largely from tillage used for weed control and from soil disturbance during harvest.

7.8 Oil palm in South-East Asia and elsewhere

Oil palm (*Elaeis guineensis*) originated in western Africa and has many unique features. It is a tree crop grown as a monoculture, and is adapted to humid equatorial tropics (within 15° of the equator) where annual rainfall is >1,600 mm. Oil palm has become the largest source of vegetable oil globally, recently surpassing soybean. More than half the production comes from corporate plantations, which are often surrounded by contract smallholder growers. All harvested fruits are factory processed locally for oil extraction, but kernels are often sold on for kernel oil extraction (see below).

Oil palm achieves high productivity because it captures most annual solar radiation, but fruit yield is sensitive to dry periods (defined here as 3 consecutive months or more, each with <100 mm rainfall). Plantings are retained until the trees become too tall for easy harvest, and thus plantings can last 25 years or more. Peak yields are reached within ~5 years after transplanting, and harvesting of fruit can take place year-round. Crop area has expanded at unprecedented rates over the past 20 years, largely into previously logged forest areas in South-East Asia. This expansion has been driven by a rapidly growing demand for edible oil, and a new demand for biodiesel, resulting from global policy incentives. Obviously, controversy surrounds several of these aspects of the crop, especially its displacement of tropical forests.

Production and yield is reported as fresh fruit bunch (FFB) weight containing inflorescence parts (stalk and spikelets) and fresh fruit (~60–65% of bunch weight). Trade normally uses an oil extraction figure of ~22% of FFB weight for palm oil (from the fleshy mesocarp surrounding the kernel), plus an additional 2.5% FFB weight for palm kernel oil from the kernel itself (Donough et al. 2009). The latter oil is much more saturated; both oils can be used for food and for biodiesel. Palm kernel meal, a by-product used for feed, amounts to ~2.5% of FFB weight.

Despite the relatively uniform tropical climate across oil palm growing regions, length of the dry season varies and is the major cause of FFB yield variation among countries, followed by variation in management, soil types and variety (Table 7.8). Indonesia and Malaysia dominate world production, having grown at a remarkable rate of 5.1% p.a. over the past 20 years. Crop area is expanding very rapidly in these countries (average 4% p.a.) and many others, possibly accounting for the yield declines in some (Table 7.8). The major South-East Asian producers and Colombia have the highest yields and show moderate yield progress (Table 7.8). In addition to progress in yield of FFB weight, it is likely that extraction percentage of oil has also risen. For this reason, most researchers and corporate producers refer to oil yield per hectare, which in 2011 reached 3.7 t/ha globally, 4.4 t/ha in Malaysia and 4.0 t/ha in Indonesia (R.H.C. Corley, pers. comm. 2013); thus it is four times that of other edible oilseed crops (e.g. soybean, canola or peanut). Global palm oil exports amounted to 37.8 Mt in 2011, with 93% from Indonesia and Malaysia.

Table 7.8 Annual oil palm production, harvested area and yield in 2008–10, and annual rate of change from 1991 to 2010, for the world and major producing countries

Country	Average 2008–10			Rate of change ^b (% p.a.)	
	Production ^a (Mt)	Area (Mha)	Yield ^a (t/ha)	Area	Yield ^a
World	219.4	15.3	14.3	3.2	^c 1.8
Indonesia	90.9	5.4	17.0	4.9	ns 0.2
Malaysia	88.1	4.0	22.2	3.1	1.1
Nigeria	9.5	3.2	2.7	1.1	na
Thailand	8.6	0.5	16.9	4.4	1.1
Colombia	3.2	0.2	19.2	2.4	1.2
Ecuador	2.0	0.1	15.0	3.0	0.8

a Fresh fruit bunch (FFB) weight; this FAO 'yield' is what the book calls farm yield (FY).

b Relative to the 2008–10 mean; all slopes significant at $P < 0.01$ or better; ns = $P > 0.10$

c The apparently high rate of world yield progress is driven by higher yielding countries becoming more dominant in the global total.

na = data not available

Source: FAOSTAT (2013)



There is a unique sense of urgency surrounding oil palm yield improvement, probably because large corporate players dominate production and processing. The corporate sector has a large role in funding research, along with some public institutions (particularly in Malaysia, Indonesia and France). Another driver is the notion that yield increase through intensification will lessen pressure for area expansion, and consequential loss of tropical forests. This is a controversial idea that is also discussed elsewhere (see Section 11.6 on off-site effects of cropping intensification).

Determining PY and PY progress is not easy in oil palm. To estimate plantation yield, breeders use the product of yield per tree (derived from trials) and tree density. This is an imprecise procedure in any crop, but especially in oil palm, because of tree-to-tree variability. The best plants cannot necessarily be consistently vegetatively propagated (cloned through tissue culture) despite much research on this issue. Corley (2006) used crop physiological reasoning to calculate a plausible (theoretical) maximum oil yield of 18.5 t/ha. However, breeder trials suggest a lower current PY for oil, at about 9–12 t/ha (Durand-Grasselin et al. 2003; Wahid et al. 2004). Also PY may be increasing at 1.2% p.a. through both greater FFB weight and greater oil extraction rates, according to data presented by Durand-Grasselin et al. (2003).

A number of breeding advances now being employed could maintain the momentum of improvement. These include reliable cloning, F_1 hybrids, selection aided by molecular

markers, and wide crossing with the South American palm (*Elaeis oleifera*). Traditionally, the breeding cycle is very long, and impact from improved genotypes is slow because plantations are replaced only every 25–30 years.

With PY conservatively assumed to be 10 t/ha oil, yield gap would be 130% in Malaysia where FY is 4.4 t/ha oil, and probably higher elsewhere. However, part of this gap reflects the long lag before impact of any improved variety. It is more common, and probably more appropriate with this crop, to consider exploitable yield gap as the difference between FY and the best plantation yields. In Malaysia and Indonesia, the best yield appears to be ~7 t/ha oil (28–30 t/ha FFB weight, with 23–25% oil extraction), so the exploitable yield gap is ~70%. This equates to a total yield gap of ~100% of FY if it is assumed, as for all crops presented in this book, that the best plantation's (attainable) yield is about 23% below PY.

Exploitable yield gap has been subject to intense investigation, leading to the notion of 'best management practices' (Griffiths et al. 2002). Inadequate nutrition, poor canopy management, poor harvesting strategies, and weeds, pests and diseases, have all been identified as common agronomic constraints. Thus, yield and profitability from existing plantings can be notably lifted through applying best management practices including (Griffiths et al. 2002; Fairhurst et al. 2010):

- leaf diagnostics for determining optimum fertiliser rate at the block level
- shade-tolerant legume cover crops
- mulched bunch remains after fruit removal
- pest and disease control measures
- management of harvesting
- trained plantation workers.

Adoption of such changes on private corporate plantations should be relatively easy, but smallholder farmer practice will change more slowly, even for farms adjoining large plantations. In conclusion, and despite the large apparent yield gap, it is unlikely that average oil yield across existing plantings will increase faster than ~1% p.a. through better management.

Added to improved agronomy is the effect of the steadily improving PY of new varieties as plantations are replaced every 25 years or so. This progress can also be expected to occur at a rate of 1% p.a., but must include the positive effect of an ongoing 3% p.a. area increase of new plantings. If the plantings are assumed to be 12.5 years old on average, new plantings will be 12.5% higher yielding (12.5 years × 1.0%) due to breeding than average plantings. Thus the estimate for PY progress from breeding progress across the expanding industry increases by 0.4% (12.5% × 3%) to 1.4% p.a.

The combined result of management plus breeding of (2.4% p.a.) for PY increase is not too different from the current global rate of 1.8% p.a. FY increase (Table 7.8). This is, however, unlikely to reduce pressure for continued expansion into forested areas.

Limiting expansion in oil palm will very likely require institutional and policy reform to better achieve protection of existing forests (Stevenson et al. 2011), and will require attention to the burgeoning demand for biodiesel.

7.9 Potato and sweetpotato

Potato

Potato (*Solanum tuberosum*) is a tuber-bearing, broadleaf annual crop with C₃ photosynthesis, originating in South America. Tubers contain ~20% DM (largely starch) and HI—calculated as tuber dry weight, divided by dry weight of tops (haulms) plus tuber—can exceed 0.8. At low altitude, potatoes are grown in summer at high latitude and in winter at low latitude; at higher altitudes they can be grown at any time, but are intolerant of frost. Potatoes need either high rainfall or irrigation.

World potato production has increased at 0.9% p.a. over the past 20 years due to moderate global yield increase. Strong area decreases in the Russian Federation and USA are counterbalanced by area growth in Asia (Table 7.9). Area decreases are also evident in traditional potato growing European nations from the UK to Poland. Area is decreasing because potato consumption (by both people and animals) is steadily falling in the developed world as traditional diets become more diverse (Walker et al. 2011).

Table 7.9 Annual potato production, harvested area and yield in 2008–10, and annual rate of change from 1991 to 2010, for the world and five principal producing countries

Country	Average 2008–10			Rate of change ^b (% p.a.)	
	Production ^a (Mt)	Area (Mha)	Yield ^a (t/ha)	Area	Yield ^a
World	332.7	18.5	18.0	ns 0.1	0.8
China	75.2	5.0	15.1	2.2	0.7
India	35.2	1.8	19.3	2.4	0.9
Russian Federation	27.0	2.1	12.7	–3.1	1.0
Ukraine	19.3	1.4	13.7	–0.7	1.1
USA	18.9	0.4	45.3	–2.0	1.3

a Weight of tubers at 20% dry matter; this FAO 'yield' is what the book calls farm yield (FY).

b Relative to the 2008–10 mean; all slopes significant at $P < 0.05$ except ns when $P > 0.10$

Source: FAOSTAT (2013)

Of more interest here, however, is the rapid increase in production (2.9% p.a.) in both China and India: area has expanded strongly, and yield has increased moderately (Table 7.9). There has been similar rapid growth in several other developing countries; for example, in Bangladesh, Pakistan, Angola, Rwanda and Uganda. Thus there has been a notable shift in potato production from the developed to the developing world. In all developing countries, potatoes are largely (or entirely) produced by farmers of smallholdings.

Potatoes are bulky and do not store well, at least in warm climates, so are largely consumed (with or without processing) in countries of production. International trade is limited and developing countries are unlikely to benefit from a growing export trade in frozen 'french fries', a relatively sophisticated product dependent on specialised varieties and management. By comparison, the modest export trade of table potatoes from northern Africa and the Middle East to nearby western Europe (Walker et al. 2011) offers greater opportunities. The storage and transport constraints for potatoes mean that production in developed countries is of little relevance to global food security.

Tuber quality dominates in advanced markets and is often best satisfied by older varieties. For example, it is estimated that national FY in the UK (42 t/ha, increasing at 0.5% p.a. over the past 20 years) is barely half of PY, and that breeding progress for yield is constrained by the effort spent on quality requirements and improving host-plant resistance to the large array of diseases and pests suffered by potato (Allen et al. 2005). Rijk et al. (2013) confirmed very slow breeding progress for potato in the Netherlands. Walker et al. (2011) estimated that despite active breeding programs in the USA, the current average age of potato varieties being grown there is 43 years, primarily because one old cultivar, Russet Burbank, retains superior processing quality.

The Netherlands also has a breeding program for industrial starch potato. In contrast to food (processing or table) potato, starch potato showed good breeding progress in 1990–2009 (Rijk et al. 2013), a rate of 0.7% p.a. relative to the 2009 yield of 86 t/ha. In this period there was no agronomic progress in the yield trials. Curiously, FY was only about 50 t/ha, implying a yield gap of 72%.

In the developing world outside of Latin America, potatoes are a relatively new crop but little is known about factors affecting yield. In China, they are grown as a summer crop at high latitude in the north and west, and 30% of harvested tubers are fed to pigs (Walker et al. 2011). The International Potato Center—or *Centro Internacional de la Papa* (CIP)—estimated that yield losses in China could be attributed in a multiplicative fashion to late blight (40% of FY), disease-infected seed (34% of FY) and virus and bacterial wilt (23% of FY), amounting to 70% total loss (G. Thiele, pers. comm. 2012). Thus diseases alone could be a major cause of yield gap, reflecting a special weakness in this crop worldwide.

In India potatoes are grown as short-duration winter crops, fitting into the rice-based cropping system of the Indo-Gangetic Plain. Evidence of a yield plateau there (Walker et al. 2011) is somewhat surprising, given that West Bengal—the major potato growing state in India—borders Bangladesh, a country that has seen very large increases

in both area (4% p.a., starting from a small base) and yield (2% p.a.) over the past 20 years. Potato production in Bangladesh has increased sixfold to reach 6 Mt from 400,000 ha in 2007–08, representing a significant cash crop for many smallholder farmers.

Potato breeding is obviously dominated by maintenance of quality and improvement in disease resistance. It is probably for this reason that very few data are available on breeding progress for PY. The most promising new technology is GE late blight resistance (see Section 9.9 on transgenes).

Sweetpotato

Sweetpotato (*Ipomoea batatas*) is a vine-forming crop, suited to moist subtropical and tropical environments. Tubers contain ~23% DM and are rich in carbohydrates. Although farmers of smallholdings in developing countries are responsible for >98% of world production, sweetpotato is not tabulated in this chapter because average annual global production was only 103 Mt in 2008–10 (FAOSTAT 2013). Over the past 20 years, global production has declined by 1.0% p.a. through reductions in both area (–0.6%) and yield (–0.4%).

China dominates sweetpotato production (76 Mt) and although harvested area has declined by 4.2% p.a. over the past 20 years, yield is increasing by 1.3% p.a. to reach an FY of 21 t/ha in 2008–10 (FAOSTAT 2013). Sweetpotato also shows considerable promise in Sub-Saharan Africa with rapid increases in area and production (both 3.7% p.a.), but average FY is only 4.8 t/ha and total production only 16 Mt. As sweetpotato is a food crop in this region, the promotion of orange sweetpotato—with its high precursor content for vitamin A—has been an important achievement for better human nutrition.

7

7.10 Conclusion for other crops

The crops considered (some briefly) in this chapter cover around 368 Mha and in aggregate produce food calorie and protein equivalents of 125% and 97%, respectively, of world wheat production (Table 1.2), although not all crops are used entirely for food. The result is a significant contribution to total world food and feed supply, as well as to diversification of global cropping.

Crop area is stagnant or declining for coarse grains, pulses (except for cowpea), sugar beet, potato and sweetpotato: area declines are very strong for barley and sugar beet (–2.3 and –5.2% p.a., respectively). However, area is increasing strongly (>1.5% p.a.) for oil palm, canola and sunflower. There are also some notable shifts in crop production areas, with sorghum and millet area shifting from India to Sub-Saharan Africa, pea from Europe to western Canada, sunflower from Argentina and western Europe to eastern Europe, and potato from western Europe to Asia.

FY changes are somewhat affected by the above shifts, but overall the picture is one of moderate FY progress, ranging from a low of -0.9% p.a. for peas and only 0.1% p.a. for sorghum and 0.3% p.a. for sunflower (all depressed by shift in production area) to a high of 2.0% p.a. for sugar beet. Canola, peanut and oil palm all show FY progress above 1.5% p.a. FY progress has responded wherever substantial research and development effort has occurred—canola is probably the best example of this, but other successes include pulses in western Canada, cassava and cowpea in western Africa, and the technologically sophisticated sugar beet industry in Europe and the USA, and the oil palm one in southeast Asia.

Annual breeding and PY progress has been recorded in only some crops studied, ranging from 0.5% p.a. (sunflower in Argentina) to 1.8% (cassava in Thailand). Over all crop estimates in this chapter ($n = 13$), mean PY progress is 1.2% p.a. with no greater progress for crops dominated by F_1 hybrids or by the private sector. Breeding progress is probably favoured in some crops because of earlier neglect (e.g. cassava, millet and cowpea). Private investment in breeding is focused on grain crops, especially those with GE traits and/or reliable systems for F_1 hybrid seed production (sorghum, canola, sunflower and sugar beet). An exception is oil palm, in all stages of which the private sector is strongly involved. Hybrid millet and sorghum in India offers a successful example of private–public partnership.

Because PY (and PY_w) have been difficult to determine, little information can be drawn for yield gap. However, gaps appear to be small ($30\text{--}47\%$) in developed countries—i.e. for barley, lupins, canola and sugar beet—and moderate to large elsewhere. An exception is potato in the developed world where quality and processing requirements mean old, low-yielding varieties are still commonly grown, while sugarcane FY appears to vary little between developed and developing countries.

Closing yield gaps

8



Key points

- It is reasonable to consider that a yield gap of 30% of farm yield (FY) represents an economically attainable level of production. However, two-thirds of the cases discussed in Chapters 3–7 revealed higher yield gaps (>40% of FY, but often >100%), and these gaps present significant opportunities for gap closing (exploitation) with known technologies.
- Yield gaps, in general, appear to be quite persistent and close only slowly; it takes on average ~20 years to reduce a given yield gap by just 10% of FY (i.e. gap change of –0.5% per annum (p.a.)). Developing countries show larger yield gaps, as do crops in rainfed conditions.
- There are multiple causes of yield gaps that are interrelated according to circumstance. Constraints can be divided into:
 - technical or proximate constraints related to land, crops and inputs
 - constraints relating to general farmer circumstances and capabilities.
- Alleviation of constraints can therefore depend on agronomic, breeding and institutional and/or infrastructural progress.
- Agricultural research has a major role in yield gap closing, for example through varieties less prone to biotic stress and technologies that are more farmer friendly. Revitalising public agricultural extension in the developing world also has a role, but new paradigms with greater involvement of the business sector and farmers (and their organisations) are also needed.
- Yield benefits from most constraint alleviations and/or interventions are not substitutive. Considered independently, no single step alone could provide sufficient conditions for yield gap closing. Due to farmers' natural caution and lower costs involved, new varieties are generally adopted more readily than new management techniques.
- Care must be taken when comparing research results on yield gaps, because studies have used different methods to estimate potential yield (PY). Where modelling or expert opinion is employed, PY values, and hence gaps, tend to be higher than those determined through field experiments.
- Assistance directed toward helping subsistence and smallholder farmers shift to viable commercial farmer status is a critical step toward future global food security. Unfortunately, the substantial investment required to sufficiently improve rural infrastructure, institutions and transfer of technology to achieve this goal has not been forthcoming.
- Recent examples have shown that where the right incentives are used (especially reliable markets), farmers of smallholdings can rapidly adopt new varieties and technologies, lifting FY and closing the yield gap at rates of 2% p.a. of FY (or better).

Closing yield gaps

8.1 Yield gaps and methodologies

Yield gap, as explained in Chapter 2 on definitions, is the difference between potential yield (PY) and farm yield (FY), averaged for individual regions of interest and expressed as a percentage of current FY. Yield gaps exist when known technologies—such as the best varieties and/or management practices (as are applied at local experiment stations to determine PY)—are not equally applied in farmer fields, despite similar natural resource endowment. Yield gaps close when farmers increase FY by adopting known technologies, including higher rates of inputs that are already used on-farm. For example, to ameliorate yield constraints caused by disease, farmers may adopt crop varieties with improved disease resistance.

Experience has shown that where farmers operate under world prices and prudently avoid risk, the yield to which farmers aim—known as ‘attainable yield’—may be no more than 70–80% of PY. This establishes a minimum yield gap, as defined here, of 25–37% of FY. Following Lobell et al. (2009) and Carberry et al. (2011), it has been suggested in the definitions in Section 2.1 that a yield gap of 30% of FY may represent an economically optimal level of FY—although the yield gap is possibly increased somewhat by risk aversion and uncertainty in farmer decision-making (especially in rainfed situations). Thus, where observed yield gap is >30% of FY there is scope for farmers to exploit the gap. However, if yield gap is <30%, it is unlikely that farmers will apply new or more existing technology for greater yield, although new technology may be applied to improve efficiency and profit (see Box 2.2 and Section 12.2, both on total factor productivity).

Farmers take a more cautious approach to adoption of new technologies than they do to increased use of existing inputs. As a rule, associated risks limit adoption of new technology to only those situations where the expected increase in gross margin exceeds twice the standard deviation of this increase, meaning there is a low chance of losing money with the investment (Keating et al. 2010). Increased prices for crop commodities (relative to input costs) may create incentive to increase inputs—and consequently raise FY—but the effect normally diminishes with increasing FY. As mentioned in Section 2.4 on confounding factors, in areas where high levels of inputs are used, price elasticity of yield is only 0.1–0.2, meaning relative yield increases are one- or two-tenths of any relative increase in the output-to-input price ratio.

Drawing on earlier discussions on commodities (Chapters 3–7), Table 8.1 summarises estimated yield gaps for major world crops. Other regional or international reports are also included in Table 8.1, including several recent detailed studies targeted at smaller areas—such as those mentioned in Lobell et al. (2009) and referred to in earlier chapters.

There is reasonable agreement between the numbers from Chapters 3–7 and those from other sources in Table 8.1, noting that not all other studies of yield gap are based on PY values determined by experimental field trials. Studies that used modelled PY values or expert opinion tended to show larger PY and consequently larger yield gaps. It is not clear why models overestimate PY relative to field experiments, particularly given that field experiments provide the data for model calibration. On the other hand, studies that used the upper-bound FY across a sample of farmers to indicate PY tended to show lower yield gaps. Both tendencies have been previously noted by Lobell et al. (2009).

Table 8.1 Current crop yield gap in various global environments, given as percentage of average farm yield (FY), as summarised in Chapters 3–7 (shaded rows) or as derived from other published studies; the final column describes the method of determination of potential yield (PY) for yield gap calculation

Source or reference	Description of environment		Yield gap (% of FY)		Source of PY
	Water supply ^a	Location	Mean	Range	
Wheat					
Table 3.6	I	Developing countries (<i>n</i> = 4)	53	41–63	Field experiments
Lobell et al. 2007	I	North-western Mexico	41	<i>n</i> = 2, both 41	Upper bound FY
Lobell et al. 2009	I, few R	India	58	5–150	Simulation modelling
Lobell et al. 2009	I	Bangladesh	45	<i>n</i> = 1	Simulation modelling
Waddington et al. 2010	I	Asia	87	54–108	Survey of experts
Liang et al. 2011	I	Hebei (China)	39	36–44	Field experiments
Table 3.6	R	Developed countries (<i>n</i> = 8)	45	26–69	Field experiments
Hochman et al. 2009 ^b	R	Australia	24	<i>n</i> = 1	Simulation modelling
Waddington et al. 2010	R	India	144	<i>n</i> = 1	Survey of experts
van Wart et al. 2013b	R	Germany	25	<i>n</i> = 1	Simulation modelling

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Table 8.1 Continued

Source or reference	Description of environment		Yield gap (% of FY)		Source of PY
	Water supply ^a	Location	Mean	Range	
Rice					
Table 4.5	I	Developing countries (<i>n</i> = 9)	59	25–107	Field experiments
Defeng 2000	I	China	68	59–75	Field experiments
Defeng 2000	I	China	27	20–35	Upper bound FY
Lobell et al. 2009	I	Philippines, India ^c	65	18–233	Field experiments
Lobell et al. 2009	I, few R	Philippines, India	92	28–233	Simulation modelling
Waddington et al. 2010	I	Asia	67	44–88	Survey of experts
Laborte et al. 2012	I	South-East Asia	72	33–133	Simulation modelling
van Wart et al. 2013b	I	China	22	<i>n</i> = 1	Simulation modelling
Table 4.5	R	Developing countries (<i>n</i> = 3)	123	80–150	Field experiments
Siddiq 2000	R	India	160	90–220	Field experiments
Maize					
Grassini et al. 2011a	I	Nebraska (USA)	31	<i>n</i> = 1	Simulation modelling
Liang et al. 2011	I	Hebei (China)	44	36–53	Field experiments
Table 5.7	R	Iowa (USA), Italy	42	36–51	Field experiments
Table 5.7	R	Developing countries ^d (<i>n</i> = 6)	194	96–400	Field experiments
Pingali and Pandey 2001 ^e	R	Asia, Sub-Saharan Africa, LAC ^f	222	150–525	Survey of experts
Gibbon et al. 2007 ^e	R	Asia	59	11–102	Survey of experts
Gibbon et al. 2007 ^e	R	Sub-Saharan Africa	249	119–407	Survey of experts
Tittonell et al. 2008b	R	Western Kenya	117	<i>n</i> = 1	Field experiment
van Wart et al. 2013b	R	USA	37	<i>n</i> = 1	Simulation modelling
Soybean					
Table 6.2	R	USA	31	<i>n</i> = 1	Field experiments
Table 6.2	R	Argentina, China	32	30–33	Field experiments

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Table 8.1 Continued

Source or reference	Description of environment	Yield gap (% of FY)			Source of PY
		Water supply ^a	Location	Mean	
Pulses					
Section 7.2	R	Lupin—Western Australia	30	$n = 1$	Field experiments
Waddington et al. 2010	R	Chickpea—India	110	84–119	Survey of experts
Waddington et al. 2010	R	Cowpea—western Africa	145	93–219	Survey of experts
Cassava					
Section 7.5	R	Nigeria, Thailand	100	$n = 2$, both 100	Field experiments
Waddington et al. 2010	R	Sub-Saharan Africa, Asia	96	60–140	Survey of experts
Other crops					
Section 7.3	R	Canola—United Kingdom	36	$n = 1$	Field experiments
Section 7.4	R	Sugar beet—European Union, United Kingdom	40	33–47	Field experiments

a I = irrigated; R = rainfed

b FY sample probably biased toward better farmers

c Excluded Asian countries sourced from Papademetriou et al. (2000) as too low (mean yield gap = 34%)

d Including Ukraine

e Pingali and Pandey (2001) refer to the late 1990s when less than 50% of the area was sown to improved varieties. Almost 10 years later Gibbon et al. (2007) estimated constraint contributions (kg/ha) to yield gaps, but non-use of best variety was not assessed, causing some underestimation of gap. Drought and temperature constraints were included in the survey but are excluded here.

f LAC = Latin America and the Caribbean

The yield gap estimates calculated for this book are based on field measurements of PY (except for rice in the Indian state of Punjab) and tend to sit above PY estimates based on FY distributions and below those estimated from models or by experts; the three recent estimations by van Wart et al. (2013b) are an exception.

Although referred to only twice in Table 8.1 (for wheat and rice), one approach to determining yield gap is to use the distributions of FY—i.e. yields from multiple fields and multiple farmers in a region—to establish some upper bound to FY (e.g. the 90th percentile yield), which can be taken as attainable yield. This approach ignores

consideration of an independently determined PY, and instead identifies the exploitable yield gap as the difference between the upper bound field-level FY, and average FY across the region.

This boundary function method is explored in more detail in Box 8.1. However, the method is clearly inappropriate for subsistence and smallholder farmer systems. For example, Affholder et al. (2013) found that in four case studies, the 90th percentile yield across such farmer fields was around half the modelled PY. In more advanced cropping situations, the method could have merit for examining yield variation within a given year. However, this method remains limited in rainfed areas because differing rain amounts could heavily determine yield variation between fields—even within a year, and especially if the region is large. In such situations, yield variation may be unrelated to level of farmer management, as is assumed by the method.

Where reliable experimental yields under representative conditions—such as those determined by the national variety trials in the United Kingdom (UK)—are not available for estimating PY (and water-limited PY (PY_w)), crop simulation modelling can play a role in yield gap estimation. Nine cases of such modelling are given in Table 8.1 for wheat, rice and maize. In fact, van Ittersum et al. (2013) argued that simulation is the best method for estimating PY, with the proviso that models are calibrated and validated in the target areas of interest, and use sound soil data and reliable, reasonably long-term daily weather data.

The basis for favour shown by van Ittersum et al. (2013) toward crop simulation modelling is that—in contrast to several recent ‘top-down’ global approaches that used empirical statistical analyses for quantifying yield gaps, but appeared to lack local accuracy (Box 8.1)—a global picture may be soundly (albeit gradually) built from a ‘bottom-up’ approach using locally relevant methods of estimating yield gap. These authors cite Laborte et al. (2012) and Grassini et al. (2011a)—also mentioned in Table 8.1—as good recent examples focusing on, respectively, the suitably small regions of Central Luzon in the Philippines, and central Nebraska in the United States of America (USA). Even so, different models can give very different PY values (e.g. Palosuo et al. 2011), and modelling PY across whole continents (e.g. Boogaard et al. 2013) or the world (e.g. Licker et al. 2010), which is becoming fashionable, is particularly prone to errors in global weather databases (van Wart et al. 2013c).

Until such point that crop simulation modelling is more carefully validated against local measurements, Table 8.1 provides an appropriate summary of all currently available information on yield gap. The table has been arranged by crop type, but the apparent differences in yield gap among crops should not be interpreted as particularly meaningful because two trends confound the data—yield gap: (1) tends to be smaller under irrigation than under rainfed conditions; and (2) tends to be smaller in developed than developing countries. The effect of irrigated vs. rainfed condition is clear enough for rice and maize, while the developed vs. developing difference shows up reasonably clearly in the case of wheat and maize.

Generally speaking, most yield gaps in Table 8.1 exceed 30%, and although some of the figures in the 'range' column present some very low values—for example, 5% for wheat in India and 11% for maize in Asia., these are considered by their source (Lobell et al. 2009) as likely to be erroneous. There are, however, several other well-documented cases from developed countries—for example, wheat in Germany and irrigated maize in Nebraska, USA—that confirm that yield gaps in some regions have become quite small.

Of the 41 cases developed in this book and summarised in Table 8.1, there are six cases for which yield gap has been determined to be $\leq 30\%$, including the lowest value of 26% for wheat in northern France and of 25% for rice in Egypt. For eight of these cases in Table 8.1, yield gaps lie between 30% and 40%. However, yield gap is $>40\%$ in the remaining 27 cases (66% of the cases), with some obvious standout values, such as the particularly large gaps for rainfed rice in India, cowpea in western Africa and maize in Africa. Yield gaps can also be considered in relation to mega-environments for wheat, rice and maize: doing this, the estimated global yield gap, weighted by production, was as a percentage of global average FY in 2010:

- 50% for wheat (Table 3.7)
- 72% for rice (Table 4.6)
- 98% of wheat (Table 5.8).

Box 8.1 Farm yield (FY) distribution and estimating yield gap

Some of the different approaches to yield gap estimation and analysis deserve further mention. A common method is to identify highest yields from the statistical distributions of farm yield (FY)—at either the farm or field level—for a defined region and use the results to estimate attainable yield (see Chapter 2). Successive rounds of rice farm surveys have been used to track rice FY in Central Luzon, the Philippines. For example Byerlee et al. (2000) took the mean yield of the top 30% of fields for AY, while Laborte et al. (2012) used the top 10% (see Section 4.2 on rice mega-environment 1 (RME1)). Another example from farm survey is given in Section 3.2 for wheat in the Yaqui Valley, Mexico, where the yield of each field (a measure of FY) was estimated using remote sensing, while potential yield (PY) was measured in well-managed field trials. The 90th percentile field-level FY lay below PY by 1.9 t/ha—a gap equivalent to 33% of average FY and probably close to AY. No individual fields yielded more than PY. These wheat observations add some credence to the approach of determining AY on a region's higher yielding farmer fields, but it underestimates AY and PY for farmers of smallholdings (Affholder et al. 2013; see text).

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The change in the distribution of yields with time can also reveal aspects of the process driving FY progress. Thus for irrigated rice in Central Luzon, Laborte et al. (2012) showed how the distribution of field-level FYs started with a positive skew early in the green revolution years of 1966–67. During this time mean field-level FY was 2.1 t/ha, with the mean top decile yield at 72% above the mean, and more fields with higher yield than a normal distribution of yields would predict. Twenty-three years later, during 1990–91, the distribution switched a negative skew, and finally (a total of 33 years later) to a normal distribution in 2000–01, by which time mean field-level FY had more than doubled to 4.8 t/ha, and the mean top decile yield had reduced to 45% above the mean. The reported change in yield distribution with time is consistent with adoption theory—that there are initially few early adopters, followed by a situation of majority adoption (excepting a few laggards) and finally, restoration of a normal yield distribution.

Use of yield distribution to determine yield gap is similar to the econometric technique known as stochastic frontier analysis (SFA), which is used to follow changes in farm productivity. SFA relies on the scattered distribution of output (such as FY or some other productivity measure) across a large sample of fields or farms, plotted as a function of some aggregate measure of inputs (e.g. use of agricultural chemicals). An upper boundary function (or frontier) is fitted, and this usually shows the amount of output increases as inputs are increased, but commonly with diminishing returns. The most efficient producers sit on the frontier, which can be considered, in terms used here, as the equivalent of the attainable yield boundary; normally many farmer or fields show <1.0 technical efficiency in accord with where they lie relative to the frontier. This approach is applied in Australia in Section 12.4 to change in total factor productivity (TFP) of crop farmers.

Using the SFA approach, a global yield gap analysis was attempted by Neumann et al. (2010). On a 5 arcmin × 5 arcmin area basis (about 10 km × 10 km) Monfreda et al. (2008) had determined by satellite imagery and ground census data, wheat, rice and maize yields, averaged for 1997–2003, across the entire globe. These values were taken as the dependent variable, and aspects of average weather were taken as the explanatory (or input) variables. By fitting an SFA upper boundary function, and calculating a technical efficiency parameter for each grid cell data point, efficiencies were then related in a separate function to possible explanatory variables (e.g. irrigation, land slope, non-urban population, and/or access to market). The global average technical efficiencies were 0.64 for both wheat and rice, and 0.50 for maize. If the gap in efficiency (determined by subtracting the average efficiency from 1.0) is divided by the efficiency value, and multiplied by 100—i.e. for wheat this would be

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$100 \times (1.0 - 0.64)/0.64$ —then the measures of technical efficiency convert, in terms used by this book, to yield gaps of 56% of FY for both wheat and rice, and 100% of FY for maize. Explanatory variables for the efficiency—or yield gap—varied regionally, and coefficients of determination were low (mostly <30%, even at the country level). The gap values are realistic in comparison to those in Table 8.1, but the explanations are barely plausible since so many inputs are ignored.

Several other recent global yield gap studies have been based on some high percentile value of observed grid-cell yield as the PY. For example Mueller et al. (2012)—again using the Monfreda et al. (2008) global yield maps—attempted to relate yield gap (determined from grid-cell yield distributions for given climate classes) to fertiliser use and irrigation, but this method was equally unconvincing because of the multitude of assumptions involved.

As an alternative to grid-cell yield distributions, other recent global approaches to yield gap use various and generally simple crop models to estimate PY. For example van Dijk et al. (2012) used simulation modelling and climate data to estimate maize PY across Sub-Saharan Africa at a high level of grid-cell resolution, then calculated yield gaps relative to Monfreda's estimate of FY for each grid-cell. The average yield gap was >500% for the continent, with great spatial variation. Most other global yield gap references, based on modelling for PY, also use the Monfreda global maps for FY.

This book concurs with van Ittersum et al. (2013), who reviewed many of the global yield gap studies referred to here, and concluded that the top-down approaches—which are often delivered by non-agriculturalists—are too simplistic, contain too many assumptions, are reliant on inadequate databases for inputs (particularly the climate data; van Wart et al. 2013a) and lack validation. In fact, the outputs are often found to be inaccurate at the local level, and thus lack credibility at the global level at which they are delivered. It is therefore likely that crop scientists will continue to follow the bottom-up approach to yield gap determination, aided by ongoing improvement in detailed crop simulation models, and improvement in the quality of local crop, weather and resource data—an increasing proportion of which will likely come from properly validated remote sensing (Lobell 2013).

In those situations where small yield gaps exist (~30% or less), further PY increases become the only route by which FY can increase (apart from increases driven by output to input price ratios; see Section 2.4 on confounding factors). Most gaps are, however, larger than 30%, and possibilities for closing the gap become increasingly important as the gap increases. Section 8.2 discusses gap closing in further detail.

8.2 Causes of yield gaps

Farmers everywhere wish to improve household welfare, including food security and incomes, but many obstacles impede technology adoption, even where experience elsewhere has shown its potential to improve income. For this reason, many yield gap studies mentioned in Chapters 3–7 (and Table 8.1) have attempted to understand what constraints cause the yield gap to be larger than expected from analysis of economics and risk aversion. After a brief overview of approaches (see also Box 8.1), several recent efforts are described in more detail below.

An early structured approach to understanding yield constraints became known in the 1980s as **farming systems research** (Collinson 2000). This approach involved participatory identification of constraints and problems in crop production at the farm level in specific regions of the developing world. A variant is the 'rapid rural appraisal' methodology (Byerlee et al. 1980), which endeavours to rank constraints after a minimum number of targeted farm visits.

Traditionally, agronomists emphasised the role of **on-farm multifactorial experiments**, as well as exploration of **relationships between surveyed yield heterogeneity and management practices** in space and time for identifying yield constraints. Other researchers have lately refined farm surveys and have used new tools like regression tree analysis to understand variation between field-level FYs, for example in African smallholder farming situations (see below; Tiftonell et al. 2008a).

Satellite imaging is beginning to be used to estimate field-level FYs and help identify constraints—see examples for wheat in Mexico (Section 3.2) and India (Section 3.3). Lobell et al. (2010) used satellite imagery to show that irrigated wheat yield declined in the Indian Punjab with increased distance from supply canals. Such methodology has excellent potential if based on adequate 'ground truthing'. This powerful technique will presumably become more useful as better quality and more extensive georeferenced databases for potential constraints to yield become available.

Crop simulation modelling is also being employed to test the importance of possible yield constraints identified in surveys (e.g. sowing time). Even in relatively uniform small regions, with little yield variation among fields, yield variation can be unravelled with crop simulation modelling; an example is described below for evaluation of irrigated maize fields in just three adjoining Nebraska counties (Grassini et al. 2011a).

Finally **surveys of experts** have also been used. For example, Waddington et al. (2010) consulted hundreds of experts—including crop researchers (52% of the total) and extension workers (25%), along with socioeconomists, input suppliers and farmers—to identify crop yield constraints in Asia and Sub-Saharan Africa that have led to the yield gaps listed under this reference in Table 8.1.

Many of the above approaches to identification of the size and causes of yield gaps have been discussed in the preceding discussions of commodity cases in

Chapters 3–7. Here attention is now given to some recent additional studies because of their relevance and/or novelty.

The most ambitious have been **global studies** which have attempted to relate average crop yield, as determined at high spatial resolution across the world (e.g. Monfreda et al. 2008), to climate and to whatever characteristics can be gleaned from national or district statistics regarding other production factors. For example, van Dijk et al. (2012), mentioned in Box 8.1, showed that smaller yield gaps for maize in Sub-Saharan Africa were associated with good road access to markets and high fertiliser use. Other studies are mentioned in Box 8.1, but the relationships derived from these massive computing exercises are generally not convincing because of the large number of assumptions.

Looking at **wheat across seven regions in Asia**, Waddington et al. (2010) reported expert opinion on the following frequency of yield constraints, given as the number of occasions (out of seven) that individual constraints appeared in the 'top five':

- nitrogen deficiency and poor nitrogen management (six)
- unsuited variety and poor seed quality (six)
- poor irrigation supply (four)
- nitrogen fertiliser supply and cost (three)
- weeds (three)
- late planting (two)
- rusts, rodents and pests (one each)
- poor access to information (one).

These losses can be compared to those outlined in more detail for irrigated wheat in the Yaqui Valley, Mexico (Section 3.2) and north-western India (Section 3.3) where satellite imagery and ground surveys were the primary tools.

For **rice in South and East Asia**, Waddington et al. (2010) again used surveys of experts, and reported some commonality in the top constraints across regions—diseases, pests, inadequate irrigation supply and poor fertiliser management. However, regional differences were also reported, and low soil fertility (especially nitrogen) and weeds were identified as additional key constraints for South Asia, while poor biocide management featured for East Asia. The constraints that Waddington et al. (2010) identified for rice in South Asia agree well with the assessment of the International Rice Research Institute (IRRI) mentioned for India (Section 4.4) and Thailand (Section 4.8).

For **maize in Sub-Saharan Africa** across five regions, Gibbon et al. (2007) also used expert opinion and reported yield losses due to various constraints (as shown in Figure 5.3). This explanation of yield loss was generally supported by an earlier broad survey by Pingali and Pandey (2001). Suffice here to point out that top priority was soil fertility (especially lack of nitrogen and phosphorus), followed by weeds (including *Striga*), diseases and insects, and finally late planting.

In mid-altitude western Kenya—a region where yield gap exceeds 100% (Table 8.1)—maize yield variation (across 159 farmers' fields subjected to **survey and regression tree analysis**) was explained in order of importance by low soil fertility, late planting, low density and weeds (Tittonell et al. 2008a). Keating et al. (2010) found soil fertility (in particular nitrogen deficiency) clearly dominated maize yield constraints in eastern Africa, followed by low plant density and weeds. These researchers were emphatic that poor soil fertility in Kenya overshadowed any constraint associated with the common absence of the best modern varieties.

Obviously there is a **multitude of interacting crop yield constraints** in most developing countries, especially in Asia and Sub-Saharan Africa. Moreover, priority constraints are likely to change in rank order between locations. This priority difference in yield constraints was demonstrated by the comprehensive expert surveys conducted by Gibbon et al. (2007) for maize, and by Waddington et al. (2010) for other crops. The survey results listed 10 constraints for each crop in each region. The top five constraints appeared to be of roughly of equal importance, but the constraints that appeared in that 'top five' changed from region to region. At the opposite end of yield gap studies, under modern agriculture in relatively uniform and small regions, a clearer and sometimes simpler picture of constraints emerges.

For example, in a landmark study of yield gaps, Grassini et al. (2011a) analysed **irrigated maize yields in three adjacent Nebraska counties** (total area 100 km × 35 km). Over a three-year period (2005–07) these authors studied 777 maize crops in 521 different fields. FY averaged 13 t/ha (coefficient of variation only 8%), compared with the average simulated PY (14.9 t/ha) when observed sowing dates, plant populations and hybrid maturities were used as model inputs. However, when optimal values for these three factors were used, PY was 17.5 t/ha, representing a yield gap of 35% relative to observed FY. Variation in FY was significantly related (in approximate order of importance) to year, rotation, tillage and the rotation-by-tillage interaction. It was also, significantly but weakly related to seed rate, planting date and hybrid maturity (and their interaction), and irrigation amount.

The Grassini et al. (2011a) study revealed that seeking higher yield carried greater risks—for example, risk of late frost damage with longer duration hybrids (frost was excluded from modelled PY)—and useful recommendations were derived for farmers wishing to increase profits through reduced costs and increased yields. But these authors also argued that, since observed FY had been static over the previous 8 years, it was approaching limits imposed by economics, risk and crop variety, and was therefore unlikely to rise further unless these limits were relieved.

A second example for modern agriculture is an analysis of **rainfed wheat farming** across southern Australia. Hochman et al. (2009) summarised experience with 334 wheat crops (a few were irrigated) over three relatively dry seasons (2004–07). These authors compared individual yields with yields simulated by the APSIM-Wheat model using observed weather and measured or estimated farmer management data—i.e. seed rate, sowing date, soil moisture and nitrogen at sowing, and nitrogen fertiliser

application. Modelled yields, FYs in this case, were closely related to observed yields ($R^2 = 0.71$, root mean square error of 0.8 t/ha) with average values of 2.0 t/ha (range 0–8 t/ha) for measured FY, and 2.1 t/ha for simulated FY.

This small difference between average and modelled FY suggests that constraints that were not included in the model—e.g. weeds, pests, diseases and temperature extremes—had negligible effects on observed yield. In contrast, when early sowing and unlimited nitrogen were included separately from other management strategies, simulated average yield rose to 2.6 t/ha. This higher yield is equivalent to water-limited potential yield (PY_w), in terminology used here, because it represents what best management can achieve. It follows from this that yield gap—the difference between average FY of 2.0 t/ha and PY_w of 2.6 t/ha—is 0.6 t/ha or 30% of FY.

Hochman et al. (2009) pointed out that farmers who were prepared to risk both earlier sowing (risking frost damage at flowering) and increased nitrogen application (risking premature exhaustion of soil water) for a higher yield pay-off would likely be more advanced and may well be operating at the attainable yield limit, as defined in this book. Also note that by taking as given the measured soil water and nitrogen at sowing, this simulation exercise excludes from consideration those pre-sowing management strategies that can augment the levels of these important inputs for yield, thereby increasing PY_w . Farmers losing yield because of poor moisture management in the critical pre-sowing fallow period would have caused a yield gap underestimate across the whole sample, but these farmers are expected to be in a low proportion.

Finally, Hochman et al. (2012) went on to focus on the smaller Wimmera region in the state of Victoria, Australia—where about 500,000 ha of rainfed wheat is grown over an area of 200 km². In order to determine variation in yield gap across the region over a 20-year period (1990–2009), they compared recorded district yields, and also FY estimates from satellite images, with simulated PY_w . In contrast to the study above, average yield gap across all wheat crops was 90% of FY. Average yield gap notably varied between years and somewhat consistently among districts, since some districts had regularly higher yield gaps than the regional mean. This powerful methodology still struggled, however, to pinpoint exploitable yield constraints, largely because critical soil and management information at the field level could not be readily obtained for the simulation component of the study.

To summarise, the **causes of yield gaps are multiple and often interrelated, and causes vary with circumstance** including year at a given location. The targeted regional examples with good field-level data and simulation tools were able to make some progress on constraints but also served to show how complex these issues are. Table 8.2 attempts to list all types of constraints that have been encountered in studies and surveys of FY, and from expert and farmer opinion, but in no priority order. The top portion lists the proximate technical constraints mentioned above. They are followed in the table by the interlinked categories reflecting general issues relating to human resources in farming, and the policy and institutional environment in which they operate.

For each constraint, Table 8.2 offers three avenues or options for alleviation, which are discussed in detail in the next section. Note that interventions can refer to either those technologies already available 'on the shelf' and well-proven actions for governments, or to new technologies and actions that research could likely develop or enhance. Table 8.2 does not include some constraints commonly mentioned by farmers (e.g. heat during grain-filling and drought) because these are part of the climate that determines PY or PY_w. Similarly, low price is not included because it is not a proximate cause.

Table 8.2 Constraints contributing to yield gap and interventions (agronomic, breeding and institutional and/or infrastructural) favouring constraint alleviation and yield gap closing

Constraints	Interventions		
	Agronomic technologies	Breeding technologies	Institution and/or infrastructure changes
Technical or proximate constraints relating to land and inputs			
Lacking major long-term soil amelioration	Drainage, land levelling, liming, deep tillage and/or gypsum	Waterlogging and/or salt tolerance	Long-term credit and secure land ownership
Excess tillage and loss of moisture	Conservation tillage options and controlled traffic	Suitable varieties—disease and/or herbicide tolerant	Credit for new direct-seeding machinery
Manageable topsoil soil toxicities	Amelioration and diagnostics (e.g. lime for acidity)	Acidity and/or toxicity tolerance	Competitive input suppliers and credit
Suboptimal nutrient supply	Diagnostics, application of nutrients, and tactics for nitrogen top dressing	Some scope for improved nitrogen, phosphorus and zinc uptake and utilisation	Competitive input suppliers and fertiliser quality control
Soil variation within and between adjacent fields	Diagnostics and precision farming to adjust application rates	Greater tolerance of soil stresses	Facilitation of access to satellite and/or airborne imagery and guidance
Growing old varieties and/or use of poor seed	Better on-farm seed management and storage	F ₁ hybrids and licensed traits to encourage strong seed industry	Strong seed industry and regulation
Incorrect time of sowing	Mechanised and reduced tillage to speed sowing	Make available varieties with range of maturities and/or herbicide-tolerant varieties	Mechanisation and/or contract seeding

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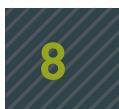


Table 8.2 Continued

Constraints	Interventions		
	Agronomic technologies	Breeding technologies	Institution and/or infrastructure changes
Inadequate plant population	Better drilling procedures and machines, and/or quality seed and storage	More robust varieties—long coleoptile in wheat and more tillering	Credit for improved machinery
Diseases and pests (above and below ground)	Biocides, sanitation, crop rotation, and/or integrated pest management (IPM)	Host-plant resistance, including genetic engineering (GE)	Competitive input suppliers, quality control, workable regulations for release of GE varieties
Weeds	Herbicides, cultivation, sanitation, crop rotation, and/or integrated weed management (IWM)	Enhance crop plant competitiveness, and/or herbicide-tolerant varieties (including GE)	Herbicide quality control, workable regulations for release of GE varieties
Poor water management in irrigated systems	Improve water application techniques and skills	Greater tolerance to water shortage and excess water	Efficient supply systems to farm, more farmer control
Long-term soil degradation	Crop rotation, fertiliser, green manure, farmyard manure, conservation tillage, and/or zero-till	Varieties adapted to biotic and abiotic stresses of high plant residue levels, and with good residue production	Secure land ownership by farmer and access to credit
Constraints relating to general farmer capabilities			
Lack of farmer awareness, conviction or skill	On-farm demonstration	On-farm testing and selection	Education, access to communication and extension services, and gender awareness
Risk aversion by farmer in the face of unpredictable weather and prices	Better weather forecasts and tactical decision-making (e.g. for nitrogen topdressing and biocide use)	Tolerance of extreme weather events (e.g. drought, heat, flooding, hail, frost and wind)	Insurance, favourable credit terms, reliable contracts, market information, and secure land ownership
Inadequate labour supply	Mechanisation, reduced tillage, and herbicides	Select for uniform maturity to favour mechanical harvesting	Facilitate labour migration, credit for mechanisation, farmer health services

8.3 Technologies and policies for alleviating yield gaps

Yield gap closing has generally been a slow process. Recall that, over the past 20 years, average differences between annual global rates of increase in FY and in PY were estimated to be:

- -0.4% p.a. for wheat (Table 3.7)
- -0.3% p.a. for rice (Table 4.6)
- -0.7% p.a. for maize (Table 5.8)
- -0.8% p.a. for soybean (Table 6.2).

Collectively these figures indicate that the mean rate of yield gap closing is about 0.5% p.a. (of FY). At this rate, it takes about 20 years to reduce a given yield gap by just 10% of FY.

Many constraints are listed in the first column of Table 8.2, but in almost every case they can be lessened or eliminated by adoption of the agronomic and breeding technologies listed in the next two columns. These options may already be available or could be developed and/or locally adapted through further research and development. Given the definition of PY used in this book, gap-closing research seeks to alleviate stresses on FY, rather than progress FY through raising PY—except that raising PY_w specifically targets water stress.

It is also easy to list desirable infrastructural and institutional changes (final column of Table 8.2) bearing on these constraints, but—as the slow rate of yield gap closing attests—is it neither easy to effect farmer adoption of technical change (i.e. farmer innovation), nor easy to change policies toward infrastructure or institutions. Potential technologies and policies for alleviating constraints associated with yield gap are discussed briefly below, before the discussion turns to farmer innovation in the next section.

Agronomic research for gap closing

Agronomic research continues to facilitate the adoption of technologies that alleviate yield constraints and help close yield gaps. Many of these technologies (and associated research) also aim to reduce costs by increasing efficiency of input use. A few examples are provided below.

Small-scale machinery

Farmers of smallholdings in South America and South Asia could adopt conservation agriculture only after research and development delivered the small-scale machinery essential for direct seeding their small fields with reduced soil disturbance. South Asia

now needs small-scale drills that can handle the heavy crop residues from rice. Similar equipment suited to a range of other cropping systems is needed, for example, in China and Sub-Saharan Africa.

Crop nutrient management

Crop nutrient management has been improved through research and development of simple diagnostics for deficiencies in individual fields, backed up by better nutrient application strategies. For example, site-specific nutrient management presents potential adopters with simple crop nutrient deficiency diagnostics and uses this and other information to determine the lowest cost, least risky and most effective fertilisation regimes. Nowadays this information can be promptly supplied through mobile phone networks, a cost-effective form of delivery especially in developing countries where mobile phones are now widely used.

Weather forecasts

Improved short- and medium-term weather forecasts provide valuable information for facilitating many farm operations. As with crop nutrient management, this information can also be delivered by mobile phone. A new research area is the use of seasonal forecasts to reduce risk in input management, thereby reducing risk-related yield gaps.

Integrated pest control

Worldwide, biocide use in commercial agriculture is complex and expensive, and hence is often less effective than possible. Research develops simpler rules for the integrated control of target organisms (e.g. thresholds, timing and non-chemical controls), which can facilitate adoption of strategies that reduce yield losses and prevent evolution of resistance in target organisms.

Breeding for gap closing

Targeted resistance breeding can help close yield gaps by making varieties more resilient to many of the constraints listed in Table 8.2. In this case the technology is in the seed. These constraints can also often be alleviated with agrochemicals, which are usually costly and complex to apply. For these reasons **new varieties are generally adopted more readily than new management techniques**, and provide the favoured route to yield gap closing because this option is much less expensive for farmers and extension organisations alike.

Oerke (2006) presented a global meta analysis of observed yield losses due to **biotic stress (insects and other animals, and diseases and viruses)**. The estimated yield losses for 2001–03 averaged about 25% of FY across major cereals and soybean (and 47% for potato). Losses tended to be higher with rice and are confirmed by an estimate of 34% of FY for rice in tropical Asia (Savary et al. 2012). Current control measures are inadequate but nevertheless very beneficial because, without control measures,

potential losses were estimated to be almost 50% of FY for the four staples according to Oerke (2006), and—as shown in Section 7.9—even greater in potato (e.g. 70% in China).

Reducing the observed yield losses due to biotic stress is the aim of **host-plant resistance breeding**, relevant to all situations where the required genetic variation exists and a major component of all crop breeding. For example, Dubin and Brennan (2009) recently documented the substantial reduction in yield losses attributed to wheat rusts globally—an outcome made possible through cooperative international breeding efforts. In fact conventional resistance breeding achieves genetic ‘progress’ simply by maintaining levels of resistance in the face of evolving pest agents (while aiming at the same time to especially strengthen the durability of resistance). Without this so-called **maintenance breeding**, yield levels would steadily fall.

James (2012) documented the growing impact of **genetically engineered (GE) insect resistance**—particularly maize and cotton, which in 2012 together globally occupied 70 Mha—and to yield gains linked to the replacement of insecticides with this more effective and less-expensive host-plant resistance. Transgenic resistance to viral disease has been deployed successfully in papaya and will soon be released in *Phaseolus* spp. beans in Brazil (James 2012). Transgenic resistance to fungal diseases—a long-held dream of genetic engineers with large potential benefits—is on the 10-year horizon (e.g. Allen et al. 2011; Wulff et al. 2011).

A particularly straightforward approach to more durable disease resistance can sometimes be achieved by pyramiding naturally occurring resistance genes from within a species or across related species. This is difficult to achieve with conventional breeding, although molecular markers for the genes now help. However, the process is made easier when a GE technique termed ‘**cisgenesis**’ is used where the same (or a related) species is the source of the resistance genes. At present, poorly informed rules pertaining to GE crops in places like Europe still classify this as ‘genetically modified’. The technique may soon deliver varieties with enough major resistance genes to control late blight in potato (Zhu et al. 2012), something currently achieved only by multiple applications of fungicide.

Overall it would seem that in the medium term (~15 years) there are good prospects for improved host-plant resistance to perhaps halve that part of the global yield gap (i.e. ~25% of FY) that is attributed to pests and pathogens. At the same time, improved host-plant resistance should substantially reduce biocide use.

The Oerke (2006) meta analysis also estimated observed losses in major cereals due to **weeds** to be ~10% of FY—noting that potential losses, i.e. without control measures, were much higher at 50% of FY—and revealed that modern varieties tended to be more susceptible to weed competition. It is interesting to note that some breeding programs are beginning to target crop competitiveness with weeds, but progress will be slow unless there are other linked advantages (e.g. improved early vigour) from the approach. This is because genetic increase in PY is probably partly related to reduced

interplant competitiveness in the crop environment; for example, such as that attributed to traits like reduced plant height and more erect leaves.

General experience in farmer fields confirms that until the advent of **herbicide-resistant varieties**, breeding had not helped to increase FY under heavy weed competition. Herbicide-tolerant varieties were first produced using natural resistance, but were soon followed in the mid-1990s by transgenic resistance. Subsequently, GE varieties carrying glyphosate- and glufosinate-resistance traits have been very successful in the North and South America for maize, soybean, canola and sugar beet. These transgenic crops have enabled better weed control, and facilitated conservation tillage and often earlier planting—factors that all lead to higher yields (see Section 9.9 on GE using transgenes).

In 2012, **GE herbicide resistance** covered 144 Mha of the global crop area (James 2012), dominated by plantings in North and South America, but continuing to spread throughout the world. However, weeds that already were, or since have evolved to become, naturally herbicide-resistant are beginning to challenge this technology, especially in the USA, where the history of GE use is longest and where herbicide resistance has generally been poorly managed. Integrated weed management (IWM), employing a suite of agronomic and breeding approaches, will remain essential for long-term weed control but has been neglected through complacency generated by successes first with herbicides and then with herbicide-tolerant crop varieties (Gressel 2011a). The **threat of losing invaluable herbicides like glyphosate** to herbicide-resistant weeds is becoming a very substantial challenge for agriculture. It will be especially serious for extension scientists and farmers in the developing world, because IWM is knowledge intensive.

A final general comment on technologies for alleviation of proximate constraints in Table 8.2 is that **yield effects from most interventions are not substitutive**. Rather, each opportunity for constraint alleviation offers one necessary step for closing yield gaps, but if other constraints remain, gap closing will be limited. As de Wit (1992) pointed out, response to physical inputs is best described by Leibsher's law that an input delivers most when others are close to their optimum. This is why many technologies are promoted as part of a package (e.g. modern varieties, plus fertiliser plus weed control), even though farmers, through natural caution, may initially test only parts of packages.

Infrastructure, institutions and farmer capabilities

At the highest organisational level in Table 8.2—beyond farmers' fields—are those constraints derived from poor rural infrastructure, weak institutions, bad farm policy and unskilled farmers. This level of constraint can create huge obstacles to adoption of improved technologies. Such constraints are particularly exhibited in price disincentives at the farm gate due to expensive inputs and credit, unreliable markets and increased risk in general. Farmers also need:

- clear product quality standards
- protection from input adulteration and false information
- secure land tenure.

Furthermore, the information supply to and skills of farmers themselves is critical to adoption of improved technologies and management; these in turn relate to educational levels, farmer health, quality of advisory services, effectiveness of media coverage of agriculture and effectiveness of information and communication technologies (ICTs).

Solutions emerge with good governance—that is, sustained public investment in advisory services and infrastructure (e.g. rural roads, communication, education and health) and sound institutions and policy (including enforcement of proper regulations) are needed. Lack of good governance has been a major contributor to the large yield gap in regions like Sub-Saharan Africa (Table 8.1). General policy opportunities are discussed in Chapter 13.

As infrastructure, institutions and policy have been widely canvassed in other general literature, a discussion of these issues has been deliberately limited in this book. However, even when focusing on proximate constraints at the field level, it is important to highlight the extent to which field constraints are influenced by these higher level ones. The impact of good institutions and infrastructure on farmer capabilities and opportunities is especially large, and is effected through empowerment benefits of proper education and health services, security of land tenure, and policies that favour grassroots farmer organisation. Finally, infrastructural and institutional interventions tend to behave like physical inputs to cropping: to a large extent they cannot be substituted, none alone are sufficient, all are necessary, and large synergies arise when all the right interventions come together. This effect is evident—yet often taken for granted—in the rural environments of developed nations.

8.4 Effecting the adoption of improved varieties and practices

Various models and approaches have been proposed for effecting farmer innovation, meaning the adoption of new technologies. The linear model—an early approach used to transfer information from researcher, to extension specialist, to farmer—has been typical of publically funded agricultural extension. Over much of the 20th century in developed countries, where free market forces have prevailed (e.g. the USA and Australia), the workforce has steadily left agriculture, and farms have inexorably consolidated. Public extension facilitated the adoption of a continuous stream of new technology, which enabled per-farm earnings to keep pace with those in the burgeoning non-agricultural economy. The same market forces have now led to a decline in public

extension, and the private sector has become much more involved in technology transfer. Funding for private sector involvement is drawn from the remaining farmers, by means that are either direct (e.g. private independent consultants or farmer self-help groups) or indirect (e.g. grain buyers and processors, or input suppliers such as seed companies).

Structural transformation of farming in much of the developing world is at an early stage. This is especially evidenced by small farm size, low level of mechanisation and a relatively high proportion of the national workforce employed in agriculture. However, the agricultural workforce is declining rapidly, and operating units in farming inevitably consolidate under free markets when national per-capita income grows.

The question here is whether those processes used in the developed world to drive farmer innovation will play the same role in the developing world. The latter situation is different from that in the developed world 100 years ago—farm size is much smaller, rural education and infrastructure poorer, farmer influence on government policy weaker and political attitudes toward farming probably less favourable. Notwithstanding the huge success of the linear model with commercial farmers of smallholdings during the green revolution (e.g. with irrigated wheat and rice in South Asia) and more recently in China, the linear model is now widely disparaged for being out of touch with the farmers' circumstances and ineffective in the developing world. This is especially so in Sub-Saharan Africa where other strategies and change agents have been invoked.

Agricultural innovation systems

The preferred approach to agricultural extension has gradually shifted over the past 30 years to more decentralised, participatory and demand-driven models. These later models—well demonstrated by the agricultural innovation systems approach (World Bank 2012b)—provide greater attention to farmers, input suppliers, and the post-farm value chain, while often working alongside public extension agencies. Regardless of the model used, however, there is little evidence that efficiency in delivering farmer innovation has improved. Moreover, the limited impact of public extension in the developing world reflects situations that remain perennially hampered by underfunding, centralised bureaucracy, poorly trained agents and poor attention to farmer feedback.

Glendenning et al. (2010) reviewed extension for hundreds of millions of farmers of smallholdings in India, each farming <2 ha. Reports in a 2003 survey found only 40% of farmers had accessed modern technical information, and that most information was obtained through more progressive farmers or input suppliers. This situation is somewhat less optimistic than that put forward by Paroda (2004) who outlined the multitude of public agencies targeting farmers in India. In this context, ICTs are often promoted as especially likely to benefit smallholders, but adding this new tool to extension is not easy and requires special attention to content and context.⁴³

43 For example see Agricultural Extension in South Asia, available at <www.aesa-gfras.net>.

China also faces a huge number of farmers of very small holdings poorly connected to a weak extension system (see Section 4.3 on rice and Section 5.3 on maize). Further, new models are being tested that vary according to farm size in the target region (Shen et al. 2013). These models include involvement of agricultural universities, decentralised R&D, organisation of farmer associations, farmer training, merging of tiny holdings, introduction of mechanisation, crop contests, and involvement of inputs suppliers with soil testing and better tailored products

Smale et al. (2011) detailed experiences with extension strategies for maize in Sub-Saharan Africa since the colonial period. Through diverse approaches—and a serious period of contraction in public spending (imposed structural adjustment) in the 1980s and early 1990s—a few keys to success emerged. Among the plurality of approaches, all cases showed increasing attention to accountability to farmer clients—and to cost-effectiveness—and a growing recognition of the role of the private sector and non-government organisations (NGOs).

When it comes to adopting improved varieties and practices, Sub-Saharan Africa has had some success stories (see also Section 8.5). For example, a recent review of 40 projects (Pretty et al. 2011) claimed that over the 1990s and 2000s, a total of 10 million farmers of smallholdings have lifted productivity by ~450 kg/ha on over 13 Mha, where previously yields were less than 1 t/ha. The principal interventions behind the increased productivity were novel partnerships and policies, agroforestry and soil conservation, integrated pest management and improved crop and livestock systems. The review also observed that new technologies—developed by both farmers and scientists—prove most valuable when combined with one or more of the following:

- focus on women farmers (who are generally the key decision-makers on farms in Sub-Saharan Africa)
- improved farmer knowledge
- microfinance (to avoid very high cost of traditional sources of credit)
- novel social infrastructures that build social capital among farmers
- private sector engagement
- public sector support (through research, development and extension, and policies, institutions and infrastructure).

These experiences reported in Pretty et al. (2011) reinforce the trends mentioned under the World Bank AIS study—particularly attention to social infrastructure, and growth of social capital among farmers of smallholdings. These attributes (through trust and cooperation) facilitate knowledge sharing and link farmers of smallholdings more effectively, and with greater bargaining power, to the wider world. This, however, requires local leadership, an enabling environment and resources from the public and/or NGO sectors.

Thus there seems no escaping the fact that facilitating adoption by smallholder farmers requires large amounts of public funds (see Section 13.3 on investments). Public investment should start with basic education for farmers, followed by specific training

of agents and farmers, leading to continued support for agents so they can function effectively. Although technical research results spillover quite readily from the developed to the developing world, agricultural innovation systems need to be tailored to each farming region to adapt new technologies to regional conditions. Transfer of successful principles and methodologies succeeds best when tailoring involves local farmers—on their own land, under local physical and cultural conditions, and faced with local constraints.

The extensive deliberations under the AIS banner seem to suggest approaches must change and that public research, development and extension must be revitalised and supplemented by many other mechanisms. To some extent this will depend on target audiences; the information needs of poorly educated subsistence-orientated farmers in risky environments differ markedly from capable commercial smallholder farmers and medium-size family farmers. The latter audience has generally already adopted modern varieties and some other inputs, and will more strongly influence future crop yields in the developing world. However, in parts of Latin America and the former Union of Soviet Socialist Republics (USSR) the presence of large private and corporate farms will also be a major factor in future of yield progress.

Thus, while a critical dimension of food security must be assistance directed toward helping subsistence farmers feed themselves while shifting to commercial smallholder farmer status, where public resources are scarce and certainly where agribusiness is involved, existing innovative commercial smallholder farmers will be the prime target for further innovations.

Privatisation of plant breeding

The trend from public to private sector breeding of major crops has been very evident in developed countries over the past three decades, and now is a new feature of the research landscape in many developing countries (see Section 9.10 on genetic resources). This trend is unlikely to be reversed, given the increasing importance of hybrid varieties (e.g. maize, cotton and rice), increasing use of patented transgenic traits (e.g. maize and soybean) and the advent and spread of legislation for plant variety rights. In many cases private breeding is dominated by the five multinational life science companies (see Section 13.2 on R&D investment). However, small and medium-sized national breeding companies are surviving, and in some situations (e.g. China) are even dominating by meeting niche variety needs.

In the developed world, large commercial maize seed companies (such as Monsanto and Pioneer) retain customer loyalty by employing agronomists to ensure that new varieties can reach their full potential on-farm. To this end, these companies may employ more agronomists than breeders. The approach adds to the sale price of seed and has effectively replaced the agronomic advice that was previously provided through public extension.

The private 'take-over' of breeding and related extension forms part of a global trend to focus public sector research on important areas of market failure—such

as, for example, strategic research, crop agronomy, orphan crop breeding and/or environmental issues—and to coordinate essential regulation of private suppliers of research products. However, in developing countries this focus should also include new extension strategies directed toward farmers of smallholdings and subsistence farmers. The private breeding trend is likely to expand in the developing world; it is already obvious in some places that breeding and seed companies can work successfully with farmers of smallholdings (e.g. cotton and millet in India, maize in eastern Africa). This development is likely to bring new varieties more quickly to farmers—a critical, but so far largely unsuccessful, task of the semi-government seed companies to be found in many developing countries.

Other agribusiness in the food value chain

In considering the role of private breeders, it is important to also note how intimately agribusiness is involved in both the input and output side of crop production and processing in commercial agricultural systems. That is to say, less than 20% of value-added in the food industry value chain is observed to accrue on-farm in developed countries. These businesses range in size from small and medium enterprises to multinationals, and are essential partners in the value chain, because agribusiness grows simultaneously with farm output.

Another World Bank report points to the potential role (but current neglect) of agribusiness in Africa (World Bank 2013). Constraints for agribusiness are much the same as the infrastructural and institutional ones listed in Table 8.2 in relation to general farmer capabilities, and largely arise from poor investment in infrastructure and poor governance and policy. The difference is that agribusiness may more easily overcome constraints because of greater access to skills and greater bargaining power with government. The agribusiness advantage is beginning to be realised in Africa. It could catalyse faster transformation of agriculture by attracting commercial farmers (including the farmers of smallholdings, who are in the majority) to a role in a modernised food value chain. This must surely offer a better prospect than corporate land ownership and farming in Africa—as has been proposed by some (e.g. Collier and Dercon 2009)—and is not unlike the predominant route to agricultural development that is currently taking place in Asia.

A recent review of the contribution of multinational corporations to agricultural development (Hebebrand 2011) points to the growing recognition for the role of agribusiness. The comparative advantage of commercial farmers of smallholdings (as opposed to subsistence farmers) has now been recognised, and in any case, there are often no 'large' farmers from whom to purchase products. Thus Hebebrand (2011) argues that agribusiness attitudes have shifted toward:

- 'creating shared value' with farmers of smallholdings
- linking farmers of smallholdings collectively to markets and the value chain
- promoting improved cropping practices
- providing access to finance.

Glendenning et al. (2010) confirm that in India, private sector companies (often local) are becoming involved in improving farming through product procurement, contract farming and rural business hubs. Coordination with public agencies, however, remains weak, as does proper public scrutiny of private recommendations to farmers. But in some situations, given perverse incentives to do so (i.e. rewards linked to sales), public agents are observed to over-recommend products—examples include insecticides in Vietnam, and insecticides and fertilisers in China.

The Crawford Fund (2012) drew attention to the growing role of the private business sector in food and agriculture in emerging Sub-Saharan African countries with high growth in gross domestic product (GDP). Again local companies are involved, along with multinational ones, sometimes in partnership together or in public–private partnerships. Micro-insurance for crops and livestock is one novel area also being explored, for example by governments and NGOs.

Non-government organisations

Another new feature of technology transfer in the developing world is a growing presence of new (and old) non-profit NGOs that are interested in agriculture. Farmer-based organisations (such as cooperatives) have been functioning for some time—and have played a key role in technology transfer in some places (such as southern Brazil)—while international and national civil NGOs have emerged more recently as important avenues for information flow.

NGOs often exist explicitly to improve the welfare of the poorest and most marginal farmers—usually subsistence farmers (Glendenning et al. 2010)—and, although they tend to lack technical skills, are usually strong on grassroots commitment and culturally sensitive approaches. In some countries, the impact from NGOs has been large—such as from local NGOs promoting microcredit in Bangladesh—but generally the scale of impact is restricted. One recent useful success story is that of the One Acre Fund, an NGO that works in Kenya, Rwanda and Burundi, providing technical advice, access to inputs and markets, and credit and insurance for farmers of lower economic status (see Section 8.5 on success stories). Another NGO whose success is more in engaging farmers of smallholdings than in promoting specific technologies is described in Box 8.2.

Unfortunately, some other NGOs—having been captured by special interests (e.g. organic farming or the anti-GE lobby)—offer only narrow technological perspectives, and this has caused confusion about mainstream, scientifically established ‘best management’ practices. In some situations, it could be argued that yield progress has been hampered by ideological opposition to agricultural chemicals or genetic engineering professed by several international NGOs. Overall, however, most NGOs have been effective in building trust and empowering farmers of lower economic status to make their own decisions regarding available new technologies. For this reason, NGOs are likely to have a growing role in aiding farmer innovation.

Box 8.2 System of Rice Intensification—a controversial non-government organisation

An interesting non-government organisation (NGO) activity surrounds the System of Rice Intensification (SRI, also its original French acronym), as described in detail by Bouman (2012). Developed in Madagascar in the 1980s by a Jesuit priest, Henri de Laulanié, SRI was a set of agronomic rules and recommendations for achieving high yields of irrigated rice.

The system initially called for labour intensive activities—transplanting young seedlings, frequent weeding and careful water level control. SRI rose to international attention when claims of yields of 15 t/ha (and even 20 t/ha) of paddy rice were made (Rafaralahy 2002)—claims that were almost certainly biased upwards because of small-plot edge effects. The system was introduced into Asia about 15 years ago and again superior yields were reported (Uphoff 2007), although these have been disputed by mainstream rice agronomists (McDonald et al. 2008; see also Section 9.5 on modelled predictions of potential yield). Others have pointed out that the management rules were no different from those traditionally recognised as facilitating high yields, for example, in Japan (Horie et al. 2005a).

Despite the controversy, SRI has gained considerable support among other NGOs, regional governments and even the World Bank, as observed on SRI's website.⁴⁴ At the same time, the recommended practices surrounding SRI have expanded and become much more flexible, so that what is now promoted is a package of practices for farmers to test, modify and adopt as they see fit. Many of these practices amount to scientifically proven, good rice management and it is not surprising that some large increases in farm yields (starting from low levels) have been documented (e.g. in Cambodia; Anthofer 2004).

Success with this system has arisen not so much through innovation in the original set of recommended agronomic practices, but through the ability of the SRI proponents to generate farmer enthusiasm for what amounts to an empowering learning alliance to promote better rice agronomy. What began with a fairly rigid set of rules that mostly required extra labour input—and some of which were specific to some regions, like the insistence on water level control adapted to the special iron toxic soils of Madagascar—has evolved into a suite of options from which farmers can choose. As long as the promoted practices have a sound scientific basis, there would seem to be value in the current strategy of the SRI movement. However, there is a need to independently validate continuing claims that SRI is facilitating very high yields, including record yields (e.g. 20 t/ha in the 2011 wet season in Bihar, India; see Section 9.5). Yield gains compared with traditional farmer practice are more plausible and a better reflection of achievement.

44 Available at <sri.ciifad.cornell.edu/>

Unique farming model in South America

A new type of corporate farming has appeared in the soybean belt of South America—a region that runs from the Argentinian pampas to the Cerrado region of Brazil. In its purest form—known as *pools de siembra* (sowing cooperatives)—groups of investors (both urban and rural) rent large areas of cropland and contract cropping activities from local machinery owners. Collective decision-making ensures that best-practice management is provided by competent agronomists, and significant economies of scale are achieved for purchasing inputs and marketing, and by spreading management and agronomic skills over large areas.

The *pools de siembra* exist alongside medium-size farmers, on one hand, and large land-owning corporates on the other. They provide a significant factor driving cropping innovation in South America (see Section 5.5 on maize and Section 6.3 on soybean). This innovation includes rapid expansion and yield increase of largely GE soybean and maize, notwithstanding the generally poor transport system in the Brazilian Cerrado and some perverse policies in Argentina (e.g. export taxes).

In great contrast to agricultural regions of Africa and Asia, the South American soybean region is of relatively recent agrarian settlement (within the past 150 years). The region has moderately large properties, a favourable climate and generally good soils, and well-developed agribusinesses, institutions and infrastructure (except transport in the Brazilian interior). It is also the region in the world where conservation agriculture has been most widely adopted. This phenomenon owes its success to earlier efforts by regional organisations of like-minded smaller farmers (see Section 8.5)—efforts that continue to this day and have been embraced by the newer, larger cropping operators.

The *pools de siembra* and other models of very large farms probably cannot provide a relevant model for Sub-Saharan Africa. However, in the former USSR and parts of eastern Europe—where governments still struggle with dismantling old state and collective farm models—the ‘very large farm’ approach has emerged and may have a future.

8.5 Some success stories

Several recent success stories have been mentioned above and earlier in this book, and those in developed countries (e.g. maize in the US Corn Belt, or pulses in western Canada) do not require emphasis here as they follow well-trodden paths. However, the persistence of large yield gaps in the developing world—and the obstacles to yield gap closing—draw attention to situations where gaps have recently narrowed, or where progress has otherwise occurred at the farm level. Some of these cases are briefly described below, starting with rice, followed by maize, cotton, potato and finally conservation agriculture.

Examples of rice innovations

An excellent example of progress is demonstrated by **rice in Egypt** (Section 4.6). Although documentation of this industry's development has, unfortunately, been poor, the key catalyst was undoubtedly policy change, leading to removal of restrictions on farm-gate prices in the late 1980s and to intensified extension to a very geographically compact industry.

Progress in the last decade in **irrigated rice yields the Brazilian state of Rio Grande do Sul** (Section 4.7) reflects an agronomic revolution in which international and state public institutions combined with farmer organisations to demonstrate and promote improvements in several areas of crop agronomy. For these medium-size farms, the outcome has been an increase in average FY of 40% between 2000 and 2010, to reach more than 7 t/ha. Yield continues to rise rapidly, and critically, this progress is driven also by farmer funding and formalised farmer-to-farmer extension.

Irrigated rice yields in Senegal and Mali now average >5 t/ha through reform of large irrigation schemes, improved fertiliser supplies, adoption of improved varieties from Asia, and focused extension support. A recent review of large-scale irrigated rice in Africa suggests that many farmers elsewhere achieve similar yields, with good irrigation management and favourable fertiliser prices as the most important factors for closing longstanding yield gaps (Nakano et al. 2013).

Maize innovations

Winter (or Rabi) maize in Bangladesh has been mentioned (Section 5.6). It is a new crop for Bangladeshi farmers, who traditionally grew rice, wheat and vegetables in the winter season. Local industry expansion has been driven by burgeoning local demand for poultry feed. Around 2000, companies that had previously been importing maize began to source cheaper local maize.

Winter maize has several agronomic advantages over winter rice or wheat, including greater yield, less risk of weather damage, less requirement for water and greater profit (Ali et al. 2008). Companies and NGOs provided private sector and government-developed hybrids and advice to farmers, and in just 8 years the area grew from a very low base of <10,000 ha in 2000–01, to >200,000 ha in 2008–09 with an average FY of 6 t/ha (FAOSTAT 2013).

The impact of avian flu on the poultry industry has subsequently led to a contraction in the winter maize area in Bangladesh, but this case study remains an excellent example of public–private–NGO collaboration bringing a new crop to farmers of smallholdings. An important lesson from Bangladesh is that—where profit can be made and where technology and advice is available—farmers of smallholdings are willing to adopt new crops (like maize), and quickly learn to use hybrid seed at the correct plant densities, line planting and with adequate fertilisation.

Contracted maize production is being tried in several countries. However, because open markets for staple grains like maize are common, parties to contracts can be tempted to opt out if prices fall outside contracted values, and as a consequence, such contracts are usually ineffective. Potential long-term benefits from contracting do exist, and efforts at contracting continue.

Contracting by farmers of smallholdings for maize production has been tried in Mexico for more than a decade, and has recently commenced in northern Ghana (World Bank 2013). Under these systems—in which contractors supply technical assistance and facilitate credit for inputs—it has been readily possible to double yields. However, it remains to be proven whether such systems can be sustainable.

Even without contracts, organised farmers in Burkina Faso (neighbouring Ghana) have been able to double maize yields through active participation with input suppliers, buyers and banks. There, progress has been supported by Innovation Platforms, an institutional innovation that brings key actors from input suppliers, extension, buyers and farmers together to coordinate value chain decision-making (Sanyang et al. 2011). A similar approach is being piloted in selected maize areas of eastern and southern African with support from the Australian Centre for International Agricultural Research (ACIAR).

Malawi grows ~1.6 Mha of maize under reasonably favourable mid-altitude conditions, largely in small farms of <1 ha (Section 5.4), and maize provides 60% of food calories there. In the 2005–06 growing season, and despite opposition from donors, the **Malawi Government introduced input subsidies for maize**, comprising a coupon scheme that provided, at essentially no cost, two bags of fertiliser (100 kg total) and a package of maize seed (sufficient for 0.4 ha) to more than one-half of their maize farmers (Denning et al. 2009). At its peak (2008) this program provided ~200,000 t of fertiliser per year, although this volume now appears to be decreasing under cost pressures.

Over the 6-year program, national maize FY reached 1.85 t/ha, equivalent to an increase of ~50% from 1.25 t/ha averaged over the preceding 5 years (FAOSTAT 2013). Much of this increase was probably due to the subsidy scheme, which yielded a modestly positive benefit:cost ratio, but also brought other social benefits that were more difficult to quantify (Dorward et al. 2011). This positive result is not surprising, because in 2005–07, The Millennium Villages Project—an externally-funded integrated rural development project operating in 14 sites across 10 Sub-Saharan countries—targeted 11,000 farms at one site in Malawi with hybrid seed, fertiliser and higher seeding density (53,000/ha), and achieved an average FY of 4.4 t/ha (Denning et al. 2009).

Debates rage about whether schemes such as this provide efficient use of government funds (Smale et al. 2013); for example, to what extent is the purchasing of fertiliser displaced by the free product, does government subsidy led to serious crowding-out of the private sector and to what extent do the poorest farmers benefit? Notwithstanding this debate, there seems little doubt that when the yield gap is large, farmers of smallholdings will adopt inputs if the price ratio is attractive.

The **One Acre Fund** is a NGO that targets African subsistence maize farmers.⁴⁵ This NGO's market-based approach was conceived in a US business management school and commenced in 2006 in western Kenya with 20 ha of maize grown by 125 farm families. By 2012, the One Acre Fund had steadily grown to reach ~135,000 participating families from within Kenya, and in the adjacent countries of Burundi and Rwanda. The model is to offer:

- access to (and credit for) improved seeds and fertiliser inputs
- assistance with product marketing (which has been a critical feature of the model as farmers graduate from subsistence to commercial operations)
- optional crop insurance
- scientifically sound technical advice.

Maize yields have on average more than doubled (compared with non-participating farmers), farm income has increased by 100% and debt repayment is now more than 95%. Most of the farmers are women, farmer organisations are fostered, and local people are hired to operate the project. More than 80% of field operating costs are now covered by the farmers. Donations are used to fund One Acre Fund expansion, which continues apace for this simple scalable model, now moving beyond maize to include other important local food crops.

Transgenic cotton in India and Australia

Although not provided here as a food crop example, an interesting case study is offered by GE-hybrid cotton incorporating the trait for insect resistance derived from *Bacillus thuringiensis* (*Bt*). In **India**, a total of 12 Mha—produced by a population of ~7 million smallholder farmers—breaks many records (James 2011) with *Bt* cotton rising from almost zero to >88% adoption in 10 years from 2002, easily exceeding the rate of adoption of the same technology (GE but not hybrid) by much larger cotton-farmers in **Australia** a few years earlier (Figure 8.1).

In this same period cotton yield in India has increased by around 100%, a large proportion of which is due to *Bt*, and production has also doubled. Progress has been driven by private seed companies, but smallholder farmers soon recognised the large economic benefits from lower insecticide use and higher yields. There has been some unfortunate confusion in the seed market as a result of this boom—with many unscrupulous seed suppliers (Stone 2010)—and the ongoing challenge for genuine suppliers will be to counter the confusion and prevent breakdown of the insect-resistance trait. There is no evidence, however, that the suicide rate among farmers has been affected by the advent of *Bt* cotton (Gilbert 2013).

45 Information gathered from T. Kalm, pers. comm. 2012 and data available at <www.oneacrefund.org>.

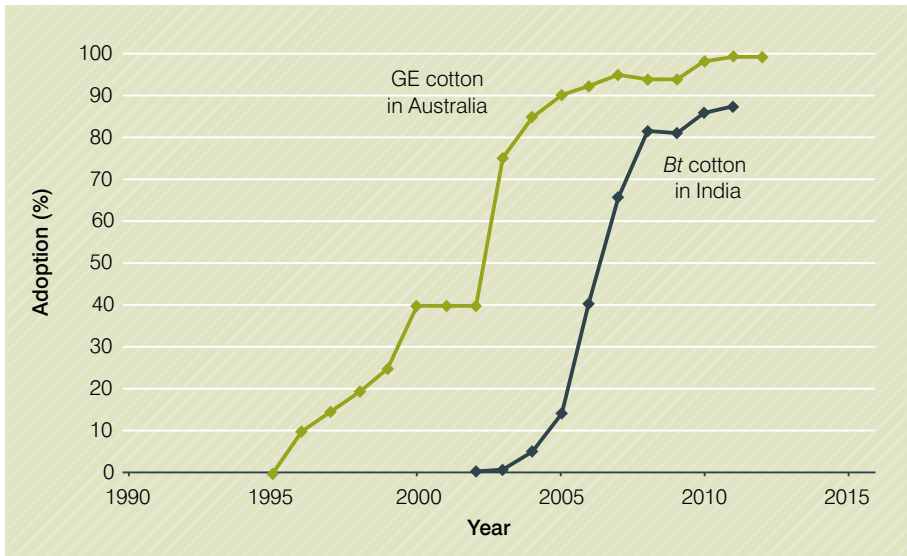


Figure 8.1 Adoption of genetically engineered (GE) *Bacillus thuringiensis* (Bt) cotton in India, and of GE cotton (mostly Bt) in Australia (as a percentage of total crop area). Source: James (2011) for India; G. Constable, pers. comm. (2012) for Australia

Potatoes in the Andes

The ‘Papa Andina’ project—developed by the International Potato Center for Andean potato growers in Peru, Ecuador and Bolivia—claims to be a successful application of many features of the AIS approach (Horton et al. 2011). These very small, largely subsistence potato growers are characterised by cultural marginalisation in a generally difficult agricultural environment, and manage a unique diversity in traditional potato varieties and processing methods.

The 10-year project adopted a **participatory market chain approach** (PMCA) and has been successful in bringing novel, high-value potato products (usually based on indigenous varieties and uses) to major urban markets. Research and development—including clean seed, integrated pest and disease management, processing and sometimes new varieties—has of course been integral to the project. However, important roles have also been played by other aspects, including attention to building social capital among growers, mutual trust along the value chain, and product protection. In one study in Ecuador, increases of 33% in FY and 600% gross margin have been achieved (Cavatassi et al. 2011). PMCA has attracted much international attention for its relevance to smallholder farmers producing potentially high-value products.

Conservation agriculture in South America and Australia

Conservation agriculture (involving zero-till, crop residue retention and crop rotation) was mentioned in the context of cropping in Western Australia, western Canada and the Great Plains of the USA, but it is southern **South America (Argentina, Brazil and Paraguay)** that presents an outstanding case of rapid adoption of this complex and almost counterintuitive technology (see Section 5.5 on maize and Section 6.3 on soybean). In this region, adoption of conservation agriculture was initially led by small to medium-size farmers, and it constituted a veritable agronomic revolution.

The zero-till technique has been shown to markedly increase rainfall infiltration and reduce soil erosion (Hobbs et al. 2008). It has also been shown to improve soil structure by increasing soil carbon at rates of 0.12–0.59 t/ha/yr (Amado et al. 2006; Bergamaschi and Dalmago 2006), although this accumulation may be mainly confined to the upper 15 cm of soil and take time to detect. In South America, zero-till was very much driven by the threat of serious soil erosion, the opportunity provided by the advent of knockdown herbicides, and some knowledge spillover from early work in the UK and USA (Ekboir 2002).

Described by Ekboir and Parellada (2002) as ‘the most important technology introduced to Argentina in the past 50 years’, zero-till was developed through a collaborative initiative formalised in 1989 as the Argentine Association of No-Till Farmers—otherwise known as *La Asociación Argentina de Productores en Siembra Directa* (AAPRESID)—which brought together farmers, input suppliers, extension providers and researchers in a true private–public partnership. These were small to medium-size farmers who grew wheat, maize and soybean. Zero-till systems required the development of planters that could handle large volumes of crop residue, and this happened locally, giving a huge boost to machinery manufacturers. Parallel development of zero-till occurred in Brazil, commencing among the farmer cooperatives in the state of Paraná; the practice is also widespread in Paraguay. Again it was small to medium-size farmers who drove this revolution. Commercialisation of Roundup Ready® soybean has notably aided adoption of zero-till since the mid 1990s.

Adoption in Argentina was rapid (Figure 8.2) and ~22 Mha (or 70%) of total cropped area was operating under zero-till by 2009 (Roberts and Johnston 2009). In economic terms, the annual value of conservation agriculture for maize and soybean cropping in Argentina in 2009 was estimated to be US\$12 bn (~\$330/ha) through cost savings and yield improvement (Trigo et al. 2009b). By the 2003–04 cropping season, 22 Mha of land in Brazil was also cropped under zero-till with full retention of crop residue, and this had increased to 26 Mha by 2009 (Roberts and Johnston 2009; Derpsch et al. 2010). Friedrich et al. (2011) estimate that in around 2010 in Argentina, Brazil and Paraguay some 58% (56 Mha) of all cropland was under conservation agriculture.

In other continents, where smallholder farmers also dominate, this revolution has yet to have much impact, but there are developments in South Asia, China and parts of

Sub-Saharan Africa. For example, in the rice–wheat belt of the north-western Indo-Gangetic Plain, Friedrich et al. (2011) reported yield advantages, and water and fuel savings, from an estimated 5 Mha of wheat now planted by zero-till—although, since the rice phase of this rice–wheat system continues to be tilled, this cannot be considered as true conservation agriculture.

Appropriate machinery has been an obstacle where smallholder farmers predominate, and everywhere there has been a strong clash between zero-till and deeply held traditions of plowing. The same clash occurs now in another frontier for conservation agriculture—the large wheat farms of northern Kazakhstan and adjacent Siberia—where wheat is grown under similar conditions to western Canada. In Kazakhstan in particular, conservation agriculture appears to be winning.

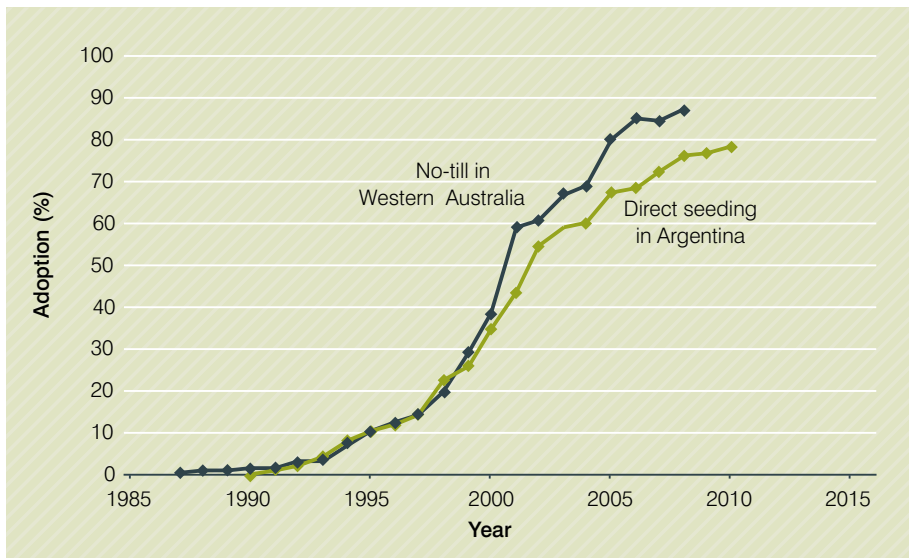


Figure 8.2 Adoption of zero-till in Western Australia (as per cent of farmers adopting) and direct seeding in Argentina (as percentage of crop area). Source: Llewellyn and D’Emden (2009) for Australia; Aapresid (2012) for Argentina

Erosion is less of an issue in Western Australia (WA) than South America, but saving costs, timeliness of sowing and soil water conservation are critical, and were early recognised benefits of zero-till (see Section 3.5 on wheat). Farmers on WA’s large farms adopted zero-till as rapidly as did smaller farmers in Argentina (Figure 8.2), noting that the 88% of adopters in 2008 planted 85% of WA cropland with zero-till (Llewellyn et al. 2012). These authors thoroughly studied the zero-till adoption process across the whole Australian Wheat Belt and reported positive impacts arising from improved farmer education, the influence of farm consultants and farmer zero-till organisations, and (importantly) low glyphosate prices. Adoption in the eastern states followed a

similar pattern to that in WA but levelled out at somewhat lower proportions, partly due to the retention of some tillage for weed control. Zero-till in Australia was estimated by Friedrich et al. (2011) to have reached 17 Mha, or 69% of total cropland.

Conservation agriculture is not immediately suited to all situations, especially locations where ruminant grazing competes as an end-use for crop residue (e.g. in Sub-Saharan Africa; Giller et al. 2009), where the crop residue keeps the soil too cool for early spring planting of crops (e.g. in the US Corn Belt) or where residue amounts are large (e.g. after winter wheat in western Europe). Often driven by farmer initiatives, however, R&D has been instrumental in the adaptation of conservation agriculture to an expanded range of environments. Patience is needed as the greatest crop benefits of conservation agriculture are not immediately evident—yield penalty can be an initial effect of a switch to conservation agriculture. This penalty may take 5 or so years to be offset through improved soil biophysical properties, and through learning how better to manage the technique in the local context (P.C. Wall, pers. comm. 2009).

8.6 Conclusion on yield gap closing

While yield gap estimations depend to some extent on the methods used to determine them, it is clear—especially in rice and maize—that more than two-thirds of estimated yield gaps are >40%, and quite a few are >100% of FY (Table 8.1). Evidence discussed in this book has shown a tendency for larger gaps to exist in rainfed situations in developing countries. Further evidence suggests that where gaps exceed 40%, the gap should be considered as readily exploitable with gap-closing interventions.

At first glance, we might think that yield gap closing should be an easier task than raising PY, given that the necessary technologies are already known, even if further research could strengthen their attractiveness and effectiveness. Moreover—where socioeconomic conditions were generally more favourable in terms of resources, infrastructure and enabling policies—smallholder farmers have already shown willingness to adopt new technologies, beginning with the green revolution in parts of Asia from the mid-1960s. Unfortunately, however, yield gaps in general appear to be quite persistent and have closed only slowly over the past 20 years, partly because favourable socioeconomic conditions do not exist in many places in the developing world. Moreover, causes of yield gaps are multiple and interrelated, and they vary with circumstances. Yield constraint alleviations are not substitutive; considered independently, no single step could provide sufficient conditions for yield gap closing.

The fundamental problem is that gap closing in developing countries—on the large scale that is needed to achieve world food security—requires massive investments in rural infrastructure and institutions, as well as in technology adaptation and transfer (see Sections 13.2 and 13.3 on investment). In contrast to PY progress through new agronomic knowledge and improved varieties, there are fewer 'short cuts' available

for gap closing (e.g. low-cost, imported technological advances), meaning that it is impossible to avoid substantial local investment.

Unfortunately, these **investments are not forthcoming**, as maize in Sub-Saharan Africa exemplifies. But new approaches, such as are envisaged by agricultural innovation systems and by the use of modern communication technologies, are now playing an increasingly important role. Also there is growing recognition of potential contributions of other players besides the traditional public sector extension agencies. These include breeding companies, other agribusinesses, NGOs and even farming corporations; obviously the private sector targets commercial smallholder farmers, while NGOs pay more attention to subsistence farmers. However, these new agents are no substitute for public investment in proper rural institutions and infrastructure—rather they are a significant complement, and an essential one in the case of agribusiness.

In summary, given a generally slow rate of yield gap closing averaging -0.5% of FY p.a. for the four staple grains and the finding that some yield gaps, commonly in developed countries, are already $<40\%$ and unlikely to close much further—it remains critically important that FY should continue to lifted, not only by yield gap closing, but also through continuing improved PY. This is the subject of Chapter 9 'Increasing potential yield'.

Increasing potential yield

9



Key points

- Current average rates of progress in potential yield (PY)—and its water-limited equivalent (PY_w)—generally lie between 0.6% per annum (p.a.) and 1.1% p.a., with a few minor crops higher. PY is continuing to increase in all crops. PY progress arises from breeding and new agronomy, but examples of the latter are becoming scarce.
- PY is a reflection of the amount (and efficiency of use in dry matter production) of captured solar radiation, and crop harvest index. Scope appears to exist for further PY increases, especially through increased photosynthetic efficiency.
- PY_w also reflects harvest index, but depends on water capture for transpiration (and its efficiency of use). Scope remains to raise PY_w by each of these routes.
- Record and contest-winning yields are not much of a guide to the future but do deserve greater independent, on-location scientific oversight and analysis.
- New agronomy for PY increase is hard to discern, but there are some possibilities in the areas of soil microbiology, soil structure management, soil evaporation reduction and seasonal climate forecasting.
- F_1 hybrid varieties are likely to expand to dominate rice, and will probably spread to wheat (and possibly other crops currently without hybrids). Hybrids can offer a one-off jump in yield of 10–20%.
- Genetic engineering (GE) will continue to bring small indirect benefits to PY, but direct PY increases through GE seem implausible in the medium term.
- More targeted exploitation of crop genetic resources and new breeding tools—especially use of molecular markers (such as genomic selection)—should help maintain, or possibly accelerate, rates of breeding progress.
- As a result of the expanding systems of plant variety rights, privatisation of crop breeding has increased investment into breeding and agronomy (and increased economies of scale), but risks of inefficiencies will need to be managed.
- Public investment in research and development continues to play a vital role, especially in general pre-breeding and agronomy, and in breeding orphan crops.

Increasing potential yield

9.1 Introduction

Earlier sections of this book demonstrate how breeding in the past 20–30 years has substantially increased potential yield (PY; see Chapter 2 on definitions) and water-limited potential yield (PY_w). This progress can come with the aid of direct or interactive effects associated with innovations in agronomy, but the former have been scarce over this period and the latter fairly limited. Although rates of progress may have slowed since the early green revolution years (see Chapter 1 'Introduction'), in all cases studied throughout this book, summarised in Table 9.1, progress has continued into the first decade of the new millennium with **no evidence that PY progress has slowed or ceased** as might be expected if crops were approaching biological limits. Table 9.1 presents mean annual rates of progress for case studies of the major crops (expressed as a percentage of PY and/or PY_w in 2005–10), which were, in descending order:

- sugar beet = 2.0%
- cassava = 1.5%
- canola = 1.4%
- maize = 1.1%
- sunflower = 1.0%
- rice = 0.8%
- barley = 0.7%
- soybean = 0.7%
- wheat = 0.6%.

Clearly, hybrid crops are showing faster progress than self-pollinated ones, except for the high rate for self-pollinated cassava, which reflects the quick progress that can be made with an initially unimproved vegetatively propagated crop. The progress is largely due to breeding, because only in maize and sugar beet is there a notable contribution from agronomic change. Moreover, across crops for which there are data—including wheat, rice and maize—the rate of **progress measured relative to current yields for PY_w has been no less than that for PY** (Table 9.1).

Table 9.1 Summary of mean linear annual rates of progress (increase) in potential yield (PY) and water-limited potential yield (PY_w), measured over varieties released in the past 20–30 years

Crop ^a	PY		PY _w		Source
	Number of case studies	Average rate of progress (% ± s.e.m.) ^b	Number of case studies	Average rate of progress (% ± s.e.m.) ^b	
Wheat	7	0.66 ± 0.10	5	0.54 ± 0.11	Table 3.6
Rice	10	0.79 ± 0.10	1	0.70	Table 4.5
Maize	6	1.08 ± 0.14	7 ^c	1.13 ± 0.15	Table 5.7 and Section 5.2 ^c
Soybean	4	0.65 ± 0.19	na	na	Table 6.2 and Section 6.5
Barley	4	0.73 ± 0.07	na	na	Section 7.2
Canola	3	1.37 ± 0.03	1	1.40	Section 7.4
Sunflower	na	na	4	0.95 ± 0.21	Section 7.5
Sugar beet	2	2.00 ± 0.40	na	na	Section 7.6
Cassava	na	na	3	1.47 ± 0.38	Section 7.7

- a Three pulses (bean 0.4%, peas 1.4% and lupins 1.4%, Section 7.3) are not listed because they represent single cases.
- b Expressed as a percentage of the estimated yield of the most recently released varieties included in the series (i.e. varieties from around 2005–10 depending on case study)
- c These seven cases came from the ERA hybrids under several managed drought environments in Chile (Campos et al. 2004) and California (Duvick 2005a)
- na = not available; s.e.m. = standard error of the mean across case studies averaged

In most situations, as new varieties and agronomic technologies have been adopted, PY (and PY_w) progress have in turn driven increases in farm yield (FY; see Chapter 2). The process by which PY lifts FY will undoubtedly continue, and where the yield gap has become small—for example, in wheat in the United Kingdom (UK; see Section 3.8) or soybean in the United States of America (USA; see Section 6.2)—future increases in FY will depend almost directly on further advances in PY. Indeed, in order to secure future food supplies, it is essential that current low rates of PY progress in wheat, soybean and rice be accelerated. This is especially the case for wheat, which has shown the lowest rate of progress despite strong growth in demand as a food crop.

Table 9.1 presents progress in breeding but also includes any positive variety-by-agronomy interactions, as was pointed out in Box 2.1. Some of the discussion covered by earlier sections of this book suggests that future PY progress will depend more on breeding than on new developments in crop agronomy. Thus this chapter begins by discussing the prospects for further breeding progress in PY and PY_w. Although it is difficult to discern totally new yield-positive agronomic innovations, Section 9.7 deals with some possibilities in this area. The discussion then returns to the likely impacts of

new breeding opportunities, and new tools and institutional arrangements in plant breeding.

There is a sense that, once breeders have optimised flowering time for each crop and environment, and pushed harvest index (HI) to its limit, genetic variation for yield must, at some time, become exhausted as the positive variation in the processes for yield formation reach fundamental biological limits—such as, for example, photosynthetic light use efficiency. This question of a limit to PY is physiologically grounded. Also, further physiological knowledge will improve trait-based breeding and agronomic efforts to achieve higher PY. This knowledge will indeed guide genetic engineering (GE) at the molecular level for this same purpose. Therefore, it is largely from a crop physiological point of view that the prospects and avenues for increased PY and PY_w are considered, using concepts outlined in more detail in Section 2.6 on physiological determinants of yield.

The crop physiologist T. R. Sinclair appropriately titled a 2010 presentation on the subject as ‘The sky’s the limit’, because the ultimate limits are of course solar radiation (for PY) and/or rainfall (for PY_w) (Sinclair 2010). Thus, the discussion on yield limits boils down to asking how efficiently crops can capture and use these limiting resources to accumulate dry matter (DM) and distribute it to the developing floral structures and ultimately to grain or other yield organs.

9.2 Physiological components of progress in potential yield

Crop physiologists have developed a useful analytical framework for exploring the progress of PY—as described in earlier chapters—and the components of PY under radiation-limited conditions. Consider equation (5), which is briefly discussed below but is fully described in Section 2.6:

equation (5) (recap) Potential yield (PY) as a function of radiation capture, dry matter (DM) accumulation and distribution

$$PY = \sum PAR_i \times RUE \times HI \quad (5)$$

where

PY is the potential yield in g/m^2

$\sum PAR_i$ is the sum in daily time steps over the crop cycle, of photosynthetically active radiation (PAR) intercepted by green tissue, measured in units of megajoules (MJ/m^2)

RUE is the radiation use efficiency measured in units of grams DM per megajoule (g/MJ) of PAR_i

HI is harvest index, the ratio of dry grain yield to total DM at physiological maturity.

Agronomic progress in PY has largely been derived from better crop nutrition, especially increased rates of nitrogen fertiliser. Improved crop nutrition has enabled crops to more rapidly reach a large enough leaf area index (LAI) for full light interception (see Section 2.6) and/or attain a greater LAI of longer duration—the outcome of which, in terms of equation (5), is an increased sum of intercepted photosynthetically active radiation (ΣPAR_i). Moreover, better nitrogen nutrition has led to modest increases in radiation use efficiency (RUE) (Sinclair and Muchow 1999), through increases in leaf maximum photosynthesis (P_{max}), the main determinant of RUE. Small gains in PY have also been achieved by altering planting date to better time the crop relative to expected seasonal solar radiation patterns (e.g. earlier spring planting at higher northern latitudes to more fully capture peak June radiation).

As discussed in previous chapters, **breeding progress in PY** in wheat, rice and tropical maize is mostly attributable to increases in HI. Increased HI arises in part from shorter stature, and in part from stronger reproductive sinks (the yield organs, normally the growing grains.) Soybean studies tend to show breeding progress in both DM and HI, but natural leaf fall towards maturity complicates HI determination with soybean (and pulses in general).

Temperate maize adapted to the US Corn Belt is also an exception: HI has increased only slightly with PY progress, but DM has increased notably. To relate back to equation (5), greater plant densities tolerated by modern hybrids have enabled ΣPAR_i to increase, especially before silking (Duvick 2005b). More persistent green leaves at the end of grain-filling (termed 'staygreen') have also helped increase ΣPAR_i .

Under good conditions, modern varieties of rice, winter wheat and temperate maize will return typical HI values of 0.50–0.55. A thorough analysis of the lodging process in winter wheat from the physical perspective (Berry et al. 2007) concluded that there appears to be little scope for further increase in HI beyond 0.55–0.60 in crops that bear above-ground grain because such crops depend on a stable structure to distribute leaf area, support grain and prevent lodging. Yet spring wheat, and many tropical maize varieties, still shows HI figures of only 0.40–0.45 (Duvick et al. 2004), leaving scope for perhaps a 20% increase in HI (and hence increase in PY)—an increase which should be attainable by breeders. However, in the case of soybean, it is difficult to know how closely HI limits have been approached; reported HI values are often overestimated because the weight of leaves that fall is lost as maturity is approached (cereal leaves lose weight as content is translocated to growing grains but with care are not lost in maturity sampling—see Figure 2.3).

Generally speaking—noting the clear exception for temperate maize—past breeding efforts have achieved relatively little to increase the production of DM at maturity. But as HI approaches likely upper limits, future PY progress must increasingly depend on improvements in DM. Some evidence suggests that this is already happening in wheat (see Section 3.2 on the Yaqui Valley and Section 3.8 on the UK and Europe) and rice (Section 4.2 on the Philippines and South-East Asia and Section 4.5 on Japan). Increased DM could come from greater ΣPAR_i , and/or through increases in RUE. Both approaches are discussed in the next two subsections.

Before leaving the general physiology of PY progress, it is useful to consider equation (6) (described in detail in Section 2.6):

equation (6) (recap) Potential yield (PY) as a function of numerical components

$$\mathbf{PY = GN \times GW} \quad \mathbf{(6)}$$

where

PY is the potential yield in g/m²

grain number (GN) is the number of grains/m² of land area

grain weight (GW) is the weight of individual grains in grams (g), but which is normally presented in milligrams (mg)

Previous sections in this book have shown that recent PY progress—whether through agronomic management or breeding—has been much more strongly related to increase in GN than to improvements in GW. In general, changes in GW have been relatively small and sometimes negative with PY progress (e.g. Bolaños and Edmeades 1996; Fischer 2007). There are, however, a few interesting exceptions; for example, higher yield in recent spring wheats in Mexico was related to greater GW (Section 3.2), and higher yield across sorghum varieties was associated with longer duration of grain-filling and greater GW (Yang et al. 2010).

In Section 2.6 it was pointed out that GN is largely determined by events leading up to and following shortly after flowering, related to:

- crop growth rate in this period
- partitioning of photosynthetic DM to growing inflorescences
- number of fertile florets per unit inflorescence DM.

To bring about the observed increase in GN, results reveal that all three traits have increased with modern varieties in one or several instances (e.g. Abbate et al. 1998; Andrade et al. 2000; Edmeades et al. 2000; Shearman et al. 2005; Takai et al. 2006). However, it remains unclear whether any change has occurred to the duration of the critical period for GN determination. This period occupies only the last portion of reproductive period defined earlier (see Table 2.1), and as such has been poorly defined and little studied.

It is also notable that wheat and rice varieties with the highest PY appear to accumulate (and later translocate) larger amounts of stem-stored pre-flowering carbohydrate to the grain (Shearman et al. 2005; Katsura et al. 2007). This stored carbohydrate (which can amount to several tonnes of DM per hectare) presumably is needed to supplement photosynthesis during grain growth and ensure proper filling of the extra grains of modern varieties. However, the extra carbohydrate from storage is less than that required to fully fill the extra grains, so that the source–sink ratio (ratio of carbohydrate supply to carbohydrate demand of growing grains, see Section 2.6) during grain-filling

is lower in modern than older varieties. Despite this, there is evidence that even modern varieties—at least in the case of wheat and soybean, although perhaps not maize (Borrás et al. 2004)—are not entirely source-limited during the grain-filling period, for spare photosynthetic capacity appears to exist, as do unused stored carbohydrates.

The next section will explore future PY increase in terms of the components of equations (5) and (6). The discussion draws on more detailed recent reviews by Foulkes et al. (2009) for grain crops in general, and by R.A. Fischer (2011) and Foulkes et al. (2011) for wheat in particular. These authors clearly take an approach driven by carbon capture, which does not accord with T.R. Sinclair who has consistently urged attention to nitrogen capture, storage and remobilisation as the primary traits limiting PY (e.g. Sinclair and Rufty 2012). However, there is little doubt that nitrogen supply and uptake must and can increase as PY increases, and this is discussed in greater detail in Section 11.3 'Nutrient use efficiency'.

9.3 Increasing the sum of intercepted photosynthetically active radiation

Radiation capture, or the sum of intercepted photosynthetically active radiation ($\sum \text{PAR}_i$), is the accumulation of PAR intercepted by the green tissues over the life of the crop. It can be increased by:

- more rapid approach of the young crop to a sufficient LAI (typically LAI = 4 or more) at which the fraction of PAR intercepted by the leaves (F_{PAR}) reaches ~ 0.9 or 'full light' interception (as described in Section 2.6)
- longer crop growth duration (emergence to physiological maturity)
- extended staygreen at the end of grain-filling when green area would normally rapidly senesce (again increasing F_{PAR}).

Once full light interception is reached, any additional green leaves will only minimally increase F_{PAR} , $\sum \text{PAR}_i$ and crop growth rate (DM production per day). Under potential conditions, all crops should reach full light interception before the onset of the critical period leading up to flowering (see Section 2.6; also below for maize in temperate regions). Through tactics such as better nitrogen nutrition and higher planting density, agronomy can ensure that the crop reaches full light interception quickly enough, and can aid staygreen. Genotype also has influence, but genetic components linked to early light interception (e.g. early vigour) and to staygreen appear to have been already optimised in most recent crop varieties.

The importance of **overall crop growth duration for PY** is less clear, but is also under strong genetic control as discussed earlier (Section 2.6). Increased overall crop growth duration is sometimes evoked as an easy way to higher PY through increased

Σ PAR. However, for rice, sorghum, soybean, maize and some minor crops, Egli (2011) points out that (in general) grain yield is more closely related to the duration of the post-vegetative periods—the reproductive plus grain-filling periods, commencing with initiation of the first flower buds in all crops—and not to that of the preceding vegetative period or to total crop growth duration. Durations of the reproductive and/or grain-filling periods do not necessarily increase as crop growth duration increases beyond ~100–120 days at normal growing temperatures ($T_{\text{mean}} > 10\text{ }^{\circ}\text{C}$; see Section 2.6); DM production may increase beyond this point but HI tends to decrease. This is illustrated in rice in a reverse sense—since the 1966 release of the first semi-dwarf high HI variety, IR8, breeders at the International Rice Research Institute (IRRI) in the Philippines maintained high PY while reducing crop growth duration by up to 15% (Peng et al. 1999) through shortening of the vegetative period.

For wheat—which was not included in the Egli (2011) review—earlier sowing and longer total crop growth duration is advantageous in some winter wheat situations. However, this appears to be related to larger seedlings and better winter survival (Fowler 1982) rather than extra crop growth duration per se. In irrigated spring wheat in Mexico, earlier planting of slower developing varieties enables an extended vegetative period, which can increase tillering and DM up to flowering, but will not increase final DM, HI or PY. Fischer (2007) argues that this is because PY is controlled primarily by DM production during the abovementioned short period (before and around flowering), which determines GN; thus PY obtains little direct benefit from a longer, largely vegetative period leading up to this critical period. In other words, a relatively short vegetative period under good management is enough to achieve full light interception, thereby maximising crop growth rate before the onset of the critical period.

Slafer et al. (2009) presented evidence for yield benefits through greater GN by artificially increasing **the duration of the critical period for GN determination** in wheat and soybean. This was demonstrated by manipulating photoperiod during the critical period. Furthermore these authors suggested increasing the critical period at the expense of the vegetative period, so that overall duration remains little changed. Although the exact critical period for GN determination remains poorly defined, and the proposed genetic variation has not been found, extended duration of the critical period nevertheless remains a promising proposition.

Data from some maize studies, from temperate locations, appear to contradict the above notion of relative independence between overall crop growth duration and PY. These data point to **more yield with longer duration hybrids** (other things equal), for example, in the south-eastern pampas of Argentina (Capristo et al. 2007) and in the Mid West of the USA (Kucharik 2008); maize simulation models mimic this effect (e.g. Yang et al. 2004). In the maize experiments reported by Yang et al. (2004) and Capristo et al. (2007), duration of the pre-silking period (emergence to silking; see Table 2.1) is found to be positively associated across hybrids with duration of the period of silking to physiological maturity. In other words, as overall duration increases, key periods for both GN and grain-filling appear to extend, thereby tending to maintain the source and sink in balance during grain-filling (F. Andrade, pers. comm. 2012). In the

Capristo et al. (2007) study, DM, HI and GN all increased with increased overall crop growth duration, and, remarkably, yield increased at a greater relative rate than that of overall crop growth duration.

It is not clear whether these temperate maize results can be reconciled with the general notion, promoted above, that emphasises the shorter critical period around flowering, and more independence of the development periods in general. The results may still be a reflection with maize, compared with other crops, of the low planting density—for example, Capristo et al. (2007) used 8 plants/m²—and its lack of branching such that a longer vegetative period is needed to reach full light interception before the onset of any critical period for GN determination. Most maize breeders would agree that this result suggests scope to further exploit positive density-by-hybrid interactions in maize, while at the same time, longer duration hybrids would appear to offer a route to higher PY, if only because the post-silking period can also be increased.

In reality, even if extra crop growth duration permitted possible further gains in PY, **constraints in the season length and/or cropping system** in many situations limit opportunities to extend crop growth duration. Sometimes the more advantageous approach to improving overall productivity in this context, especially in warmer locations, may instead be further shortening of crop growth duration while holding PY constant—an approach that would possibly permit greater cropping intensity and hence more yield per day.

Crop growth duration is further considered in Section 10.4 in conjunction with discussion about climate change and adaptation to chronic warming. However, it can be concluded here that (except for maize) increased $\sum PAR_i$ does not present a very likely route for further raising PY. However, at least in wheat (and possibly rice), if the critical development period for GN determination can be increased independently of other developmental periods—thus increasing $\sum PAR_i$ during this period—GN and PY could be lifted; if the vegetative period was correspondingly decreased without impairing the attainment of full light interception, PY could increase without change in overall crop growth duration.

9.4 Increasing radiation use efficiency

Equation (5) implies that increased rate of DM production by increased RUE is translated into increased PY, provided that HI behaves as an independent trait (which is generally the case). The positive response of grain yield to DM increase with CO₂ fertilisation (at least in C₃ crops; see Sections 2.4 and 2.6) is taken as strong evidence for the limiting role of rate of DM production (Long et al. 2006). Further evidence is the common grain yield response to greater DM production through higher daily solar radiation (other things equal). So the challenge of raising RUE and its constituent components attracts many plant scientists. To quote Duvick (2005a), 'Finally ... maize

breeders can always hope for the Holy Grail of plant physiologists, major [increases in RUE], effected without disrupting the rest of the infinitely complicated network of interacting genetic systems ...’.

It has frequently been observed that modern varieties maintain RUE at higher levels during grain-filling compared with older varieties, and this is largely explained as the effect of a greater GN (sink strength), perhaps in some cases (e.g. maize) helped by better maintenance of leaf chlorophyll (staygreen) late in grain-filling. The preceding commodity chapters have also provided evidence that modern varieties have increased RUE before grain-filling—for example, wheat in Australia (Section 3.5) and the UK (Section 3.8), rice in Japan (Section 4.5) and maize in Canada (Section 5.2) and Argentina (Section 5.5). One recent evaluation of RUE in modern maize hybrids in Nebraska, USA, determined a value of 3.8 g DM/MJ over the full crop cycle (Lindquist et al. 2005), a figure that approaches the upper limit of the range for maize cited in Section 2.6 (2.3–4.1 g DM/MJ) and suggests that RUE may have already increased with breeding selection. Similarly, Sinclair (2010) suggests RUE in rice, reaching 2.8 g DM/MJ in modern varieties could now be closer to that previously mentioned in Section 2.6 for wheat. Even higher RUE values have been recorded under low radiation conditions—up to 3.9 g DM/MJ for rice (Katsura et al. 2007) and 5.4 g DM/MJ for maize (Tollenaar and Migus 1984). However, such results are probably from the expected effects of frequent cloudiness (i.e. higher proportion of diffuse radiation favouring higher RUE; see Section 2.6) rather than unique genetic effects.

CO₂ losses through dark respiration loom large in the carbon budget of crops and hence as a factor determining RUE (see Section 2.6). However, the growth respiration component seems invariant for a given composition of DM, although from time to time there is discussion of **improving the efficiency of maintenance respiration**. There was even some success with direct selection for low respiration leading to greater DM production in ryegrass (Wilson and Jones 1982). But reviewing this subject, Loomis and Amthor (1999) concluded that crop respiration is already very efficient, with only modest prospects for improvement through targeted selection for low respiration rates. No evidence has emerged to challenge this view.

Almost 45 years ago crop physiologists predicted that RUE should be improved with **more erect leaves** (e.g. Loomis and Williams 1969, see Section 2.6). Since canopy architecture is quite heritable, it is not surprising that the canopies of most modern varieties seem to fit the theoretical optimum and are very erect. It is, however, difficult to prove this point and more studies are needed for modern varieties of broadleaf crops (such as soybean, sunflower and sugar beet), as uppermost leaves tend to be less vertical. Young oil palm fronds are also erect, and the narrow leaves in general diffuse light into the canopy, which is desirable for maximum RUE. With the possible exception of some dicot crops, it is concluded here that little scope remains to improve RUE through alteration of canopy structure.

Given limited room to improve canopy structure, future increases in RUE from breeding efforts are most likely to occur through increases in the other major trait linked to

RUE, maximum photosynthetic rate per unit leaf area (P_{\max}) (Section 2.6). Excluding general reports of greater P_{\max} during grain-filling in modern varieties—which again may be explained as the indirect effect of greater sink strength—there is also recent evidence of **greater P_{\max}** in uppermost leaves in the critical period around flowering in modern crop varieties. This recent evidence has been reported for spring wheat in Mexico (Section 3.2) and winter wheat in China (Section 3.7), temperate rice in China (Section 4.3) and Japan (Section 4.5), and soybean in the North America (Section 6.2) and China (Section 6.4). Some of these reported cases of greater P_{\max} , at least in wheat and rice, are associated with **greater leaf nitrogen concentration**. Results for maize mainly point to more sustained P_{\max} during grain-filling through improved staygreen, probably also related to higher leaf nitrogen (Section 5.2).

There is also evidence that RUE leading up to flowering is greater in modern varieties of both winter wheat (Shearman et al. 2005) and maize (Luque et al. 2006), but these studies did not report P_{\max} measurements. A recent study by Sadras et al. (2012) found RUE to have increased by ~30% across wheat varieties released between 1958 and 2008 in South Australia. These authors measured P_{\max} in only the uppermost (flag) leaves but found no variety effect, so the greater RUE was attributed to the measured increase in leaf nitrogen concentration deeper in the canopy (in modern varieties), suggested as leading to greater photosynthetic activity in that canopy region.

These positive results with RUE and P_{\max} are in contrast with older studies of vintage sets of crop varieties summarised by Evans (1993). Similarly, the results conflict with generally unsuccessful efforts to raise crop yield through selection for higher P_{\max} (Crosbie and Pearce 1982; Austin 1989; Evans 1993). However, lack of yield improvement in these older studies could have been related to **hidden trade-offs**—for example, between P_{\max} and leaf size—a concern also emphasised by Sinclair et al. (2004). The trade-off may, or may not, remain relevant today with higher rates of nitrogen fertilisation and different genetic backgrounds. Nevertheless, the possibility of trade-off emphasises the need for caution when considering focused selection on P_{\max} as an opportunity for yield improvement.

Reviewing the subject, Long et al. (2006) calculated a theoretical limit to RUE⁴⁶ of 5.8 g DM/MJ for C_3 crops and 6.9 g DM/MJ for C_4 crops operating at 25 °C. The result is essentially based on the slope of the leaf net photosynthesis (P_{net}) curve at low light (Figure 2.2)—the point of maximum efficiency of utilisation of PAR—although to arrive at the theoretical limits, the authors then discounted the efficiency for all likely respiratory losses. For comparison with RUE as commonly measured, the RUE limit must also be discounted for the DM translocated to roots, which averages ~10% over the crop cycle (but is much greater early in the cycle).

46 This RUE is calculated from Long et al. (2006), who derive a maximum possible fixation of 5.1% and 6.0% of total solar radiation energy intercepted for C_3 and C_4 species, respectively, for a canopy operating at 25 °C, assuming an energy content of 17.5 MJ/kg DM (carbohydrate). Allowance for the ash or mineral content of plants would increase RUE slightly, while synthesis of more energy-rich compounds (protein at 23 MJ/kg DM or lipids at 39 MJ/kg DM) would reduce it—notably in the case of lipids, as seen with soybean during seed filling.

In addition to seeking small gains through further optimisation of leaf inclination, Long et al. (2006) went on to propose many changes to the leaf photosynthetic machinery that would lift P_{\max} to bring observed photosynthetic efficiency closer to the above RUE limit. Other more substantial improvements could lift P_{\max} and the RUE limit for C_3 crops by $\sim 30\%$ if, for example, it were possible to eliminate photorespiration altogether, or by $\sim 18\%$ with a change to C_4 photosynthesis.

An ambitious project is underway at IRRI to use GE to move the C_4 pathway into rice, thereby simultaneously improving P_{\max} , nitrogen use efficiency, transpiration efficiency and ultimately PY (Hibbert et al. 2008). Moreover a comprehensive review by Parry et al. (2011) outlines a new global project headed by the International Maize and Wheat Improvement Center—otherwise known as *Centro Internacional de Mejoramiento de Maíz y Trigo* (CIMMYT)—which proposes to lift P_{\max} in wheat through both conventional and less ambitious GE strategies than complete conversion to C_4 , including:

- alteration of the principal CO_2 -fixing enzyme, Rubisco (see Section 2.6)
- faster regeneration of the substrate for Rubisco, ribulose-1,5 bisphosphate (RuBP)
- incorporation of biochemical mechanisms to increase the concentration of CO_2 around Rubisco.

Parry et al. (2011) claim that the GE traits for greater P_{\max} could be delivered in 5–20 years, depending on complexity. However, leading plant scientists Sinclair et al. (2004) and Hall and Richards (2013) envisaged greater obstacles and forecast a longer lead time. Furthermore, general experience with complex GE efforts suggests that engineering such traits as greater P_{\max} in wheat—not to mention C_4 traits for rice—will be very difficult to achieve, and that the milestones suggested by Parry et al. (2011) are probably overly ambitious.

Thus it is concluded here that it would be unwise to depend on increased rates of PY progress through engineered increases in P_{\max} over the next 20 years. But conventional techniques working on existing variation may deliver some gains within perhaps 10 years (rather than 5 years as suggested by Parry et al. 2011). For example, considerable P_{\max} variation is known to exist in wheat; not only that reported above, but also especially high rates in the diploid ancestors (Evans and Dunstone 1970). The CIMMYT Wheat Yield Consortium is beginning to look at P_{\max} variation within wheat and related species (Reynolds et al. 2012). Elsewhere genetic variation in P_{\max} in rice is being dissected into genes from key controlling chromosome regions, known as quantitative trait loci (QTLs)—large-effect chromosomal regions possibly linked to major genes—which if favourably recombined, could lift P_{\max} by at least 10% (Gu et al. 2012).

Finally, a poorly understood area of photosynthesis physiology is the suggested **feedback inhibition of photosynthetic rate by lack of sink capacity** during grain-filling in cereals, often invoked as the cause of reduced RUE at that time; even modern wheat varieties appear to have excess photosynthetic capacity during grain-filling (Reynolds et al. 2005). It was generally thought that lack of sink capacity could not limit photosynthesis before flowering, but results in which sugarcane was genetically

engineered to produce an alternative disaccharide (isomaltulose), in addition to sucrose, in stem storage tissues challenged this view (Wu and Birch 2007). Some lines when grown in the glasshouse produced the normal sucrose concentration in mature cane (i.e. ~15–16% of fresh weight) plus another 10–12% of fresh weight as isomaltulose. The almost doubled stem sink capacity (in terms of sugar storage) was associated with increased leaf P_{\max} and leaf longevity. Unfortunately when later field grown (Basnayake et al. 2012), the transgenic lines again demonstrated isomaltulose production, but with no extra total sugar concentration.

Increases in atmospheric CO₂ levels are likely to continue to lift PY, PY_w and FY in all C₃ crops, but are unlikely to improve yield outcomes very much in C₄ crops (see Section 10.3 on direct measurements and crop modelling). Some field studies have been conducted with C₃ crop varieties to see whether interactions in the response of crop growth and yield to CO₂ level have unintentionally arisen in the course of yield selection. For example, the grain yield of a crop of a Canadian spring wheat variety released in 1903 was compared with a modern 1996 release (Ziska 2008). The 1903 release responded much more to a 250 ppm CO₂ increase above the ambient baseline, such that yields of the two varieties did not differ under elevated CO₂. Compared with the 1996 release, the 1903 release showed greater increases in tillering, total DM (+50% vs. +20% in the 1996 release) and grain yield (+66% vs. +20% in the 1996 release).

Varietal differences in response to elevated CO₂ have also been reported for field experiments with rice (Moya et al. 1998) and soybean (Ziska and Bunce 2000). The variety-by-CO₂ interaction for yield in each crop was matched by an even bigger interaction in total DM production, but RUE may not be the basis of yield response, at least in soybean for which leaf photosynthesis did not respond differentially to CO₂. The wheat interactions seen in Ziska (2008) are hardly adaptive since the newer variety was selected under higher CO₂, yet the variety lost its yield advantage under even higher CO₂. These results suggest that there are genotypic differences that could be exploited by breeders as CO₂ continues to increase, even if they have not been unintentionally exploited already (see also Section 10.4 on scope for adaptation to climate change).

Apart from improved crop nutrition and water supply, **other agronomic changes lifting RUE** cannot be totally ignored. Unusually high RUE values have been occasionally reported with special management. For example, Tollenaar and Migus (1984) grew a hydroponic maize crop in a controlled growth room at a constant PAR of 5.4 MJ/m²/d. They obtained an RUE of 7.4 g DM/MJ—a slightly greater result than the previously mentioned absolute limit for C₄ crops of 6.9 g DM/MJ as calculated by Long et al. (2006). The experiment was repeated in the field in Ontario, Canada, in the same artificial growing medium and with hydroponic nutrition. Crop growth rates before grain-filling were 80% above those of well-fertilised soil-grown maize, and RUE reached 4 g DM/MJ. Crop nutrition and water supply differences did not appear to explain the boost in growth, which the authors conclude was at least partially due to the root growth medium that offered little mechanical resistance to root growth (note that roots were not included in the calculation for growth or RUE). Similar results were reported for rice grown hydroponically outdoors (in the same medium, under high nitrogen)

in the dry season at IRRI, with a peak crop growth rate of more than 40 g/m²/d before flowering—amounting to an RUE greater than 3.5 g DM/MJ—but growth rate at flowering fell dramatically because of high dark respiration losses (Akita 1989).

Waterlogging is another poorly understood agronomic issue affecting RUE, and is especially important in sensitive crops like maize. Raised beds reduce waterlogging during irrigation events, as does field drainage, and in doing so may benefit photosynthetic performance. Aerobic culture of rice (sprinkler irrigation) lifted RUE by 8% (up to ~2.8 g DM/MJ) compared with flooded rice (Katsura et al. 2010), and was associated with greater nitrogen uptake. All these observations deserve further investigation.

9.5 Modelled predictions of potential yield and understanding record and contest yields

The value of modelling for PY predictions, and record and contest-winning yields are considered in this section.

Potential yield predictions with simple and more complex models

Notwithstanding the uncertainties, a number of noteworthy estimations exist for future PY—or theoretical yield by the definitions here (see Section 2.1 on definitions). Surprisingly, some of the least plausible estimates have excellent pedigrees.

In 2008, Monsanto projected that USA maize FY would double between 2000 and 2030 by rising from 8.5 t/ha to 17 t/ha—that is, equivalent to FY progress of 3% p.a. relative to the 2000 FY—which Monsanto suggested would come equally from conventional breeding, marker-aided selection and GE. Similarly, Rothamsted Research in the UK recently announced its plan to raise UK winter wheat FY to 20 t/ha in 20 years (2.5% p.a. progress) by using breeding, novel genetic resources and GE.

In the past, such high relative rates of FY progress were seen briefly in wheat and rice in Asia, when the FY base was low and FY improved rapidly in the early years of the green revolution. However, recalling that FY increase is PY increase plus yield gap closing (Chapter 2), the FY increase proposed by Monsanto and Rothamsted Research for modern systems with relatively small yield gaps implies a very unlikely annual PY progress figure of 2.5–3.0% (compare Table 9.1 where maize shows 1.1% p.a. and wheat 0.6% p.a. PY increase). The proposition gives every impression of an aspirational goal for publicity purposes, and runs the danger of creating false hopes and distorted investments. Note, however, that where low yield bases and huge yield gaps still exist in

favoured parts of Sub-Saharan Africa, such high rates of FY improvement may be seen again if sufficient effort is made.

More credible predictions for possible future PY are based on physiological models, either simple or complex. Good examples of the former are predictions for the PY of winter wheat and canola (and spring pea) in the UK (Berry et al. 2012). For UK wheat the following was assumed:

- increase in $\sum PAR_i$, which was projected by the authors to reach 60% interception of annual incident solar PAR, arising through faster leaf area production in the spring and small delays in canopy senescence towards maturity, without necessarily changing the average flowering date (12 June); recall that UK winter wheat is sown in September and harvested 10–11 months later in July–August
- RUE of 2.8 g DM/MJ—noting that the best varieties studied by Shearman et al. (2005) in Nottingham, UK, reaching 2.6 g DM/MJ, are almost at this level
- HI of 0.56 close to the structural limit discussed earlier.

Without water shortage, these assumptions result in a theoretical yield of 18 t/ha (at 15% grain moisture), a figure that is roughly 70% above the 2010 PY of 10.7 t/ha (see Section 3.8). Because of the longer duration of high LAI involved, these winter wheat crops would likely run short of water in about one-half of the arable area in the UK (e.g. in the drier south-eastern regions, or in sandy and shallow soils), so the authors revised their theoretical national PY down to 17 t/ha.

Earlier (Sylvester-Bradley et al. 2005), the same research team, had projected a UK wheat PY of 19 t/ha by 2050—equivalent to a rate of progress of 2% p.a. of the 2010 PY—but (perhaps wisely) these authors put no timescale to their new estimate in Berry et al. (2012). For winter canola in the UK, theoretical PY was determined to be 9 t/ha, reduced to 8.5 t/ha because of lack of water in some areas; the theoretical yield is lower than for winter wheat largely because of the high energy cost of oil synthesis (Berry et al. 2012). In 2007, PY was 4.5 t/ha (Section 7.4).

In a comprehensive analysis of the underlying physiology of tropical rice, Akita (1989) estimated that in the dry season at IRRI, HI could reach 0.6 and PY could reach 15 t/ha. Later, Mitchell et al. (1998) projected that increasing rice RUE from 2.2 g DM/MJ to 2.7 g DM/MJ would deliver new varieties with the duration of widely grown cultivar IR72, and a theoretical yield of 12 t/ha in the tropics and 18 t/ha in the subtropics. Furthermore, they projected even higher rice yields if HI could be lifted above 0.5. Currently the best inbred and hybrid varieties show a dry season PY at IRRI of about 9.5 and 10.5 t/ha, respectively (Section 4.2).

Crop simulation models, usually running on daily time steps, are more complex. They contain considerable well-founded physiological detail, but empirical relationships nevertheless still abound and models are often not calibrated against the latest genotypes. It is easy enough to demonstrate yield increase by changing appropriate genetic parameters, but difficult to be sure that all the feedbacks and environmental

interactions have been considered. Thus apparent progress may be illusory, even if such genetic variation in the parameters does exist in some genetic backgrounds.

Crop simulation models are probably now capable of exploring the effect of simple traits to help set breeding priorities, but these models cannot yet tell the way forward on yield breeding (or limits to PY) with any more confidence than simpler models based on well-understood processes. An old example of the latter is the demonstration of the importance of erect leaves for maximising canopy photosynthesis (Loomis and Williams 1969)—this notion has probably had a positive influence on visual selection for erect leaves and higher yield in several crops.

Recently, simulation modelling of PY_w (rather than PY) has become more common. Perhaps this is because more environmental variability arises under water stress, and these relatively easily quantifiable variations provide more traits about which to speculate. For example, Hammer et al. (2005) examined the influence of four traits (earliness, osmotic adaptation, transpiration efficiency and staygreen) on the predicted PY_w for grain sorghum across the state of Queensland, Australia. Results showed large yield responses and plausible interactions with water stress patterns, and produced useful guides to faster breeding progress. More PY_w possibilities are discussed further in the next section.

Modelling such as that in Hammer et al. (2005) has given rise to the term 'gene-to-phenotype modelling'. Since then, this field has boomed, but the models still lack physiological depth, and uncertainties are widespread (R.A. Fischer 2011; Palosuo et al. 2011). Thus yield predictions remain nothing more than a useful tool—a plausible guide to priority traits and more efficient breeding. Simulation modelling cannot provide the guaranteed pathway to higher yield as needed by breeders and the world.

Crop yield records and contest-winning yields

It is useful to revisit briefly the subject of record yielding crops (see Section 2.1), at least those for which we can be confident of the observed yield measurement. The focus remains on irrigated or high rainfall crops because of the complications of interpreting records of crops grown under water shortage.

A well-documented world record in wheat (Armour et al. 2004) is the 15.5 t/ha (at 14% moisture) irrigated winter wheat crop grown in 2002–03 in the Canterbury Plains of New Zealand (latitude 44 °S) and confirmed in farmers' fields nearby. The record crop was a 1998 released UK feed variety that received excellent agronomic management and encountered very favourable solar radiation (~20–25 MJ/m²/d) and temperature ($T_{\text{mean}} \sim 12\text{--}16$ °C) in the critical month either side of flowering in early December (P. Jamieson, pers. comm. 2010).

The New Zealand record is very similar to a record yield of 15.4 t/ha (at 13% moisture) for irrigated spring-planted spring wheat claimed for the Chaidamu Basin of central China—latitude 36 °N and 2,000 metres above sea level (masl)—where exceptionally

high solar radiation and low night temperatures ($T_{\min} = 4\text{--}10\text{ }^{\circ}\text{C}$) can adequately explain the high yield without invoking an unusually high RUE or HI (Sinclair and Bai 1997). Thus neither of these record yields for wheat appears extraordinary when consideration is given to the solar radiation and temperature data for the very favourable seasons and locations.

Irrigated rice yields are clearly higher in irrigated dry summer environments at temperate latitudes (rice mega-environment 4; see Section 4.1), but the highest recorded yields appear to come from the province of Yunnan in China, a subtropical location at 1,170 masl and latitude $27\text{ }^{\circ}\text{N}$. The top yields with modern Indica (warm area) hybrid varieties appear to range between 16 t/ha (Katsura et al. 2008) and 18 t/ha (Li et al. 2009). Moderately high solar radiation and low to moderate night temperatures are believed to be the cause of the consistently high yields in Yunnan province. A record rice yield of 20.2 t/ha from the Nalanda district, Bihar state of India ($25\text{ }^{\circ}\text{N}$, 50 masl) in 2011 was recently claimed by the proponents of the System of Rice Intensification (SRI); see Box 8.2 and Diwaker et al. (2012). The crop was a modern hybrid variety that had received deep ploughing, heavy dressings of farmyard and poultry manure, vermicompost and chemical fertiliser (N, P, K and Zn), soil-aerating weeding and sprinkler irrigation; this surprisingly high yield in the warm cloudy wet season needs, but unfortunately lacks, independent verification.

Maize yields of 22.3 t/ha have been observed in small replicated irrigated plots in Chile's Central Valley where the Mediterranean climate—coupled with the cooling influence of the Humboldt Current that flows north along the west coast of South America—gives cool summer temperatures and cloudless skies (H. Campos, pers. comm. 2009). Irrigated maize in the central valley of California, USA, is almost as productive (Campos et al. 2004). These yields undoubtedly reflect the favourable climate plus the best hybrids and management, and nothing more.

The highest maize yield reported in the yield contests of the US National Corn Growers Association (NCGA) in 2011 was an irrigated crop in the state of Virginia that reached 26.8 t/ha (NCGA 2011). Butzen (2010) summarised hybrid and management details for the 2005–09 NCGA winning maize crops. Not surprisingly, winning crops included a predominance of full maturity disease-resistant hybrids, planted early after soybean the previous year, at very high populations; they also received seed insecticide, split nitrogen and foliar fungicide. Unfortunately, the growing practices of non-winning entrants were not described.

Yield contests for soybean in the USA provide intriguing data. Even in the 1960s, national contest-winning yields approached 7 t/ha (four times the national average yield at the time) while maximum yield experiments reached 8 t/ha in the mid 1980s (Specht et al. 1999). State contests continue and the soybean yield record now stands at 10.8 t/ha (Van Roekel and Purcell 2012), achieved in the state of Missouri by a grower who also delivered an average yield of 9.2 t/ha over 3 years. Limited recorded agronomic and weather details make these yields difficult to interpret, but initial physiological studies have failed to identify anything exceptional (L. Purcell, pers. comm. 2012).

Unfortunately, these reports of record and contest-winning yields often do not provide sufficient weather information. When records are available, high solar radiation and reasonably low temperature appear to capture the favourable aspects of weather, but other weather subtleties may not have been recognised (e.g. low wind, high humidity or a high percentage of diffuse radiation). Agronomic management and soil properties are even less well reported, and very favourable soil properties could explain part of superior performances, for example, through the effects of mechanical impedance on RUE hinted at in the maize studies of Tollenaar and Migus (1984) (see Section 9.4). Quite separately, soils that are high in organic carbon, or soils recently receiving heavy doses of organic fertiliser, could produce unusually high soil CO₂ emissions, sufficient to boost photosynthesis in dense canopies with low wind mixing. For maize, very well drained soils that totally eliminate anoxia in the root zone may also be critical for winning yields.

It is a wasted opportunity that record yielding crops are not studied more closely, with at the least the prevailing weather conditions, agronomy, and soil and key physiological traits properly and publically documented. It is possible that such information would provide a guide to lifting PY generally, particularly through the novel agronomic techniques that winning farmers tend to use. At the least, record and contest-winning yields show that there are no intrinsic limitations to yield in the makeup of crops, but simply limitations that derive from light capture and utilisation.

Duvick and Cassman (1999) looked at the time trends in contest-winning US maize yields, which provide another possible measure of PY progress. While there was good progress in most situations, these authors noted an apparent lack of progress in winning yields for irrigated maize in the state of Nebraska. They suggested this result may signal an end to breeding (and agronomic) progress in PY in a region that has been highly targeted by breeding companies—a harbinger of the yield ceiling to be encountered elsewhere before too long. However, Butzen (2010) showed that the US national maize winning yields still appear to be increasing, at least up until 2008, with rates of progress of 1.6% p.a. (NCGA non-irrigated) and 2.4% p.a. (NCGA irrigated). For the state of Iowa, alongside Nebraska and also highly targeted by the breeding companies, the figures are 1.4% p.a. and 1.3% p.a., respectively (R. W. Elmore, pers. comm. 2012). None of these figures supports the notion of a plateau in PY.

9.6 Physiological components of progress in water-limited potential yield

Just as with PY determination, crop physiologists have developed a simple model for understanding PY_w. Equation (8) is explained in detail in Section 2.6 and is given briefly here:

equation (8) (recap) Water-limited potential yield (PY_w) from water supply, transpiration efficiency and harvest index

$$PY_w = (ET - E_s) \times TE_1 \times HI \quad (8)$$

where:

PY_w is in kg/ha (kg/ha are used to accommodate the common units of TE)

ET (mm) is crop water use, E_s is soil evaporation, so (ET – E_s) is transpiration (T in mm)

TE (kg DM/ha/mm) is transpiration efficiency

HI is harvest index

Past progress in water-limited potential yield

Annual rates of recent breeding progress for PY_w (Table 9.1) have shown similar relative (if not absolute) values as those for PY, but there have been only a few examples of physiological research into the basis of the progress. Rather, some general notions have emerged elsewhere—including from crops not normally considered as commonly grown under water shortage (such as rice, maize, soybean and potato). These other crops are sensitive to whatever water stress does occur, and hence often also provide opportunities for analysis (and possible genetic improvement by targeting yield loss due to water shortage).

Adaptation of varieties to dry environments has often initially involved selection for **earliness in flowering**, thereby still leaving some soil-stored moisture for post-flowering transpiration to guarantee completion of the crop cycle on a limited water supply. In winter crops at intermediate latitudes, traits for earliness can bring the critical flowering period into more favourable environmental conditions—for example, when maximum temperature and vapour pressure deficit (vpd) are lower and sometimes the chance of rain is higher. However, this mechanism of progress has probably now been exhausted, as optimal flowering dates have already been achieved by the suite of current varieties available to most farmers.

The second major mechanism for high PY_w is a clear spillover from breeding progress in PY, in the form of **higher HI**. This has occurred, for example, in shorter stature wheat varieties, and is one reason why breeding progress in PY_w usually matches that in PY in wheat. It is probably a gauge of such progress that (in terms of equation (8)) the upper limiting slope of the relationship of PY_w vs. the difference between ET and E_s—the product of TE and HI—is now close to 25 kg grain/ha/mm (Sadras and Angus 2006), rather than 20 kg/ha/mm as when the equation was originally formulated by French and Schultz (1984) for southern Australia. But HI is often lower when water shortage coincides with grain-filling, or because of specific damage to reproductive structures inflicted by water deficits around flowering when GN is determined. There is little evidence that breeding progress has reduced this **sensitivity at flowering**, except in temperate maize (Edmeades et al. 2000; Campos et al. 2004).

The first term in equation (8), evapotranspiration (ET; see Section 2.6), points to the obvious importance of crop transpiration. Evidence of breeding progress in ET is limited, although well-recognised benefit is gained from improved **agronomic practices** that increase water storage during pre-crop fallow periods and reduce evaporation losses in the crop (i.e. through surface mulches). Indeed the contribution of conservation agriculture—in particular the replacement of fallow tillage by the retention of surface residue (plus fallow weed control with herbicides when necessary)—has been clear in low-rainfall cropping environments, so much so that the extra stored water enables an increase in cropping intensity, from one crop every 2 years to one per year in wheat in western Canada (Section 3.6) or two in 3 years in wheat in the Great Plains of the USA (Section 3.9).

Greater transpiration is a likely result from crops with **deeper roots** that can extract more soil water—provided, of course, that soil water is available at depth. There is, however, surprisingly little evidence that breeding for PY_w has resulted in deeper roots, perhaps because of the cost in carbohydrates of building more roots (Palta and Watt 2009), or the trade-off between earliness of flowering and root depth (since root extension tends to cease after flowering). One possible example is the hypothesis of Hammer et al. (2009) that modern US Corn Belt maize hybrids have deeper root systems. This is an intriguing suggestion based on modelling and, to date, limited soil sampling.

As for **differences in transpiration efficiency (TE)**—the remaining component of equation (8) to be discussed in relation to breeding effects—there is little hard evidence that breeding progress for PY_w is associated with increased TE. Reports of higher P_{max} in modern varieties do not automatically correspond with higher TE—rather, as explained in Section 2.6, the lower intercellular CO_2 concentration needed for higher TE can arise from lower stomatal conductance (reduced P_{max}) or higher mesophyll conductance (increased P_{max}). However, for some C_3 crops in some environments, modest gains in PY_w have been made by direct selection for greater TE (Richards 2006) using the innovative carbon isotope discrimination method. Across wheat varieties, high TE is unfortunately associated with lower stomatal conductance (lower P_{max}) and slower growth of leaf area, meaning that gains from higher TE can be counterbalanced in certain environments by higher soil evaporation (E_s) that results when the crop is slow to achieve full groundcover. Conversely, the higher TE trait is advantageous in environments that encounter less in-crop rainfall (i.e. less frequent wet soil surfaces and hence lower E_s) and rely more heavily on soil-stored water (Condon et al. 2002).

Physiological studies on maize improvement in temperate North America do not follow the model of equation (8) because they relate to conditions that usually have ample soil water. However, it is apparent that **modern maize hybrids are more 'stress' tolerant in general**. This has been referred to in the context of performance at higher densities, but is also evident in tolerance to various oxidative stresses such as water shortage and cold (Section 5.2). This has also led to claims that the major yield gains in maize can be attributed not to increases in PY , but primarily to increases in tolerance to the multitude of minor stresses (including transient water stress) that

can be faced even when maize is optimally managed for maximum yield (Duvick and Cassman 1999; Tollenaar and Wu 1999). For example, modern maize hybrids suffer lower relative yield losses under managed water shortage, or under drought, than their older counterparts (Campos et al. 2004; Duvick 2005a). The leaf photosynthetic apparatus of modern hybrids is clearly more tolerant of water stress, with slower senescence at times of moderate stress and more rapid crop recovery from water stress (Tollenaar and Lee 2006).

Modern maize hybrids have also already been noted to exhibit greater water stress tolerance at silking (Section 5.2 on the US Corn Belt). This trait arose unintentionally in the US Corn Belt breeding programs, but was targeted specifically in tropical maize by CIMMYT breeders in Mexico through selection for a **reduced anthesis to silking interval** (ASI, see Table 2.1 for definition of anthesis and silking). The reduced interval is achieved by a stronger, faster growing ear sink right from its very early stages, and this helps to ensure greater pollination and maintenance of HI, even under stress (Edmeades et al. 2000). This trait also appears to have been built into drought-tolerant CIMMYT maizes, which were selected for reduced ASI and other drought traits under managed severe water stress in the field in Mexico. A rate of PY_w progress of ~ 160 kg/ha/breeding cycle (or about 2–3% p.a. at 2 t/ha yield levels) has been achieved in seven tropical maize populations over several decades, and is mainly reflected in increases in ears per plant and HI under drought stress (Edmeades 2013). The selection methodology is now delivering useful gains in varieties and hybrids for farmers' fields in eastern and southern Africa (Bänziger et al. 2006). More recently, the private sector in the USA has commenced similar targeted trait selection in temperate maize germplasm for performance under water shortage, and is also delivering good PY_w progress (Edmeades 2013).

Prospects for water-limited potential yield

Armed with equation (8), and bearing in mind recent progress described above, the question arises about what further physiological changes can support breeding advances in PY_w . At the outset it needs to be emphasised that PY_w is a more difficult breeding target than PY because of the greater variance due to genotype-by-environment interaction relative to that due to genotypes—in other words, lower heritability—arising essentially from the annual variability of the crop water supply.

Crop ET is linked to water supply from rain and from pre-sowing soil storage, the latter connected to good pre-crop agronomy. In situations where current varieties are unable to access available soil water at depth, new varieties with **deeper roots** could increase transpiration, assuming such water is replaced every year or so, when rainfall exceeds evapotranspiration. Such situations may exist, and genetic variation in rooting depth is available, but despite the obvious importance, the link between deeper roots and PY_w had been little studied. Fortunately, it appears that current research has taken up this challenge. For example Lynch (2013) has postulated a maize rooting ideotype designed to maximise the capture of water (and nitrogen) for least carbohydrate cost, and some

of the necessary genetic variation appears to exist. Furthermore, easier methods for predicting differences in root depth are showing promise, such as, for example, relating depth to seedling root angle in rice and wheat (Kato et al. 2006).

Increasing transpiration as a proportion of ET by reducing in-crop E_s is another possibility. It has been postulated that **early vigour** in wheat, giving a rapid approach to full groundcover, can reduce in-crop E_s in situations where E_s tends to be high—for example, under frequent rain or where topsoil is fine textured. Growth of low-rainfall crops, however, needs to be controlled so that demand does not exceed the limited total water supply. Genetic variation in early vigour in wheat is substantial (Rebetzke and Richards 1999) and may bring other benefits such as improved weed competitiveness and better establishment in poor, dry seedbeds. Genetic variation in **osmotic adaptation** (meaning the osmotic pressure generated by root and other cells) also exists. There have been claims that increased osmotic adaptation might bring benefits such as increased soil water extraction permitted by greater root osmotic pressure (Morgan 1995). Reviewing osmotic adaptation in general, Serraj and Sinclair (2002) recognise that this aspect deserves follow up, although they argue that most other field studies show no practical yield benefits from increased osmotic adaptation. Blum (2005) disagrees with this conclusion, arguing that osmotic adaptation can increase drought tolerance at no cost to PY.

Cereals are very susceptible to water stress around flowering, which can lead to a sharp reduction in GN and HI (Bruce et al. 2001; R.A. Fischer 2011). Progress in tolerance to such stress in maize has been mentioned above. In wheat and especially rice, water stress around flowering induces pollen sterility and hence reduces GN. The basic physiology of responses to water stress at flowering in wheat has been elucidated down to the molecular level. There is evidence of **genetic variation in sensitivity of grain set** that could be exploited by conventional breeding (Ji et al. 2010).

Stomatal behaviour has received much attention because of its obvious potential role in **genetic variation in TE**—reflected in the intercellular concentration of CO_2 during photosynthesis—and the ease with which stomatal conductance can now be remotely sensed (by leaf temperature). If stomatal conductance alone is decreased, intercellular CO_2 concentration will decrease and TE will increase, but photosynthesis (and transpiration) will also decrease. On the other hand, intercellular CO_2 concentration can also decrease (and TE increase) if the leaf photosynthetic machinery is more active or efficient (by increased mesophyll conductance), even though stomatal conductance may remain unchanged—in this situation, photosynthesis will increase while transpiration remains unchanged. Unfortunately, the higher P_{max} reported earlier in modern wheat varieties (Section 9.4 ‘Increasing radiation use efficiency’) means stomatal conductance increases more than mesophyll conductance, so that the concentration of intercellular CO_2 increases and TE decreases. Thus, selection for increased TE within wheat pays the price of lower P_{max} , but nonetheless has been effective for raising PY_w in certain dry situations (Condon et al. 2002). In other situations, for example with higher soil evaporation losses, the lower early growth found with higher TE means there is a penalty in terms of $(ET - E_s)$ in equation (8) above, and no yield

gain or even a loss, a situation that Blum (2009) argues is a common risk with traits that increase TE. There is recent evidence that the situation may be different across selected sorghum genotypes, where RUE increase was associated with water use efficiency increase (Narayanan et al. 2013). However, these increases need to be confirmed with P_{\max} and TE measurements.

A number of crops show **stomatal sensitivity to increases in vpd**, which increases TE, not simply because intercellular CO_2 concentration decreases, but more so because transpiration (and photosynthesis) are reduced at the time of the day when vpd is greatest and TE least. The trait conserves soil water, which could thereby protect the crop during temporary dry spells; it has been observed in maize, sorghum and sugarcane (Sinclair et al. 2005). Those authors used simulation modelling to demonstrate that stomatal sensitivity to increases in vpd—essentially putting an upper limit on maximum transpiration rate—could increase PY_w in sorghum in eastern Australia by ~10% in low-yielding years (i.e. years in which yield is <4.5 t/ha) while somewhat decreasing PY_w in better years. There appears to be genetic variation in this trait, at least in peanut (Devi et al. 2009), and in soybean where it is the basis of the non-wilting phenotype (Sinclair et al. 2010).

Another genetic trait, **pre-anthesis stored carbohydrate**, could buffer grain yield against water shortage during grain-filling to maintain HI and GW. Genetic variation of this trait is known. There is already some evidence in wheat that greater pre-anthesis stored carbohydrate is linked to higher PY_w (Richards 2006). This review also discusses other potential traits for PY_w in wheat.

Physiologists have been particularly active in proposing these and many other traits for drought tolerance over many years. However, most traits have not yet proven useful when used as selection criteria (with the notable exception of the trait-based selection in maize and selection for TE in wheat, both mentioned already). Reasons could be that individual trait effects are too small and measurement too difficult, or some traits may carry hidden trade-offs, or there could be a yield penalty under well-watered conditions. At the same time, empirical breeding continues to make significant PY_w progress, but with its perceived slowing, there is renewed optimism—as seen, for example, in Richards et al. (2010) and Serraj et al. (2011)—that including selection for validated physiologic traits, linked to molecular markers where appropriate, can boost breeding progress for PY_w .

One encouraging recent success has been advances, after many years of stagnation, in drought tolerance in rice (Serraj et al. 2011). This outcome is important given that ~40% of rice is grown in diverse rainfed situations (see Section 4.1). Recent advances include identification of a **single QTL** that added 47% to rice PY_w under severe managed drought at IRRI (Bernier et al. 2007). It seems likely that it is linked to deeper rooting which improves plant water status and protects processes around flowering, since HI in the Bernier et al. (2007) trial was increased. This has catalysed QTL selection and field drought screening for rainfed rice, which now claims rates of PY_w progress of 4–10% p.a. (Venuprasad et al. 2008). As with conclusions recently reached for PY_w

in wheat (Richards et al. 2010) and maize (Edmeades 2013), the keys to this new success in rainfed rice may be proper management of water stress for screening in field plots, and the application of physiological understanding and molecular markers in breeding (see Section 9.10). On an optimistic note, Edmeades (2013) concluded that conventional targeted breeding combined with marker-aided selection could lift PY_w in maize (at yield levels about 25% of PY or 3 t/ha conditions) by 2% p.a. over the next 20 years.

As mentioned in Section 9.5 on PY, more complex crop simulation models have also been used to explore PY_w . Although such models may still lack sufficient physiology for confident predictions in regard to desirable new plant traits, models can be very useful tools for characterising the likely patterns of water shortage in any rainfed environment. By adequately capturing the inevitable variability of water supply in such situations, such crop simulation models can be a useful complement to the simple model of equation (8).

Thus, using the APSIM-Wheat model, Chenu et al. (2011) took 100 years of historic rainfall records over 12 regions of the north-eastern Australian Wheat Belt and determined that wheat there faced three major water stress patterns:

1. moderate to severe grain-filling or terminal drought stress—affecting 50% of production environments (i.e. both location and year)
2. flowering stress relieved during grain-filling (34%)
3. no stress (16%).

This knowledge not only helps breeders understand genotype-by-environment interaction in their target region, but also points to the key stage of development for stress resistance—stress at flowering covering 84% of the situations in this example. A similar exercise had already been carried out for sorghum in this same region by Chapman et al. (2000), who determined that sorghum faces the above three types of stress environments, plus two variants of the pre- and post-flowering stress. Such modelling would be valuable for breeding in all rainfed crops and regions.

Although breeding for PY_w has here been treated separately from that for PY, the distinction is to date somewhat unnecessary. First there are remarkably few studies of varieties showing yield crossovers (rank changes) as testing moves from moderately dry to well-watered (PY) conditions; usually PY_w in cereals (apart from rice) must fall to 2 t/ha or so before crossovers can be found (Blum 2005). Traits that are yield-positive or neutral under the full range of moisture supplies must therefore dominate empirical breeding outcomes, compared with traits that are yield-positive under water shortage but otherwise yield-negative. Good examples of the former are high HI and hybrid vigour (see Section 9.8 on GE); high P_{max} linked to high TE would be another example if such genetic variation could be confirmed.

Second, in any dry rainfed location, annual variation in rainfall is such that expected PY_w can range from a fraction of PY, right up to full PY. Years of low rainfall loom large

in the economic welfare of smallholder farmers of lower socioeconomic status, but in advanced farming situations, overall farm income is more a question of taking full advantage of higher rainfall years. Plant breeding has been dominated by the latter thinking, successfully combining responsiveness with reasonable performance under moderate water limitation, no doubt because the yield testing has always been conducted under a wide range of moisture supplies.

In conclusion, plant breeders continue to make slow but statistically significant progress with PY_w (Table 9.1) using largely empirical methods. There is some expectation that progress may be aided by attention to better environmental characterisation, by the use of managed environments, and by incorporating better validated physiological traits as selection criteria, nowadays aided by molecular markers; if PY_w is not boosted by this attention, then it should at least be maintained at current rates of progress for this difficult breeding target.

9.7 New agronomy for greater potential yield under limited and unlimited water

The contributions made by agronomy to past PY and PY_w gains have included:

- earlier sowing
- effective crop sequences and/or rotations
- higher density and precision spacing (in maize)
- improved crop nutrition (in particular, nitrogen supply)
- no-till and conservation agriculture
- selective herbicides.

In most cases these changes involved positive agronomy-by-variety interactions. However, apart from possible further gains with even greater density in maize, future new agronomy leading to increased yield is not easy to envisage. A distinction must be made, however, between new agronomy for increased yield and new agronomy for improved input efficiency, as the latter field still offers enormous opportunities particularly with irrigation water, nutrient and herbicide management (see Chapter 11 'Resource use efficiency, sustainability and environmental impact of cropping'). In this context, yield increases have been claimed for precision agriculture, but most gains currently appear to be efficiency related, although the opportunities created for mechanised intercropping warrant exploration.

Without doubt, soil factors pose the greatest uncertainty in the current crop production system. Some soil factors (chemical, physical and/or microbiological) may become

more manageable with greater knowledge, but for the moment—even in experiments carefully designed to measure PY—it is difficult to be certain that soil factors are not limiting yield.

Small (<20%) but highly significant effects of the **soil physical structure** on shoot and root growth can arise no matter how carefully the soil is managed to optimise nutrition, water, aeration and compaction (e.g. Kay et al. 2006). Crop nutrition is probably the easiest agronomic factor to resolve, as this can be achieved with fertilisation according to soil and plant diagnostics and (in some cases) through generous applications of animal manure. Sometimes there are yield responses to manure that suggest undiagnosed deficiencies. However, other explanations are also plausible, such as canopy CO₂ fertilisation from breakdown of the manure (Section 9.5 on record yields) or suppression of soil pathogenic fungi as a result of increased soil organic carbon.

Negative crop growth responses to **soil mechanical impedance** are not explained by lack of nutrition or water from constrained roots (Passioura 2002). Conversely, the unusually high RUE values seen with crops in hydroponic systems (i.e. no mechanical impedance) have been mentioned in Section 9.4. Several approaches attempt to overcome soil mechanical impedance where yield responses justify action:

- deep tillage delivers responses in situations where natural or artificial hard pans can be broken
- controlled traffic seeks to avoid compaction at all times (beyond the wheel tracks), with claims of yield responses (and fuel savings) in readily compactable soils
- deeply tilled and raised beds, which are not trafficked, commonly are favoured to grow many leafy vegetables.

Finally, consideration should be given to **soil microbiology**—a field that is currently undergoing a renaissance due to the advent of molecular tools for characterising microbial populations. Yield often declines with continuous cropping but recovers somewhat with change in crop sequence (rotation); the recovery varies in magnitude according to the exact crop sequences (e.g. Kirkegaard et al. 2008; Anderson 2011). This effect strongly suggests that microbiological changes induce negative or positive crop growth responses.

Responses are not necessarily related to changes in known soil pathogens, although a clear relationship may be evident, such as in the case of rapeseed (canola) eliminating several root diseases of wheat. Also, some crop sequence effects may be allelopathic, whereby chemicals from one crop plant are antagonistic to another crop plant (or weed); however, allelopathy remains a much under-researched field. Denison (2009) made an interesting point that natural selection could not have favoured genotypes adapted to crop sequences, and that therefore there may be good scope for breeders to select genotypes suited to the soil changes (probably microbiological) arising in key crop sequences. Exploring and exploiting such genotype-by-agronomy interactions will not be easy.

Positive responses to **microbiological additives** that are often delivered with the seed—although notoriously variable and difficult to repeat—could bring modest PY and PY_w gains in some situations, probably by improving the crop's ability to capture early soil resources. Ultimately, however, the limits on RUE and/or TE must prevail, and it is not clear whether final grain yield can be increased much by such soil 'magic'. In some cases, however, it is clear that desirable soil properties can positively affect RUE through increased stomatal conductance and/or increased photosynthesis (Tollenaar and Migus 1984; Passioura 2002; Kay et al. 2006; H.W. Li et al. 2012).

Three agronomic innovations could **impact particularly on PY_w** . The first is already deployed in millions of hectares of small-scale cropping in China—**inter-row plastic film**. The film is placed for the spring planting of grains (e.g. maize and wheat) in order to warm the soil and reduce soil evaporation (E_s). Yield responses in dry situations can be remarkable (see Section 5.3 on maize in China), but the cost and environmental consequences of the current technology represent a major research challenge if this agronomic innovation is to be applied globally—for example, biodegradable, spray-applied, ultra-thin films would be an improvement to this technology.

The second agronomic innovation for PY_w relates to using **improved seasonal rain forecasts** to reduce the risk in decisions made around planting time (i.e. crop, variety, density and/or nitrogen use), and in particular, to encourage dryland farmers to take advantage of forecasted good seasons, as discussed in Section 3.5 on wheat in Australia. This trail was blazed with forecasts based on analogue years classified according to the El Niño – Southern Oscillation (ENSO) phenomenon (Hammer et al. 2002). More recently, seasonal forecasts based on global circulation models (GCMs) are starting to show better levels of skill. Such forecasting is largely independent of climate change forecasting.

Data of Hansen et al. (2009) showed yield benefits of 2–11% from adjusting maize planting density and nitrogen rate according to the GCM-based rain forecast in dry mid-altitude locations in Kenya; gross margins were greater (2–24% increase) because costs did not increase greatly. These authors suggested farmers of smallholdings could benefit from such forecasts, especially with further improvements in forecast skills. In parts of the Australian Wheat Belt, a forecast that could (70–80% of the time) identify wetter than median growing seasons before wheat planting date (1 May) would permit higher nitrogen use in such seasons, and improve average yield and gross margin moderately (Asseng et al. 2012).

The benefit from such forecasts is of course increased in situations where farmers show greater risk aversion (reluctance to invest in inputs for fear of loss in poor seasons). Improved forecast skills would greatly help adoption, but Asseng et al. (2012) suggest that seasonal forecasts will only slowly improve. Any agronomic strategy relying on forecasts should also be compared with alternative options like tactical in-season nitrogen management, noting that this can also benefit from forecasts, particularly shorter ones (which offer somewhat greater certainty). Going beyond the realm of agronomy, drought insurance is another important risk management option that can

encourage risk-averse farmers to invest in greater inputs and thus achieve higher yields; such insurance is widely available in the USA, but globally this form of insurance has not yet been widely applied.

The third possibility for PY_w refers to agronomic change that would be encouraged by genetic change—**earlier planting (say, in wheat) associated with earlier flowering enabled by improved frost resistance** at heading. For cool-season crops at intermediate latitudes, earlier planting would in turn reduce the risk of drought and heat during grain-filling and thereby increase yields. Frost damage to the spike or inflorescence takes several forms but is most spectacular when developing anthers are frozen and the spike (with otherwise normal size and external appearance) is rendered sterile. Genetic improvement in frost resistance is a goal that will not be easily achieved, but genetic variation does exist—especially in barley (e.g. Frederiks et al. 2012), but also in wheat (B. Biddulph, pers. comm. 2012)—and must be pursued. At the same time, earlier planting may require agronomists to develop special moisture-seeking seeding machinery.

There is no escaping the need for more nitrogen in cropping systems in many parts of the world in order for yields to increase. While the nitrogen challenge is not new, more photosynthesis will very likely need more nitrogen-rich photosynthetic enzymes, in particular Rubisco. Nitrogen is removed from the cropping system when the product is harvested—as a linear function of yield and grain nitrogen concentration—thus higher yield equates to more nitrogen removed. Of course higher nitrogen application rates will call for much greater attention to agronomic innovations that maximise nitrogen uptake efficiency and minimise losses (see Section 11.3 on nitrogen use efficiency).

Opportunities for new crop agronomy may seem to be shrinking but two things need to be remembered. First, opportunities arise not only with a particular crop—they can also be found in the soil management and crop sequence of the years preceding the crop, and hence in the optimisation of whole cropping and farming systems. Second, opportunities can come from developments in entirely unanticipated fields—as has been seen with remote sensing and precision cropping, and which may come with more robotics—and from genetic changes such as with herbicide-tolerant GE varieties that facilitated conservation tillage and early sowing. So agronomists need to be alert to these possibilities, and may well continue to contribute to PY and PY_w advances, besides helping with other efficiencies (see Chapter 11).



9.8 Hybrid vigour

Hybrid vigour (otherwise known as heterosis) is present in first generation of progeny (F_1 hybrids) derived from crossing two genetically dissimilar parents. Hybrid vigour is usually expressed as the yield advantage of the F_1 hybrid relative to the mid-parent value (average of the two parents).

Hybrid vigour can be considered as a form of stress tolerance, and, for this reason, often has a greater relative positive impact on PY_w than on PY . The physiological basis driving hybrid vigour is still poorly understood, and although there is no easy way of predicting the magnitude of hybrid vigour, molecular marker information has shown some promise. In general, hybrids offer a one-time 15% yield advantage over open-pollinated parents in maize and canola, but a smaller advantage in self-pollinated species such as rice (10–15%) and wheat (10%). The yield advantage of hybrids over the best commercial varieties, known as 'commercial heterosis', can occasionally be greater than this value because breeders actively seek uniquely favourable combinations of inbred lines—this is also known as strong specific combining ability.

Maize hybrids have been widely used for 80 years (see Box 5.1), and are now used in ~70% of global maize area. Hybrids are also widely used in other cross-pollinated species such as sorghum, millet, canola, sunflower and sugar beet. Hybrid breeding in self-pollinated species, recently reviewed for cereals by Longin et al. (2012), is challenged primarily by the poor yield of the female parent line when it is forced, in the face of many natural barriers, to outcross (receive pollen from nearby genetically distinctive plants) to produce hybrid seed; the outcome is expensive seed production. The seed multiplication ratio (number of seeds produced per seed planted) is also lower for wheat or direct-seeded rice crops (from ~50 up to 100) than for maize (~300) or canola at an even higher ratio (>500). Thus, more wheat and rice hybrid seed must be sown in proportion to the final commercial yield—again, adding to the expense.

Despite obstacles for self-pollinating species, Indica rice hybrids have been adopted in ~50% of China's rice area. Similarly, from an initially low base, tropical Indica rice hybrids are being rapidly adopted in South and South-East Asia. In wheat, the technical issues in seed production and lower average hybrid vigour have prevented any large-scale adoption, meaning that hybrids are so far limited to <1% of world wheat area (Longin et al. 2012), with the biggest effort probably in China (see Section 3.7). Since 2000, small areas of hybrid barley and triticale have appeared in Europe.

The seed yield constraint in self-pollinated wheat and rice will likely be resolved in the next 10–20 years, most probably through transgenic technology. Furthermore, breeding progress from hybrid breeding will be improved by following the route taken in maize. This route is the development of genetically different heterotic groups; that is, groups of genotypes exhibiting greater hybrid vigour in intergroup hybridisation because of complementary gene action. Together, hybrid breeding and development of heterotic groups will permit hybrids to take over much of the global rice and wheat area. In the case of wheat, this view is challenged by a theory that argues that because wheat is a polyploid plant, hybrids are unnecessary and many heterotic effects can be fully fixed into true breeding varieties—but there is not much evidence for this so-called 'fixed heterosis'.

If the seed yield constraint is indeed resolved to enable 100% adoption of hybrids in self-pollinated crops, the outcome would be a one-off yield increase of ~10% in global wheat and rice yields. At the same time, global maize yield should rise by ~5% as the proportion of hybrids under cultivation rises from 70% to close to 100%.

Because the seed of hybrid plants (F_2 seed) neither shows much hybrid vigour nor breeds true, there is an on-farm advantage to planting fresh F_1 hybrid seed every year. Thus hybrids foster a viable commercial seed industry with their built-in superior intellectual property protection. This creates a positive environment for private investment in crop improvement. If freely competitive, this environment can deliver improved hybrids efficiently and with seed of better quality (e.g. better germinability and/or vigour) than that of farm-saved seed. The advantage of hybrid seed is such that smallholder farmers in the developing world have quickly adopted hybrids—for example maize hybrids are almost everywhere, and millet and cotton hybrids are widespread in India. Ultimately, apomixis (whereby seed carries only the maternal plant genotype so that the F_2 genotype is the same as the F_1 one) could make hybrids true breeding and thereby benefit farmers wishing to retain seed. Apomixis has been a target for GE research for over 15 years, but little progress has been made, and success would pose difficulties for the hybrid breeding seed industry.

9.9 Genetic engineering for yield

The term **GE** was originally used to refer to the insertion—through the molecular technique of transformation—of genes from species that would not normally cross with the target species. Frequently this is now known as **genetic modification** (GM) but GE is used in this book because any plant breeding involves genetic modification, whereas the word ‘engineering’ correctly implies a greater degree of manipulation of the breeding process. Another common description for the GE process is **transgenesis**—the prefix ‘trans’ emphasising the cross-species approach. To this must now be added **cisgenesis**, when the molecular engineering tools are used to more efficiently transfer or manipulate genes within species that can be readily crossed.

Prospects for augmenting PY by increasing P_{\max} and RUE through GE have already been discussed and found too challenging for even medium-term success (see Section 9.4). Other promising traits and GE routes to higher PY are often claimed, but very few successes have been demonstrated in the field. This is probably because proponents have overlooked the complexity of a trait such as yield; compensatory responses between yield components or other hidden trade-offs become evident once the material is tested in field plots (Sinclair and Purcell 2005; Struik et al. 2007; Denison 2009; Basnayake et al. 2012; Passioura 2012).

One example is the much cited and elegant molecular work of Ashikari et al. (2005), which isolated a grain number gene (coding for cytokinin oxidase) and showed an inverse relationship between its activity in the inflorescence growing point (meristem) and grain number per plant. Transformation with a mutant copy of the gene, which lacked the gene’s normal function, increased grain number per panicle. This gene would seem to be at the heart of PY—control of GN (which has been central to yield improvement)—but results on performance in field plots have not been forthcoming.

Some GE progress has been made through **better abiotic stress resistance**; for example, submergence tolerance in rice (Serraj et al. 2011), and aluminium and salinity tolerance in wheat and barley (reviewed in R.A. Fischer 2011). In contrast to the work of Ashikari et al. (2005), these examples of progress in abiotic stress resistance correlate to better performance in the field, and they suggest that GE improvement in water stress tolerance and in PY_w could be more easily achieved than improvement in PY (but see below). The submergence tolerance in rice is additionally interesting because, although rice researchers are referring to the results as a product of ‘transgenesis’ (Serraj et al. 2011), the gene that has been used for GE is in fact a rice gene. Strictly speaking the terminology all hinges on whether any deoxyribonucleic acid (DNA) transferred from a totally unrelated species (like *Agrobacterium tumefaciens*, often used as a vector in GE) remains as flanking sequences to the inserted rice gene. This is because without the extraneous DNA, the process used for the rice could have been called ‘cisgenesis’ (Lusser et al. 2011). Unfortunately, in the perception of the non-scientific public, both transgenesis and cisgenesis have been branded too simply and singularly as ‘GE’, implying equal needs for expensive regulation.

For more than two decades molecular biologists have been showing apparently dramatic drought tolerance responses with GE. Some of the putative drought tolerance genes relate to survival not productivity, and others seem plausible for the real world. But inevitably performance in glasshouse pots has not been matched under water limitation in the field (Sinclair and Purcell 2005; Passioura 2012). For example, for over a decade CIMMYT has investigated dehydration-responsive element-binding (DREB) transcription factors from the widely studied plant, *Arabidopsis thaliana*, by transforming this into wheat. Unfortunately, when properly tested in field plots, the most promising transformants from the glasshouse did not show superior performance under drought (Saint Pierre et al. 2012).

Other recent studies point to possibilities of greater drought tolerance in transgenic rice (e.g. Xiao et al. 2009), and rice is a common candidate crop since the full genome is sequenced and publically available. Given that rice scientists are pioneering transformation of rice using rice genes for drought tolerance (Serraj et al. 2011), their chance of success may be higher than for transgenetic approaches. However, apart from submergence tolerance, to date there are few convincing published reports of yield benefits in the field arising from GE in rice. Performance under water limitation is obviously a quantitative trait, likely to be much more complex than submergence or aluminium tolerance, and unlikely to respond easily to GE efforts. Perhaps a focused approach to apparent bottlenecks in PY_w determination—for example, the dramatic negative effects of water shortage on male meiosis—may present a more tractable objective for GE.

Less than 5% of the transgenic traits in the commercial pipeline for release before 2015 are related to abiotic stress tolerance (Dunwell 2011), but one is worthy of comment. Following the apparent abandonment of GE maize with drought tolerance based on an *Arabidopsis thaliana* transcription factor (Nelson et al. 2007), Monsanto have proposed a 2013 release of a commercial GE maize hybrid (DroughtGard™) carrying a cold shock

protein gene from the bacterium *Bacillus subtilis*. The gene functions under drought stress as a protein that protects nucleic acid from degradation. It appears that this transgene is active throughout the life of the maize crop (rather than affecting stress tolerance only at flowering), and more importantly, it increases PY_w by 6–10% under a moisture stress that would otherwise reduce yields to ~50% of the irrigated control PY levels (Castiglioni et al. 2008). Monsanto trial results for the 2012 dry season in the Mid West of the USA delivered a 7% yield advantage around the 4 t/ha yield level (Edmeades 2013). This result may mark a major breakthrough for GE breeding that targets abiotic stress resistance, but its physiological basis remains unknown. The performance of these GE hybrids, when released to farmers in 2013, will be of great interest and should be measured independently and openly.

Relevant to this is the intent by Monsanto to release, without royalty claims, the above *Bacillus subtilis* transgene (known in GE parlance as an ‘event’) for use in maize adapted to Sub-Saharan Africa, through the Water Efficient Maize for Africa Project (WEMA), involving as partners CIMMYT and the African Agricultural Technology Foundation. Such private–public sharing of cutting-edge technology would benefit those who need it most. A similar model of private–public sharing is being followed with nitrogen use efficiency transgenes (see Section 5.4) currently under development at Pioneer Hi-bred through the Improved Maize for African Soils (IMAS) Project, in partnership with CIMMYT and African national programs.

Clearly, the view here is not one of optimism for the role of GE technology in contributing directly to increases in PY or PY_w in the medium term (20 years). This may not be the view of molecular biologists but it is common among others (e.g. Sinclair et al. 2004; Hall and Richards 2013), including the scientists involved in a recent UK review (Foresight. The Future of Food and Farming 2011). This view needs to be expressed here, because too often in the past GM claims relating to yield processes have failed to deliver. This appears to be especially because research has continued to reveal greater complexity. This complexity occurs not only in the relationships between genes and gene regulation at the molecular level, but also in their connections to whole plant and crop processes—which in modern crop varieties are already finely tuned through many decades of breeding to maximise grain yield in the field.

The situation with GE traits and yield is not unlike that with the many physiological traits for water-limited situations proposed over the years by crop physiologists—except that water-limited trait proponents have now become more realistic about yield improvement prospects through trait postulation. In reality, if it is to deliver as proposed, the GE approach needs to be much better linked to physiological understanding at the field crop level (Sinclair and Purcell 2005; Struik et al. 2007; Passioura 2012).

Insect and herbicide resistance dominate the transgenic trait pipeline, comprising 65% of GE events (Dunwell 2011), presumably because of the past success of these traits. Thus crops (maize, soybean, cotton, canola and sugar beet) carrying these transgenes have already been strongly adopted by farmers worldwide (globally occupying 170 Mha in 2012; James 2012), delivering positive FY effects that have been

discussed in the context of maize in the USA (Section 5.2). Although yield increase associated with GE insect and herbicide resistance is not the product of increased PY or PY_w , it is nevertheless noteworthy. Brookes and Barfoot (2012) estimate that *Bacillus thuringiensis* (*Bt*) genes have increased maize FY by 9.6% averaged over 1996–2010 and over the total area planted to these genes. In cotton, the corresponding effect on FY was 14.4% yield increase; the figure is greater than for maize because cotton incurred greater insect damage, despite heavy use of insecticide before the advent of *Bt* transgenes. Indirect yield increases associated with herbicide tolerance were overall much smaller, and often nil, although others often claim yield benefits associated with the earlier sowing that is facilitated.

GE is also used to combat other biotic stresses. GE virus resistance has been very effective in squash and papaya (James 2012), is about to be released in beans in Brazil, and could easily become available in other crops. Moreover, transgenic options for durable fungal disease resistance are likely in rice and wheat in the next one to two decades following experimental success already evident with late blight resistance in potato. If this success holds up, and regulatory barriers (see below) can be overcome, it would sharply reduce the need in wheat and rice for maintenance resistance breeding (i.e. the continual search for, and incorporation of, new natural resistance genes as those used in varieties in the field are steadily broken down by the pathogens they target). Maintenance resistance breeding consumes ~50% of current breeding effort in rice and wheat—a much larger proportion than in maize, where genetic diversity is greater in hybrids and open-pollinated varieties, thereby facilitating host-plant resistance. Overcoming the need for maintenance breeding would release considerable breeding resources to focus more on raising PY and PY_w in wheat and rice.

GE for biotic stress resistance faces the same challenge as conventional host-plant resistance breeding—the evolution of resistance in the target organisms. Smarter GE technologies can reduce this risk, and are likely in the medium term, but in the meantime, especially with GE glyphosate resistance, the weeds are mounting a powerful counter-offensive especially in systems where farmers have relied excessively on this GE trait. Smarter GE technology will need all the help possible from integrated weed management if this GE trait is to remain useful.

9.10 Genetic resources, and new tools and institutional structures for yield breeding

Conventional plant breeding is relatively slow, normally taking more than 10 years from initial cross to new variety (Hall and Richards 2013). The somewhat empirical process has nevertheless been very successful, resulting in steady breeding progress contributing to progress in both PY and PY_w (Table 9.1). Conventional breeding is

built on the genetic diversity existing within the crop species and has depended on substantial investments in yield testing across multiple environments.

Progress was aided initially by unencumbered widespread sharing of genetic material and by developments in genetic theory, computing and biometrics, and plot mechanisation. In the last two decades or so, breeding progress has benefited from further advances in computing and biometrics, robotics, crop simulation modelling, and non-GE biotechnology such as rapid generation advance technologies (e.g. use of double haploids, in which, to achieve homozygosity, chromosome number is artificially doubled in seedlings derived from, for example, cultured haploid pollen grains). However, the sharing of germplasm faces more barriers posed by international treaties, ill-informed national governments and commercial interests, and as a result, sharing has become more difficult.

Despite this steady stream of new tools, **annual PY and PY_w progress**, lately dominated by breeding and breeding-by-agronomy interactions—measured over the past 20 or so years as a percentage relative to current yield, and sometimes in an absolute sense—**has been declining for most crops** (including rice and wheat). Yield progress is generally <1%, although maize is still just above 1%, and canola and cassava are at ~1.4% (see Section 9.1).

Efficiency in breeding (yield gain per unit of investment in breeding) is very difficult to assess. The general picture is one of positive returns for public international breeding efforts (Evenson and Gollin 2003), but the situation in the private sector is less clear. Duvick and Cassman (1999) concluded that efficiency has been declining for some time in maize breeding in the USA (which is >95% conducted by the private sector), since PY progress has been around 25% between the 1970s and the 1990s, while the number of breeders and associated operation costs have increased by 340%. The substantial growth in private sector breeding investments in the USA in maize (and soybean) is widely assumed to dwarf that for wheat and rice where both the public and private sectors operate (see Section 13.2 on R&D investment). New breeding strategies and tools that constantly appear ought to raise efficiency, but the question is whether they can help accelerate or even maintain PY and PY_w progress.

One avenue for possible acceleration of yield progress is **greater exploitation of the wide genetic diversity** in agricultural crops. This route appears to be relatively assured (although not inexpensive), with gene banks currently storing thousands of accessions (gene bank entries). Included are many accessions from before the days of plant breeding, such as landraces (farmer selections) and related wild species accessions. It can be expected that yield-related genes will exist in this material, and fortunately, this genetic material is generally available to all bona fide breeders.

An early example of successful wide crossing was the development of **triticale** (× *Triticosecale*), achieved by crossing wheat (as female) with rye (*Secale cereale*). This difficult cross was first achieved in the late 19th century, and even as recently as 1967, the PY of spring triticale in CIMMYT in Mexico was only 3 t/ha—about one-half of that of wheat at the time (Zillinsky and Borlaug 1971). However, after 45 more years of

breeding effort, today's best triticale at CIMMYT yields as well as the best bread wheat (up to 9 t/ha) and still carries unique traits from the rye parent (e.g. tolerance to soil acidity). Similar progress has been made in the few breeding programs operating with winter triticale in northern Europe (e.g. Germany and Poland). Annual world production of triticale (2008–10) averaged 14.6 Mt (FAOSTAT 2013). Some now believe triticale has better PY prospects than wheat (K. Ammar and A. Condon, pers. comm. 2013).

In the late 1980s CIMMYT generated hundreds of new bread wheat varieties by crossing durum wheat (*Triticum turgidum*) with many accessions of the wheat ancestor, *Aegilops tauschii*, repeating the cross that in nature (some thousands of years earlier) gave rise to all current bread wheats (*Triticum aestivum*). These new **synthetic bread wheats**, as they are known, were in turn crossed with many modern bread wheat varieties. Some 25 years later, there is finally clear evidence that some of the progeny have exceeded the PY_w of the best non-synthetic derived control varieties in global tests (Manes et al. 2012). Among other things, this PY_w result can probably be attributed to greater root mass at depth (Lopes and Reynolds 2011).

In rice, a whole suite of transgressive segregants (traits exceeding parental values) for stress resistance and possible yield traits have arisen from crossing distant cultivated rice (*Oryza sativa*) gene bank accessions with modern rice varieties (Ali et al. 2006). CIMMYT recently launched a similar project to identify novel genetic variation in important alleles in its extensive wheat and maize collections.

Crossing involving related species is termed 'wide crossing'. Wild relative species, despite their generally unpromising phenotype, can be useful sources of new genetic variation for yield, as seen particularly in rice and tomato (Swamy and Sarla 2008). Xiao et al. (1998) crossed cultivated rice to its close wild ancestor *Oryza rufipogon* and then crossed to an elite rice hybrid. These authors identified, with the aid of molecular QTL markers, two regions of the *O. rufipogon* genome that caused transgressive segregants to out-yield the elite hybrid parent. This wild introgression (incorporation of a piece of related species chromosome) has subsequently been incorporated into at least one Chinese hybrid 'super rice' variety, now planted in China on an accumulated area of 2 Mha (S. McCouch, pers. comm. 2012). Similarly, for several years, the most popular and highest yielding variety of processing tomato (*Lycopersicon esculentum*) grown in California, USA, came from an interspecific cross. This tomato contained a small piece of the genome of the wild species, *L. pennellii*, which confers improved fruit yield and quality (Eshed and Zamir 1994; D. Zamir, pers. comm. 2012). The physiological bases of all these wide-cross yield increases have generally not been elucidated (Swamy and Sarla 2008).

The main drawbacks to exploiting these more distant but prospective sources of yield genes are time and cost. Thus this research is very much a strategic high-risk task for the public sector, as it is unattractive to the private sector. Modern molecular marker tools can definitely help search for and track novel alleles as they are tested and transferred into useful parental material, a process known as pre-breeding. These materials can then be taken up by breeders for incorporation into new varieties.

It took 20 years for CIMMYT's crosses with *Aegilops tauschii* to produce candidate bread wheat varieties, but the time required was almost halved in the more recent example of rice crossed with its wild ancestor, *O. rufipogon*, because molecular markers could be used.

Molecular markers offer even greater hope for accelerated progress in the selection phase of conventional breeding for yield. Cost per molecular marker data point has fallen dramatically over the past 20 years, and hence these technologies have advanced very rapidly to a point of becoming feasible for all crops (Varshney et al. 2012).

Originally, **marker-aided selection and marker-aided backcrossing** were feasible only for individual qualitative traits that were difficult to characterise phenotypically, but that were also under relatively simple genetic control. The technology began by using flanking markers (molecular tags to one side of, but relatively close to, the target gene), and later moved on towards more and better markers. For example, functional markers (targeting the allele of the gene itself) have now been developed for almost 100 alleles across 30 wheat loci associated with processing quality, agronomic traits and disease resistance (Liu et al. 2012). Many of these markers are now used by breeders in the selection processes.

Marker associations with polygenic or quantitative traits like yield were not considered feasible until the arrival of lower cost markers enabled finer mapping of the genome (based on more markers). This permitted **association mapping across the whole genome**, whereby variation in quantitative traits could be linked to QTLs. Many QTL analyses have now been conducted on wheat and rice populations, and the process has discovered multiple QTLs for traits like PY or PY_w and underlying physiological components. However, since QTL patterns are specific to the parents of the population of the studied progeny, and since individual QTLs for yield generally explain only a small part of yield variation in any population, there has been little uptake of QTLs in breeding. The major QTL for drought performance in rice, mentioned earlier, was an exception because it explained enough variation to be useful in breeding.

New possibilities have opened with the detection of high genomic variability at the level of single nucleotide polymorphisms (SNPs)—that is, when only one of the constituent nucleotides is changed in a DNA sequence—coupled with huge technological advances for inexpensive detection. This technology has permitted use of thousands of SNP markers, densely covering the whole genome of a crop at reasonable cost. Crosbie et al. (2006) predicted that selection based on such marker 'platforms' could deliver faster yield gains in elite maize germplasm. Monsanto went on to verify this in what was then called **marker-aided recurrent selection** (involving thousands of SNPs); the procedure more than doubled rates of gain for yield compared with conventional selection in both maize and soybean (Eathington et al. 2007). Monsanto's claim for a doubling of future maize yield in the USA, referred to earlier, relies partly on accelerated gains anticipated with such molecular marker-aided selection.

The most recent development in molecular markers, **genomic selection** (sometimes also known as genome-wide selection), contrasts with the above marker association techniques because it no longer assumes the user knows which alleles are favourable (or by how much). Genomic selection could be a revolutionary advance in breeding efficiency and warrants some attention here (see Box 9.1).

Box 9.1 Genomic selection and related developments

The theoretical promise and cost feasibility of genomic selection for crop yield improvement is supported in comprehensive reviews from the public sector by Heffner et al. (2009) and Lorenz et al. (2011). Genomic selection uses:

- a high density of molecular markers based on single nucleotide polymorphisms (SNPs) across the whole genome of the many genotypes studied
- new statistical methods for dealing with the resultant multidimensional marker sets
- large computing power.

Although genome selection commonly uses established marker platforms (i.e. markers already linked to aspects of phenotype), this is not a requirement because a technique called genotyping by sequencing can generate the SNP markers needed in the breeding population—even for a complex polyploid genome (like wheat) with multiple (but related) sets of chromosomes (e.g. Poland et al. 2012).

As with association mapping, genomic selection has been driven by the dramatic reduction in the cost of genotyping with such markers—a contrast to the increasing cost of phenotyping for yield, or in other words, growing genotypes in replicated plots in the field. The relationship of markers to yield is determined in smaller training (or calibration) populations that are grown in the target set of environments; it is then used to indirectly select for yield in larger breeding populations at an early generation (for which only marker information is required). The populations must of course be related and the training population must be continually updated to represent the breeding gene pool. Genomic selection may never be as accurate as phenotypic (yield) selection, but the breeding cycle is so shortened that progress is faster for the same annual cost.

Theoretical validation studies of genomic selection on existing populations for which yield (PY or PY_w) data existed and marker data were subsequently generated have been the most promising. Large gains have been achieved in the annual rate of breeding progress (Lorenz et al. 2011), similar to that shown

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by Monsanto under their marker-aided recurrent selection strategy (Eathington et al. 2007). Because genomic selection is so new, few empirical results of observed success exist in the public sector, but those that do appear promising (Lorenz et al. 2011; M. Sorrells, pers. comm. 2012). The large breeding companies are likely to invest heavily in genomic selection, but the extent has not been disclosed. CIMMYT is also beginning to explore the utility for genome selection in both wheat and maize breeding (e.g. Crossa et al. 2010).

As Lorenz et al. (2011) point out, genomic selection is a 'black box' approach to exploiting genotyping technology for yield advance. There need be no knowledge of the underlying components of yield, or consideration of the functional physiological or biochemical relationships of these components to yield (a knowledge area referred to as gene-to-phenotype research). In this respect, genome selection is not so different from the approach of those conventional breeders who place great reliance on yield testing, but it should be considerably more efficient.

Genomic selection therefore contrasts with the strategy of those who believe that yield must be built through understanding and exploiting its underlying key component traits, whether physiological or morphological. Both approaches practice indirect selection for yield in early generation. Genomic selection uses molecular markers, while more traditional breeding uses phenotypic traits. The winning technique will depend on how early the selection can be practised, at what cost, and what is the resulting strength of the relationship with yield—in other words the time and cost to develop an improved-yield variety.

It is too early to say whether genomic selection will supersede the role physiology has often tried to play in indirect yield selection (and in parent selection), or whether new complementarities will emerge involving both approaches, but the latter seems likely. One way this may arise is better understanding genotype-by-environment interaction for yield. Neither genomic selection nor any other molecular marker selection eliminates the need to measure yield in each of the key genotype-by-environment domains. Better crop models to deal with gene- and trait-to-phenotype relations could assist in this regard.

Further, through genome-wide association (GWA) mapping, the research world is beginning to see a melding of the results of high-density, low-cost genotyping on the one hand, and the understanding of gene action, biochemistry and physiology on the other. The genetic architecture of important quantitative traits other than yield—such as flowering time, vitamin A content and leaf angle in maize—has been disaggregated into the action of many small-effect alleles (e.g. F. Tian et al. 2011). Trait prediction based on these alleles is remarkably accurate, while knowledge of the allele sequences can lead to known genes and key enzymes in the controlling pathways (e.g. Chan et al. 2011).

Leading seed companies continue to invest considerable resources in, for example, maize breeding, and appear to be blending conventional breeding and extensive multilocation testing with these new molecular selection techniques. The extent to which association mapping—to identify key genomic regions and candidate genes associated with specific traits—has been overtaken by genomic selection remains unclear. Either way, hundreds of diverse lines of known pedigree are extensively genotyped with SNP markers, and at the same time are evaluated in an array of field environments (providing known abiotic or biotic challenges) to which the breeding companies, especially the multinational ones, have unrivalled access. The identification of key genomic regions offering resistance to important stresses, or linked to increased PY, then leads to either the incorporation of these marked regions directly into elite germplasm, or to the search for more effective alleles in the same region of accessions in the gene bank.

Progress will also depend increasingly on **high quality phenotypic data**, that is, measures of plant traits and (most importantly) field performance, including yield, product quality and disease resistance. Phenotyping capability is expanding much more slowly than the ability to genotype huge arrays of germplasm in the laboratory. Although cost per phenotypic data point is declining much more slowly than cost per genotypic data point, both classes of data are critical to future success in crop improvement.

A lot of investment is going into glasshouse and controlled-environment phenotyping facilities. Such facilities use robotics and automatic sensing of plant images, but the results have yet to be shown to be very relevant to field performance. Yield measurement across target field environments will continue to be critical, and probably needs expanding, with attention to which environments are used and the extent to which environmental stresses are managed. For example, drip irrigation in low-rainfall locations to create managed droughts has proved very useful in breeding for drought tolerance in wheat and maize. Remote sensing in the field brings possibilities of shortcutting the yield selection process, and can even speed yield measurement by enabling quick viewing of large numbers of plants and plots in full electromagnetic spectral detail.

In summary, basic and strategic research in many disciplines continues to deliver new tools for breeders whose business is about assembling the best combination of alleles across the whole genome for performance in the target environment(s). Some of the new molecular techniques outlined here appear to reduce the cost of breeding progress, but it is too soon to say for how long the use of molecular markers can accelerate progress. Faster progress may more quickly exhaust the possibilities of allele recombination in existing populations, thus ultimately slowing progress and drawing attention to the importance of broadening genetic pools referred to initially in this section. However, given the number of genes and alleles present in existing populations, and the seemingly endless ways of recombining them through conventional breeding—plus the possibilities of favourable gene mutation—this exhaustion of genetic variability may continue to be as imperceptible as it has so far been. This point was made with respect to steady barley yield improvement in the

limited gene pool of the Minnesota breeding program (Rasmusson and Phillips 1997), yet barley is a diploid crop with a small genome and presumably fewer possibilities for recombination.

In conclusion, if investment continues to increase in breeding and related R&D (see Section 13.2 on R&D investment), then current absolute rates of PY and PY_w progress—equivalent to 0.5–1.0% p.a. relative to current potentials—should be at least maintained for decades to come, and may even increase somewhat in the short term.

However, as the latest developments in ‘molecular’ breeding unfold, several other challenges face the seed industry (Miller et al. 2010). One is the training of breeders with the breadth of skills in quantitative genetics, plant molecular biology and classical breeding needed to efficiently apply the new tools (Fridman and Zamir 2012). Another, which is picked up in the next section, refers to institutional arrangements and the respective roles of the private and public sectors in future breeding, especially for those crops in situations that are currently unattractive to private breeders.

9.11 Intellectual property, breeding privatisation and transgenic regulation

Intellectual property (IP) rights and trade secrets are considered constraints to the widespread use of molecular breeding techniques, yet it is these constructs that offer the protection that has driven the large jump in **private investment in crop breeding** in the past 20 years (see Section 13.2). IP protection over varieties (plant variety rights and patents), coupled with use of hybrids (where farmers and companies benefit from annual purchase of seeds), provides a powerful incentive for investment in crop improvement. This mutual benefit probably explains the greater breeding progress seen in maize and canola compared with rice or wheat (Table 9.1).

IP has inevitably driven industry consolidation, because there are advantages in breeding on a global scale. This was seen initially in the breeding programs of the international centres of CGIAR (known at that time as the Consultative Group on International Agricultural Research)—for example, CIMMYT, IRRI and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)—and currently is evident in the global operations of multinationals like Monsanto, Pioneer (Dupont), Syngenta and Bayer. At the same time, in order to satisfy the needs of national or niche markets, viable business models for crops of interest can be generated by research alliances between the multinationals and:

- small-to-medium enterprises (SMEs), such as small- to medium-size local seed enterprises

- national public breeding programs
- CGIAR centres.

Some of these alliances are public–private partnerships (e.g. WEMA and IMAS mentioned earlier) where patented technologies are made available royalty-free to maize farmers of lower socioeconomic status, presumably with a valid aim of encouraging viable seed markets in the long term.

For crops in which the private sector is not currently involved, sharing of molecular breeding technology is another opportunity for public–private alliances. These so-called ‘orphan crops’ are often important for food security in developing countries, are ripe for the application of these technologies, and are the target of breeding efforts in national and CGIAR public institutions whose efforts are generally underfunded and under-resourced for achieving maximum progress (Varshney et al. 2012).

A broader issue is whether the rapidly consolidating private seed industry retains a healthy degree of competition and an efficient level of technology sharing. Monopoly privileges that accelerate invention but lead to rent-seeking (i.e. the manipulation of the business environment for undeserved economic gain) are a risk of the modern capitalist economy, and conditions exist for natural monopolies with IP rights in plant breeding, regardless of disclosures with patenting. For example, Monsanto alone, through its own varieties and through cross-licensing to others, owns ~90% of the patented GE ‘trait-acres’ of maize, soybean and cotton in the USA—that is, each trait weighted by the area planted to that trait (Fuglie et al. 2012a). Moreover, inefficiencies can also arise through the duplication of effort that occurs from wasteful lack of knowledge sharing, and excessive promotional and legal costs (Gray 2011; Alston et al. 2012). Normally monopoly is controlled through the promulgation and application of antitrust laws, and wasteful costs kept down through competition. It is therefore not clear why seed costs have risen so sharply in North America in the past decade. In 2010, seed prices reached US\$185/ha for maize, US\$128/ha for soybean and US\$114/ha for canola. According to Gray (2011), these figures exceeded private seed company R&D costs by a factor of almost 10, and seed production costs by even more.

As pointed out by Alston et al. (2012), there are other options to the privatisation of breeding: the best may be government-facilitated levy-funded breeding, as already occurs with pulse breeding in Australia and western Canada. However, Wilson and Dahl (2010) argue that in the USA—where the private seed industry is most evident—industry concentration is now stable and not excessive, with the top four companies handling ~70% of seed sales in maize and soybean. Thus farmers have a greater choice of crop varieties, although the cross-licensing of Monsanto traits to other breeders (mentioned above) reduces choice more than is apparent at the variety level (see also Section 13.2).

The public sector is generally no longer in a position to compete in the case of crops where breeding has been privatised (e.g. maize and soybean in the USA, and wheat in Australia and Europe). Public activity has thus been relegated to more strategic

breeding research, delivering techniques and products of pre-breeding to private companies, a process that can suffer if it is separated from and out of touch with the breeding itself (as can the training of future breeders, which also sits largely in the public sector). A greater degree of openness and sharing between the sectors seems desirable. Moreover, independent variety testing and analysis is a valuable role for the public sector, as is seen for example in the operations of the Home Grown Cereal Authority of the UK (see Section 3.8 on wheat in the UK).

How these relationships evolve in the developing world is of particular importance for the efficient delivery of improved varieties that carry all the benefits of 'molecular' breeding. The delivery of **GE varieties** is an especially expensive activity. Molecular transformation techniques may have become relatively cheap now, but associated expensive undertakings include:

- the search for appropriate candidate genes and transformants that function as predicted
- IP agreements
- regulatory compliance
- commercialisation.

The latest survey of the six largest biotechnology crop firms found that the average cost of a new plant trait delivered through GE over 2008–12 was US\$136m, and the average time from initiation to commercial launch was 13.1 years (CropLife International 2011); 26% of the costs were in regulatory testing and registration. Even so, more candidate genes are being tested than ever before (which may explain part of the seed cost increase mentioned above).

Although some molecular techniques may be becoming more efficient, high costs exclude most public institutions in both developing and developed countries from producing transgenic varieties; this includes CGIAR centres as well as most SMEs. Welcome signs of corporate social responsibility and public–private collaboration are exemplified by the agreements to waive IP restrictions on the use of technologies associated with high pro-vitamin A 'golden rice', and with the recent WEMA and IMAS projects that connect Monsanto and Pioneer, respectively, to CIMMYT and African organisations. In the public–private partnership associated with delivering 'golden rice' to farmers of lower socioeconomic status, regulatory hurdles dominated all other costs and caused the greatest delay (I. Potrykus, pers. comm. 2010). Moreover, indirect exclusion of the public sector from production of GE varieties (at least in the developed world) has undoubtedly heightened public concern about GE and facilitated distrust of claimed benefits, propagated fear of potential risks, and increased the perception of undesirable monopoly ownership.

Reflecting societal unease with GE technology, regulatory compliance costs surrounding GE have increased greatly in recent years. Regulation is especially concentrated in the European Union, where objections relate to health, environment and monopoly risks. However, 16 years of experience with GE crops (170 Mha planted

globally in 2012; James 2012) has produced no scientific evidence to support either of the first two risks and, in the light of this, the regulatory barriers against GE crops are now excessive—a point strongly argued for by scientists even in Europe (e.g. Fagerström et al. 2012).

The regulations are looking even more arcane as research moves inexorably towards molecular techniques, which are often not dependent on antibiotic-resistance markers or other foreign genes—cisgenesis—and/or are less disruptive and more targeted in terms of gene insertion or gene activity change (Lusser et al. 2011). As such, GE can now be less disruptive at the genome level than traditional and widely accepted techniques like mutation breeding or wide crossing. Furthermore, reduced regulatory costs would facilitate more breeders and competition in seed markets and could lower the worrying dominance by a few multinationals.

Although the efficient operation of totally private research, development and markets for seed may be of some concern, the final points here are that GE traits need to be considered on their individual scientific merits. They do not need a private breeding industry to operate and they undoubtedly have great potential to help in many areas. The world's governments must not unnecessarily constrain GE and what it reasonably has to offer for genetic improvement, since it is clear that breeders need access to all the possible tools to meet future food production goals. After 16 years of experience with transgenics, the precautionary principle needs to be relaxed to foster innovation and cost saving by a much broader array of players than is currently engaged in GE research and development. In this endeavour it would not be surprising if the developing world—for example, China, India and Brazil—took the lead, since the potential advantages loom large for these countries. For China and India in particular, all possible options need to be explored to ensure food security.

Therefore, it is reasonable to assume that while GE technology will still be monitored in 2050, it will be cheaper and far more widely available. GE should, by then, undoubtedly be continuing to help close the yield gap and further reduce the use of biocides, and may also be directly increasing PY and PY_w in the staple food crops (although the latter seems unlikely before 2030).

9.12 Concluding comments—new technologies towards 2050

Prophecy is an uncertain business, but it seems evident that the critical need for global food security is the accelerated progress in FY of staples from ~1% p.a. to 1.1% p.a., or better (say 1.2–1.3% p.a.). PY increase through breeding, and breeding interactions with new agronomy, will contribute to part of the FY increase; closing of the gap between FY and PY forms the other part of the solution.

Currently, however, annual PY increase is only about 0.5–0.8% p.a. for the staples (with maize slightly higher at 1.1% p.a.), and although PY increase has been slowing over the past 20 years relative to earlier periods, it has not yet ceased anywhere. Note that slowing of PY progress is independent of any climate change; effects of climate change have been avoided by the means used here to measure PY progress, and in any case, up until now climate change has exerted (at most) only a small influence on crop yields (see Chapter 10 on climate change). In the light of the discussions in this chapter, it can be seen that chances of accelerating PY progress are limited, or at best, very speculative.

Dissection of the key crop physiological determinants of PY (ΣPAR_i , RUE and HI) and PY_w (transpiration, TE and HI) into underlying physiological processes appears to have identified some limited headroom for further increases, although understanding is admittedly incomplete. New agronomic technologies also appear scarce. Besides, just as several others—Sinclair and Purcell (2005), Struik et al. (2007) and Hall and Richards (2013)—have done, this chapter points to:

- difficulty in improving pivotal processes such as P_{max} or water uptake by roots
- susceptibility of GN to effects of water stress at flowering
- likelihood of trade-offs with any trait modification (both recognised and/or unanticipated).

The prospect for the future of PY and PY_w progress is more likely to be maintenance of current rates of gain using a combination of conventional and new breeding tools, but with increasing difficulty. The following areas for **increased research investment** are highlighted as opportunities to better achieve PY and PY_w goals, and these are briefly summarised in more detail below:

- increasing rate of photosynthesis
- root systems and water stress tolerance
- molecular selection technologies
- pest and disease resistance
- hybrid vigour
- agronomic innovations
- policy implications for R&D.

Increasing rate of crop photosynthesis is a key research goal. Reputed gains in P_{max} in modern varieties will initially need to be confirmed and better understood, before further variation is sought within crop species and relatives. A longer term focus should be on GE modifications for increasing efficiency of net photosynthesis (P_{net}) in higher CO_2 and warmer environments by modifying Rubisco, Rubisco activase, RuBP supply and the enzymes that lead to photorespiration in C_3 plants.

In the even longer term, some attention should be focused on exploring the conversion of rice to C_4 photosynthesis—a prospect that could also deliver spin-off gains for less-

challenging modifications of photosynthesis—but to rely on this avenue to lift PY in the medium term (20 years) would be unwise. Since crop plants have finely balanced source–sink relations (Denison 2007), any change in source (photosynthesis) may take several decades of adaptive breeding and sink improvement to deliver full benefits as grain yield (Hall and Richards 2013).

For PY_w in particular, **deeper root systems** for more water capture and **tolerance to low plant water** status around flowering demand more attention. Improved TE may be difficult because of apparent trade-offs with photosynthesis under natural genetic variation, but some mooted GE changes to photosynthesis could be win–win (i.e. greater P_{max} and greater TE seem possible). Genetic variation in stomatal sensitivity to high vpd is a relevant field of study that is gathering momentum.

Molecular selection technologies focused on increasing PY and PY_w based on low-cost sequencing and markers (like genomic selection) seem to offer a major breakthrough for accelerating progress with such quantitative traits. This approach will involve ongoing genotyping with appropriate molecular markers of a diverse but representative array of rice, wheat and maize genotypes in appropriate breeding populations. It must also be linked with high-throughput, precise phenotyping using managed input levels in field production environments that represent the major environment types faced by farmers. Genomic selection can then be used to exploit useful variation wherever it is found in the genome. The relevance of specially built indoor phenotyping facilities to field performance still needs to be established.

Shared access to **well-annotated genomic data in a global database** will encourage further data mining, provided that IP rights are not excessive, but can still be honoured and preserved.

GE may have a limited direct role in breeding for PY and PY_w , but a major role in protecting breeding progress through **pest and disease resistance**—and likewise in increasing resistance to some specific abiotic stresses. Indirectly this could free up breeding resources for greater focus on yield.

Hybrid vigour in wheat and rice modestly boosts yield and brings a degree of tolerance to water shortage (thus probably benefiting PY_w more than PY). Eliminating or circumventing natural barriers to outcrossing, so as to facilitate hybrid seed production in these crops, would overcome the main obstacle to greater use of hybrids.

Agronomic innovations can neither be overlooked nor fully anticipated. While emphasising the gaps in knowledge, especially regarding soil processes and crop yield, opportunities for new agronomy can arise from ‘left field’—engineering, remote sensing, robotics, meteorology, materials science, and not the least, genetics.

A suitable **policy framework** is needed to sustain public research and development, to attract private investment, and to efficiently develop technology and guide its benefits to those most in need. This should include the following considerations:

- Much of what is called for here implies more public sector research and development; the importance of this in driving innovation is covered in Section 13.2. Public research is the source of higher risk basic and strategic research (e.g. pre-breeding), and also covers important fields mentioned above where market failure precludes the private sector.
- A strong emphasis is needed on IP protection for molecular and varietal products, and on F_1 hybrid production in maize, wheat and rice. But this emphasis requires vigilance against abuse of the natural monopoly on traits and techniques that this creates.
- GE can greatly increase the tools at the breeder's disposal and the supply of useful traits for farmers and consumers alike, although this may not include yield for some time. However, regulations have become excessive and associated costs inhibit the wider use of GE. Special efforts are needed to win wider societal acceptance of GE food products, in the light of their manifest safety and benefits for the environment.
- Win-win social contracts that see technology outcomes shared with resource-poor countries are needed. International research in agriculture, by both private and public sectors, is the key component of efficient and effective research, along with strong national agricultural research systems in larger countries and strong national breeding companies. In this context, there are obvious benefits to strengthening the CGIAR system to enable strong international partnering with (and counterbalance to) the booming transnational commercial activities in breeding. In addition, and as has been achieved over the past 40 years, a strengthening CGIAR system will continue to provide knowledge and strategies for breeding of neglected crops, improved crop agronomy and better rural socioeconomic outcomes.



Climate change, crop yield, adaptation and mitigation

10



Key points

- Climate change is slow, uncertain and geographically heterogeneous. For this reason, this chapter considers only those effects associated with warming and increases in concentrations of carbon dioxide (CO₂) and ozone. Crop weather records of the past 20–30 years reveal widespread evidence of warming.
- Inter-annual crop yield deviations often show a negative relationship to inter-annual variations in growing-season mean temperature (T_{mean}). For cereals, yield sensitivity is around –2% to –5% per °C warming, but this includes the response to any other weather parameters that vary in association with T_{mean} . Measurements and crop simulation modelling suggest cereal yield responses to growing-season T_{mean} alone range from –4% to –7% per °C increase in temperature.
- Chronic warming reduces yield largely by hastening crop development, although shorter hot spells can also exert negative effects on seed number and grain size. CO₂ rise currently benefits yields of C₃ crops (such as wheat) by ~0.2% p.a. but has little effect on the yields of C₄ crops (such as maize). Ozone levels are high enough to reduce crop yields in densely populated industrial areas, but ozone concentrations are generally expected to decline (except in some developing countries).
- Overall, without adaptation and relative to 2000, it is estimated that the 2050 combined yield effects from +2 °C warming and +100 parts per million (ppm) increase in CO₂ (or a rise of +26%) for C₃ crops such as wheat, rice and soybean will be close to zero, but about –8% for C₄ crops such as maize.
- Plant breeding and crop agronomy offer considerable scope for adaptation to warming. Because research into these areas is already ongoing, special pre-emptive research on adaptation to climate change is hardly warranted. An exception is perhaps in the area of tolerance to heat, but otherwise, current research agendas are adequate if fully supported.
- Cropping continues to substantially contribute to global warming through nitrous oxide (N₂O) emissions—especially from nitrogen fertilisers and manures applied to soils—and through methane from flooded rice. Mitigation will be difficult, but efficient use of fertiliser will help reduce N₂O emissions.
- Cropping can also cause net changes in soil organic carbon, and hence net CO₂ emissions. Deliberate sequestration of carbon in cropping soils will be difficult and expensive, but crop yield increase, which lessens the need to clear new land, will prevent substantial soil carbon emissions.

Climate change, crop yield, adaptation and mitigation

10.1 Introduction to cropping under climate change

Climate change is clearly important for crop yield prospects. While it is widely accepted that greenhouse gases are inducing climate change with possible negative implications for crop yield (IPCC 2007; World Bank 2012c), it is important that crop scientists continue to observe caution with several features of predicted climate change.

First, while there is relative certainty in predictions of higher concentrations of carbon dioxide (CO₂), increased temperature, greater frequency of temperature extremes and rising sea levels, the rates of these changes will be slow and uncertain. Second, predicted changes in precipitation (positive or negative) remain especially unreliable, differing widely between geographic regions, and again, will occur only slowly. Third, the predicted changes to 2050 in both temperature and precipitation are small relative to inter-annual variability.

It can be argued that every time an annual crop is grown or a field experiment is run, farmers, plant breeders and agronomists are adapting to climate change. Moreover, inter-annual variations in weather are so great that a good proportion (>25%) of years already match the warmer average climates predicted to arise in a few decades; these years can be identified as reliably as future climates can be predicted, and serve as early tests of adaptation strategies. For example, Peltonen-Sainio et al. (2011) used such an approach to look at Finnish crop yields under projected 2025 weather, taken as the hottest years from 1976 to 2007.

On the theme of existing adaptation, it is evident that crop species already contain substantial thermal adaptation because individual crops are successfully grown over wide ranges of temperature. Hence there is a need to be cautious about investing in

unique, pre-emptive 'climate change' research, not only because of the uncertainties surrounding climate change and the challenges of artificially creating future climates for testing purposes, but also because greater investment in ongoing 'conventional' research will itself improve adaptation to future climates. Over the next few decades, when the biggest pressures will fall on food supplies, the greatest protection against negative effects of climate change will be skilful, profitable farmers supported by plant breeding and agronomic research, combined with better rural services and policies (Asseng and Pannell 2013).

The surge of climate change related research publications seen in the past decade suggests a distortion of allocated funding away from essential 'conventional' research. In fact the trend parallels declines in productivity growth that have arisen in the wake of previous diversion of production research funds towards issues of environment and health in agriculture (Section 12.4 on total factor productivity trends). This trend would not be so problematic if truly new lines of crop research could present solutions to climate change, but excepting the area of emission mitigation, this seem to be unlikely. As pointed out by Rötter et al. (2011) and Semenov et al. (2012), the burgeoning interest in climate change has attracted many newcomers to crop yield modelling. Unfortunately these new modellers appear less cautious in applying the models than do the crop scientists who built them and who better understand their limitations.

Because of this flood of recent research publications, this chapter provides a necessarily limited overview of progress in climate change research and its implications for crop yield increase in the next 40 years. This chapter focuses on the crop yield effects of increases in temperature, CO₂ and ozone. Possible changes in precipitation are not considered in this chapter because the predicted changes are too uncertain and relatively small, and because few changes have appeared in the climate record so far. Some exceptions include rainfall decline in Western Australia (Section 3.5 on wheat) and India (Auffhammer et al. 2012; see below), and rainfall increase in Argentina (Section 6.3 on soybean). These changes all arose quite suddenly and largely before 1980, and hence before the past 20–30 years (the period of interest in this book). Overall there has been no net change in global precipitation in cropping regions since 1980 (Lobell et al. 2011b; see below).

Reduction in solar radiation—otherwise known as dimming—has also been mentioned as another component of climate change; this has arisen, for example, in densely populated Asia due to aerosol pollution (e.g. Auffhammer et al. 2012). However, dimming itself is not seen here as a serious threat to crop yield. This is because small reductions in total incident solar radiation will likely be compensated by increased radiation use efficiency (RUE) that will result from the increased proportion of diffuse radiation with aerosol pollution (Sinclair and Muchow 1999; see Section 2.6). Besides, away from Asia, most recent solar radiation trends have indicated reduced dimming (Wild et al. 2009).

The Intergovernmental Panel on Climate Change (IPCC 2007) indicates that global temperature is currently rising at a rate of 0.2 °C per decade. Popular talk of a plateau in

warming over the past decade is dispelled by thorough analysis of 1979–2010 surface air temperatures. After correcting for the effects of El Niño, volcanic aerosols events and the solar cycle, the current average global rate of anthropogenic warming was 0.17 °C per decade; the Northern Hemisphere rate was ~0.1 °C per decade higher than the Southern Hemisphere one (Foster and Rahmstorf 2011). Moreover, given growing rates of CO₂ emission, it is estimated that the rate of increase to 2050 will accelerate to 0.4 °C per decade (IPCC 2007), which is indicative of a 2 °C increase in average global temperature by 2050 (relative to 2000). The numbers refer to mean air temperature (T_{mean}), which in crop research is defined as the average of the daily maximum (T_{max}) and minimum (T_{min}) temperatures (see Section 2.6). The IPCC (2007) also points out that T_{min} is increasing more rapidly than T_{max} and thus decreasing the diurnal temperature range ($T_{\text{max}} - T_{\text{min}}$). Generally it is predicted that relative humidity will not change with global warming, which implies increases to vapour pressure deficit (vpd) (Lobell et al. 2013a).

Atmospheric CO₂ concentration is monitored at a global reference position high on the mountain of Mauna Loa in Hawaii, where the rate of increase was 2 parts per million (ppm) per year over the first decade of this century (NOAA 2013). Measurements of ambient CO₂ above crop canopies around the world show values linked to, but some 20 ppm lower than, at Mauna Loa. By extrapolating from the 2000 Mauna Loa level of 380 ppm, and using a middle estimate of likely future emissions (IPCC 2007), it is estimated CO₂ will reach 480 ppm (+26%) by 2050.

This chapter also considers increased ozone levels, a corollary anthropogenic effect on the Earth's atmosphere, but one having a more irregular distribution in time and space than CO₂ increase.

In the final parts of the chapter, adaptation options to protect crop yield from the negative effects of climate change are considered, along with opportunities to mitigate greenhouse gas emissions from cropping.

10.2 What time series tell us about climate change

Weather records over recent decades indicate that the global climate is changing. Inter-annual changes in weather have been associated with changes in crop yields.

Evidence for climate change in recent weather records

The IPCC (2007) reports that, between the 1950s and the 2000s, global average (terrestrial) temperatures have increased by ~0.13 °C per decade, with greater warming

at higher latitudes. Earlier commodity chapters of this book already noted several significant trends of increasing temperature over the past 20–30 years, including for:

- the wheat season in Denmark, Finland, northern China and the Indian state of Punjab (Sections 3.3 and 3.6)
- spring temperatures in parts of North America (Sections 3.6, 3.9, 5.2 and 6.2)
- the maize and soybean season in northern China (Section 5.3 and 6.4).

Only one clear trend of decreasing temperatures was observed— T_{\min} in the wheat season in the Yaqui Valley, Mexico (see Section 3.2). There were few significant radiation trends, although one example is the reduced radiation seen in the wheat and rice seasons in parts of the Indo-Gangetic Plain (see Sections 3.3 and 4.4). Some additional reports are now mentioned briefly.

Asseng et al. (2011) focused on both mean and extreme temperatures during the 2-month period of grain-filling for wheat in Australia and other major wheat-growing regions of the world. Over the past 30–50 years, these authors found widespread warming, with T_{mean} over the grain-filling period increasing by 0.26–0.63 °C per decade across locations. Perhaps more important is the number of hot days ($T_{\text{max}} > 34$ °C), which were also reported to have increased by 0.1–2.0 days per grain-filling period per decade.

Looking at trends across 20–25 years to 2004 for the rice cycle at seven major sites in Asia,⁴⁷ Welch et al. (2010) found that T_{\min} rose at all sites by an average of 0.3 °C per decade, except in southern Vietnam where there was a decrease of 0.2 °C. Meanwhile, T_{max} at all sites was found to have risen by an average of 0.15 °C per decade, except in southern Vietnam where it rose by 0.3 °C. Solar radiation fell at all sites by an average of 2.8% per decade, except in Tamil Nadu (India) where it increased by 1.8%. Auffhammer et al. (2012) reported that in the nine predominantly rainfed rice states of India, T_{\min} for the grain-filling months of October–November rose at 0.25 °C per decade between 1961 and 2002.

Peng et al. (2004) had earlier reported T_{\min} to have risen at 0.5 °C per decade since 1979 at the International Rice Research Institute (IRRI) in the Philippines. Further north in China, Tao et al. (2008) found significant increases in both T_{\min} and T_{max} , averaging about 0.5 °C per decade across provinces for the wheat, maize and soybean growing seasons during 1980–2003. However, these authors reported increased T_{\min} for the rice season to be only 0.15 °C and not significant for T_{max} .

Targeting all major crops and cropping areas in the world, Lobell et al. (2011b) comprehensively studied changes in temperature and precipitation (1980–2008) at high spatial resolution. These authors examined values adjusted to the growing seasons

47 Locations in the province of Zhejiang (China), Red River Delta (northern Vietnam), island of Luzon (Philippines), Central Plain (Thailand), state of Tamil Nadu (India), Mekong Delta (southern Vietnam) and Sukamandi (Indonesia)

for wheat, rice, maize and soybean. Trends in growing-season T_{mean} clearly indicated warming in most places, although in the Mid West of the USA, growing-season T_{mean} for maize and soybean fell slightly; the Mid West temperature decline was also reported by Twine and Kucharik (2009). Importantly, Lobell et al. (2011b) observed that the median of global precipitation trends was close to zero.

Taken together, these studies confirm that climate trends (at least for temperature) have generally supported the direction predicted for future climate change. However, two important points emerge from these studies:

1. relative to historical inter-annual variation, temperature changes are occurring only slowly
2. rates of temperature change vary considerably among geographical locations.

Associating inter-annual changes in crop yield and weather

Many attempts have been made to understand the effects of climate change on crop yield. Most commonly, these effects are examined by an empirical regression analyses (sometimes called a statistical approach) in which associations are sought between the dependent variable (yield) and climate-related variables, which may or may not show a trend across years. Such studies require caution at every step (Sheehy et al. 2006b; Lobell 2010; Lobell and Burke 2010a; Semenov et al. 2012), especially so where simulated (rather than observed) yield values are used. However, after removing any influence arising from technology trends (usually assumed to be linear with time), and any influence from location, the relationship between weather deviations from trend (often known as anomalies) and recent crop yield deviations can be usefully explored (see Box 10.1).

Several regression studies are discussed briefly in Box 10.1 and below, and where possible the results are summarised in Table 10.1. Note that Table 10.1 shows relationships between farm yield (FY; see Chapter 2 on definitions) and temperature derived from time series or panel data (time series pooled across locations), but does not necessarily imply a temperature trend with time. Yield responses in Table 10.1 are not subject to direct effects of change in CO_2 because linear trends in yield across years were always removed.

The remainder of this section discusses in detail the results summarised in Table 10.1. The first item listed under each of the four commodities in Table 10.1 provides a global summary for the relationship between temperature and yield for each crop. These global studies across various crops (Lobell 2007; Lobell and Field 2007; Lobell et al. 2011b) reflect increasingly refined analyses of the data available.

Box 10.1 Exploring empirical regression and modelling approaches to weather and yield variation

The **first difference method** is the simplest empirical regression approach to an annual time series of yield against, say, mean growing-season temperature; this method is used in Section 3.2. The method requires yield differences between adjacent years to be regressed against the temperature differences, and these differences are obtained by subtracting the value for 'year n ' from that for 'year ($n + 1$)'. The slope is the sensitivity of yield to temperature, which can be expressed as absolute yield or percentage yield change per °C increase in temperature. As cautioned by Sheehy et al. (2006b), note that each estimate is dependent on the underlying mathematical model chosen and the mean temperature within the range of temperatures studied. When multiplicative models are used—for example, log yield vs. log temperature (see You et al. 2009b)—matters become even more complicated, and probably biologically inappropriate; yet economists often take this approach.

There have been several attempts to investigate whether statistical relationships agreed with knowledge about crop function. Sheehy et al. (2006a) and Lobell and Ortiz-Monasterio (2007) did this with relatively simple local time series of time trend – uncorrected rice and wheat yields, respectively. At Los Baños in the Philippines over the 1992–2003 dry seasons, the strong negative empirical relationship between rice yield and T_{\min} (–10.0% per °C; Peng et al. 2004) was similarly predicted by two physiological rice yield models. This result is not listed in Table 10.1 since it was shown that **the statistical temperature sensitivity was biased by a negative relationship between T_{\min} and solar radiation**. Rather, a better estimate of temperature sensitivity (at constant radiation) is given by the simulation models (Sheehy et al. 2006a) shown in Table 10.3.

Lobell and Ortiz-Monasterio (2007) conducted similar analyses of irrigated wheat yields over 16–24 years at three locations in central-western North America. The empirical regressions indicated sensitivities to T_{\min} , T_{\max} and solar radiation, which varied with location but were generally confirmed by the CERES-Wheat model. **Furthermore an empirical multiple regression (with all three weather variables) gave sensitivities to T_{\min} and T_{\max} changes that mostly matched the simulation model sensitivities**. However, at one location the empirically estimated yield sensitivity to T_{\min} was again biased upwards because of a negative relationship between T_{\min} and solar radiation, reaffirming the caution needed because empirical results can be affected by subtle differences in the relationships among key weather variables, most of which are omitted from the simple regression. Similarly, CERES-Wheat modelling revealed another area of uncertainty: a major effect of the diurnal temperature range at a given T_{mean} .

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(Lobell and Ortiz-Monasterio 2007). See also Tables 10.1 and 10.3 for results from Lobell and Ortiz-Monasterio.

Across 40 years and 198 sites in Sub-Saharan Africa, Lobell and Burke (2010a) tested three common statistical approaches for relating yield to growing-season T_{mean} and rainfall (but the latter is not discussed here). The yardstick for crop function was a 'true' maize yield, derived from a process-based simulation model (CERES-Maize) using 40 years of daily weather data (also simulated) and information on soil water-holding capacity at each site. The statistical approaches comprised a **time series model** (198 temperature coefficients), a **panel model** (a single pooled temperature coefficient, corrected for location effect) and a **cross-section model** (a temperature coefficient derived from across location differences). Each model was fitted to the 'true' yields, and then responses of yield to an increase in temperature of 2 °C derived from the statistical models were compared with those derived from the crop simulation model. Temperature response coefficients were comparable, enabling those authors to affirm the usefulness of all the statistical approaches, especially at broader spatial scales. Their simulation results on yield sensitivity to an increase in temperature of 2 °C are presented in Table 10.3.

Maltais-Landry and Lobell (2012) later completed a thorough and complex study of yields over time (1984–2008) for six key maize and six key wheat counties across the USA. They used, for the statistical approach, a time series in which (for each county) observed average yield anomalies (also known as residuals, as they are deviations from the linear yield vs. time trend line) were fitted in a **multiple regression** to anomalies in growing-season real county or district weather (T_{mean} , rainfall and radiation, similarly de-trended with respect to year). The resultant weather sensitivities were compared with weather-driven yield sensitivities derived from crop simulation modelling (using CERES-Maize and CERES-Wheat and observed daily county weather). Response coefficients derived from the two methods were not nearly as well matched as in Lobell and Burke (2010a), above, as the statistical approach showed yield sensitivities to temperature that were about one-half of those derived from simulation modelling. For maize the statistical sensitivity averaged -0.35 t/ha/°C and the simulated one -0.70 t/ha/°C; for wheat the values were -0.13 t/ha/°C and -0.35 t/ha/°C, respectively. Moreover, errors were high for the statistical temperature coefficients and the outcome depended on the period used in the analysis (shorter periods than the whole 25 years were also tested). The authors concluded that the discrepancies were due to errors in the simulation models and possible collinearity in weather variables. These results surely also urge caution when estimating weather-related yield responses, and suggest multiple approaches should be used as has been adopted here. The results of Maltais-Landry and Lobell (2012) are not recorded in Tables 10.1 and 10.3 because of unclear statistical significance. Greater detail on modelling approaches to weather and yield variation can be found in Lobell (2010).

Table 10.1 Crops and regions showing the slope of relationship between annual deviations or anomalies in farm yield (FY) and those in growing-season temperature,^a derived from empirical regression approaches applied to data of the past 20–30 years

Region ^a	Slope, per cent change in FY per °C increase (%/°C) ^{b,c}	Notes ^d	Source
Wheat (n = 23)			
World	-5.4	Slope more negative for T _{min}	Lobell and Field (2007) table 1
World	-5.5	Trial yields (not FY); sensitivity greater at higher temperatures	Gourdji et al. (2013)
United Kingdom, France	-8.0, -7.2	–	Lobell (2007) figure 2
Germany	-1.6		
India, Pakistan	-3.8, -3.0		
China, USA	ns, ns		
France, USA	-3.2, -4.5	–	
India	-7.7		Lobell et al. (2011b) figure S7
China	ns		
Yaqui Valley (Mexico)	-10.4	Local multiple regression with T _{min} , T _{max} and solar radiation	Lobell and Ortiz-Monasterio (2007) table 8, scenario ΔT _{min} = ΔT _{max} = 1 °C
San Luis-Mexicali (Mexico)	-9.1		
Imperial Valley (California, USA)	-6.6		
China	-3.5	Calculated at T _{mean} = 13.5 °C; sensitivity decreased as T _{mean} increased	You et al. (2009b)
Northern Europe	-0.6 to -1.3	Spring wheat only	Peltonen-Sainio et al. (2010)
Finland	-2.0 to -4.0	–	Peltonen-Sainio et al. (2011)
Yaqui Valley (Mexico)	-6.7	T _{min} only	This book, Section 3.2
Punjab, India	-3.3	T _{min} only	This book, Section 3.3

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Table 10.1 Continued

Region ^a	Slope, per cent change in FY per °C increase (%/°C) ^{b,c}	Notes ^d	Source
Rice (n = 16)			
World	ns	–	Lobell and Field (2007) table 1
Vietnam, Bangladesh	–3.3, –3.3	–	Lobell (2007) figure 2
Indonesia, India	–2.0		
India	–12.1		
Japan	+3.4		
China	ns		
India	–7.4	–	Lobell et al. (2011b) figure S7
Vietnam, Bangladesh	ns, ns		
Indonesia, India	ns, ns		
North-eastern China	+7.0, +2.0	$T_{min}; T_{max}$	Tao et al. (2008)
Rest of China	ns	–	
India (rainfed)	–4.8	T_{min} Oct.–Nov.; slope for $T_{min} = 20$ °C	Auffhammer et al. (2012)
Maize (n = 18)			
World	–8.3	Slope more negative for T_{max}	Lobell and Field (2007) table 1
USA, Argentina, Brazil	–8.3, –8.8, –6.9	–	Lobell (2007) figure 2
China, France	ns, ns		
USA, Brazil, China	–4.0, –5.0, –5.9	–	Lobell et al. (2011b) figure S7
France	ns		
Eastern USA	–3.7 to –7.6	Method dependent	Lobell (2010) table 5.1
Eastern USA	ns ($T_{max} < 29$ °C), –23 ($T_{max} > 29$ °C)	Greater if $T_{max} > 29$ °C	Schlenker and Roberts (2009)
Sub-Saharan Africa (well watered)	+9 to –40	T_{mean} 15–28 °C; used trial yields, not FY	Lobell et al. (2011a) figure 2b
Sub-Saharan Africa (droughted)	–7 to –43	T_{mean} 16–26 °C; used trial yields, not FY	

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Table 10.1 Continued

Region ^a	Slope, per cent change in FY per °C increase (%/°C) ^{b,c}	Notes ^d	Source
Soybean (n = 7)			
World	-1.3	0.05 < P < 0.10	Lobell and Field (2007) table 1
USA, China, Brazil, Argentina	ns, ns, ns, ns	All negative (-1.5 to -3.5) but large errors	Lobell et al. (2011b) figure S7
Eastern USA, or > 32 °C	ns (T _{max} < 32 °C), -22 (T _{max} > 32 °C)	Greater if T _{max} > 32 °C	Schlenker and Roberts (2009)

- a Sources are arranged so that global studies are listed first (with countries grouped according to similar sensitivities), followed by more focused studies in chronological order.
- b This refers to the percentage change in yield per degree increase in growing-season T_{mean} unless commented on otherwise in the 'important notes' column (for example, sometimes T_{min} or T_{max} is the independent variate, or sometimes hours of air temperature above a set threshold); all slope values significant P < 0.05, except ns when slope is not significantly different from zero (P > 0.05).
- c Multiple figures are shown for each of multiple studies.
- d See text for full explanation.
 – = no relevant notes; n = number of studies

The first **global study**, using the first difference method, related yearly anomalies in world average yield for various commodities during 1961–2002 to those in temperature and precipitation, spatially averaged for the various commodity regions and appropriate growing seasons (Lobell and Field 2007). Statistically significant relationships to T_{mean} (all negative) were observed for wheat, maize, barley and sorghum, but the relationship was weak for soybean and not significant for rice (Table 10.1). Wheat yield was more sensitive to anomalies in T_{min}, and maize to anomalies in T_{max}.

Again using the first difference method, Lobell (2007) continued research into temperature and yield relationships by considering wheat, rice and maize in individual countries. Significant negative relationships were identified for each of the three crops in some countries (Table 10.1) but not others—for example, an insignificant relationship for wheat in the USA, and for all three crops in China. The high negative sensitivity for rice in India may reflect the large proportion of rainfed rice there, the yield of which may be more sensitive to temperature. Of note was the positive relationship for rice in Japan, reported as an increase of 3.4% in FY per °C increase in temperature, which is plausible given that Japan has the coolest rice growing season (T_{mean} = 21 °C) of all rice growing countries. Lobell (2007) also considered anomalies in the diurnal difference between T_{max} and T_{min}, but found relationships to be weak.

Finally, in a more refined global study, Lobell et al. (2011b) regressed 1980–2008 country yields against growing-season T_{mean} and precipitation. The regression was controlled for country fixed effects and time trends, and included quadratic T_{mean} and precipitation terms to allow for the possibility of optima in a curvilinear response to T_{mean} and precipitation. The authors found that relationships between growing-season T_{mean} and crop yield were either significantly negative or not significant (Table 10.1). For example, per °C increase in T_{mean} , Lobell et al. (2011b) reported 1–10% reduction in wheat yield, and a 0–6% reduction in maize yield. However, the effect of increasing T_{mean} on yield was only once significantly negative for rice (India), and although always negative for soybean, never significantly so. Regression coefficients relating yield to precipitation in Lobell et al. (2011b) were small and rarely significant (not shown in Table 10.1).

Returning this discussion of regression studies now to the remaining **wheat examples** summarised in Table 10.1, a study of international trial yields across global sites of the International Maize and Wheat Improvement Center—otherwise known as *Centro Internacional de Mejoramiento de Maíz y Trigo* (CIMMYT)—is provided by Gourджи et al. (2013). Note that the average world sensitivity figure of –5.5% shown for Gourджи et al. (2013) in Table 10.1 conceals sensitivity variation that increases with increased mean temperature of the wheat season.

Beyond the global wheat analysis follows a series of more geographically focused wheat studies, including that by Lobell and Ortiz-Monasterio (2007) in North America, including Mexico (as introduced in Box 10.1); You et al. (2009b) with panel data across Chinese provinces, corrected for detailed changes in technology; and Peltonen-Sainio et al. (2010; 2011) working on European and Finnish data, respectively, similarly corrected for technology change.

Peltonen-Sainio et al. (2010) used panel data from northern European regions to show that 1975–2008 spring wheat yield anomalies were negatively associated with anomalies in both T_{min} and T_{mean} during the pre- and post-heading stages of crop development; results showed ~1–2% decrease in yield per °C increase in both of these temperature measures. In winter wheat, the negative trend was observed only during the post-heading stage. In both spring and winter wheats, associations with T_{max} were generally very weak. Later, using panel data to specifically examine cereals in Finland (>60 °N), Peltonen-Sainio et al. (2011) noted that spring wheat yield decreased by ~2%, and winter wheat by 4%, for each °C increase in T_{mean} that occurred during the first half of the crop life cycle, an effect associated with hastened crop development.

Finally for wheat in Table 10.1, summaries are given for original calculations made and reported in Chapter 3 in relation to response of wheat yield to inter-annual change in T_{min} . More detail about the 6.7% FY decrease per °C warming in the Yaqui Valley, Mexico, can be found in Section 3.2 and detail about the 3.3% FY decrease per °C warming for the Indian state of Punjab is in Section 3.3. These figures represent a valid correction of yield trends for weather trends in the specified locations, but may be biased measures of sensitivity to temperature alone because other possibly correlated weather variables (e.g. solar radiation) were ignored.

Analyses with **rice** have been dominated by concerns about variation in T_{\max} and in T_{\min} and both have been correlated with yield decline. A widely cited early statistical approach was a time series regression of experimental dry season rice yields in Los Baños in the Philippines. In that study, Peng et al. (2004) showed that as dry season T_{\min} rose from 22 °C in 1992 to 24 °C in 2003, rice yield fell at a rate of 10% per °C. This much-quoted result, however, was found to be a biased measure of temperature sensitivity (see Sheehy et al. 2006a in Box 10.1). T. Zhang et al. (2010) also challenged this result, showing that 1981–2005 experimental yield anomalies in irrigated rice across China were not negatively related to T_{\min} anomalies, and tended to be positively related to T_{\max} and solar radiation anomalies—all three meteorological variables were positively related. Earlier Tao et al. (2008), using the first difference method at the provincial level, also found rice yield anomalies to be positively related to anomalies in temperature in north-eastern provinces, but not elsewhere (Table 10.1). The difference in these slopes no doubt reflects lower prevailing temperatures in that part of China (as in Japan).

Across India over 1966–2002, Auffhammer et al. (2012) reported increased T_{\min} , while aerosol pollution had caused dimming, reduced rainfall and lowered T_{\max} . These authors examine all these climate effects on yield anomalies in this period for wet-season (*Kharif*) rice in the nine predominantly rainfed states of India; anomalies correlated only with June–November rainfall (positive correlation) and October–November T_{\min} (negative correlation, see Table 10.1).

Moving on to **maize**, Lobell (2010) explored various statistical approaches for 1950–2005 yields, averaged across counties in eastern USA, to establish a range of significantly negative sensitivities to T_{mean} depending on how yield was de-trended and whether yield or log yield was the dependent variable (Table 10.1). In another example, Lobell et al. (2011a) fitted 1999–2007 yields from maize variety trials under optimal management at more than 120 locations in Sub-Saharan Africa; ~15% of trials received managed drought conditions (grown in the dry season with limited irrigation). Yield was strongly negatively associated with growing-degree days (GDD) above 30 °C, especially under managed drought. The association with GDD was much greater than that between yield and T_{mean} , for which Lobell et al. (2011a) predicted that, under optimal management, warming of 1 °C throughout the growing season would increasingly reduce yield as T_{mean} increased above 23 °C, resulting in 40% yield reduction if T_{mean} reached 28 °C. Under drought conditions, warming decreased yield to an even greater extent whenever T_{mean} values exceeded 16 °C and thus included all maize areas of Sub-Saharan Africa. Compared with the other maize studies shown in Table 10.1, these reported temperature sensitivities for Sub-Saharan Africa are very high, probably because temperatures during the maize season are generally higher there than elsewhere.

Heightened maize sensitivity to temperatures above 30 °C does agree with the results of Schlenker and Roberts (2009) who appear to have separated the effects of chronic warming from those of hot spells (see Section 10.3 on modelling and measurement). These authors took 1950–2005 county yields for maize (and soybean) across the USA, controlled for technology and location. They considered temperature throughout each 24 hours, and calculated a temperature function comprising hours accumulated

during the crop growing season at each degree between 0 °C and 42 °C, to which the remaining yield variation was fitted. A plausible yield vs. temperature function was derived, with yield rising modestly to a critical temperature of ~29 °C for maize (and ~32 °C for soybean) then falling sharply with exposure to higher temperatures as shown in Table 10.1. For example, 24 hours (not necessarily consecutive) at 40 °C was shown to reduce maize yield by 7% relative to 24 hours at 29 °C.

Although the temperature fit used by Schlenker and Roberts (2009) explains only ~15% of residual yield variation, it provides a much better fit than approaches that use average growing-season T_{mean} as the independent variable. Furthermore, it points to large negative effects from time spent above respective critical temperatures—the phenomenon of hot spells, which are likely to increase in frequency with climate warming. Schlenker and Roberts (2009) claim the modelled temperature response is robust across periods within the growing season, and across latitude and time (1950–77 vs. 1978–2005). Furthermore, as might be expected, the sensitivity to time above the critical temperature is less for maize when there is more precipitation. Lobell et al. (2013a) reported that number of degree-days above 30 °C appears to have a strong negative effect on maize yields in Iowa, USA. Similarly Hawkins et al. (2013) found days with T_{max} above 32 °C showed the best temperature-based correlation with French maize yield deviations, after correction for technology and precipitation variation.

Finally Table 10.1 shows several **soybean** studies for which relationships, although negative, were not strong or not statistically significant ($P > 0.10$). An exception is Schlenker and Roberts (2009) who showed a threshold temperature (32 °C) above which yield fell sharply—24 hours at 40 °C reduced yield by 5% relative to 24 hours at 32 °C.

In summary, the regression studies shown in Table 10.1 largely point to negative effects of increased temperature. Of 62 reported relationships, 41 were found to be significantly negative and only three were significantly positive—one for rice in Japan and two in north-eastern China (Table 10.1). Including non-significant results as equal to zero, the slopes of the relationships between yield and increasing T_{mean} (per °C) averaged for each of the four crops shown in Table 10.1 were:

- -4.1% for wheat ($n = 21$ after excluding sensitivities derived from T_{min} alone)
- -2.3% for rice ($n = 13$ after excluding Japan and north-eastern China)
- -4.9% for maize ($n = 12$ after excluding Schlenker and Roberts (2009) and Lobell et al. (2011a) where sensitivity itself—mostly negative—was a strong function of temperature)
- -0.3% for soybean ($n = 5$, excluding Schlenker and Roberts (2009), where sensitivity—mostly negative—was a strong function of temperature).

Obviously the negative sensitivity of yield to increased temperature will depend on the general level of temperatures; where studied, sensitivities mostly increased with increase in temperature, and this probably accounts for some of the variation among regions. The extent to which sensitivity is demonstrated will also depend on the selected regression model (Sheehy et al. 2006b; Lobell 2010).

It is therefore not surprising that a few cooler locations showed positive crop yield responses to increasing temperature—examples include rice in Japan and north-eastern China, and maize in highland parts of Sub-Saharan Africa (Table 10.1)—but total production in these regions is small relative to the global total. In addition, because of inconsistent results for changes in T_{\min} vs. those in T_{\max} , and in light of other uncertainties, it seems that changes in T_{mean} (assuming that extremely high temperatures are not involved) can provide a more appropriate tool for trend analysis of yield response to changing temperature. The responses to extreme temperatures claimed in Schlenker and Roberts (2009) and Lobell et al. (2011a; 2013a) need further validation, as these are physiologically somewhat surprising; for example, with well-watered crops, canopy cooling to well below air temperature becomes especially important in such situations and this depends on prevailing vpd.

The regression models used in the studies reported above generally explained only a small part of the residual variation in yield, even after correction for time and location. Also it is possible the sensitivity is biased because some important weather variables correlated with temperature have been omitted, as was seen when T_{\min} was the only independent variable and was negatively related to solar radiation (Sheehy et al. 2006a). In such cases, multiple regression would have been a better approach, but even so, bias from omission of other weather-correlated variables could remain a possibility. Once verified free of bias, results can be used to correct for past weather trends and predict future outcomes, but prediction models should not be used to extrapolate too far beyond the real weather variability to which they are fitted. Such prediction assumes that relationships among key weather variables do not change with climate change.

Generally, few significant yield effects were associated with changes in solar radiation or precipitation in the regression studies—the latter is less surprising because most of the referenced examples were dominated by irrigated crops or humid areas. However, as expected, some reports showed a greater effect of high temperature on yield when combined with low precipitation (e.g. Schlenker and Roberts 2009; Lobell et al. 2011a).

In contrast to regressions that involve time series or panel data, it has been argued that farmer adaptation to geographic differences in average climate will be reflected in regressions based on cross-sectional data. In Schlenker and Roberts (2009), yield sensitivity to temperature across years and US counties was the same for both panel and cross-sectional data. This finding led those authors to suggest that the studied crops showed limited historical adaptation to geographic differences in average temperature. This conclusion is surprising and could be explained by genetic and agronomic adaptation to increases in temperature across counties being countered by bias from important omitted variables. It is also worth pointing out that tactical management decisions to unfolding seasonal weather could change the slope seen in time series yield vs. climate associations. Examples of tactical adaptation include applications of supplemental nitrogen fertiliser in cool, wet years; earlier planting in warmer springs at higher latitudes; and the increasing use of skilful seasonal climate forecasts to guide crop management.

Temperature trends were strong enough for FY to be corrected for the trends in some situations already discussed in order to better reveal the technology trends (see Sections 3.2, 3.3, 5.2 and 6.2). Also the Lobell et al. (2011b) global study (Table 10.1) concluded that the global warming trend alone during 1980–2008 would have reduced wheat yields by 5.5% and maize yields by 3.8% (relative to the initial yield), while noting that these crops showed yield increases of ~35% and ~46% (respectively) over the same period (see Figure 1.5). Yield gains are of course largely due to improved technology (breeding and agronomy), but these authors estimated that CO₂ increase would have accounted for ~3% of the yield gain (at least for wheat). In addition, these authors claimed that rice and soybean global yield trends were not affected by climate trends apart from CO₂ increase. These conclusions of Lobell et al. (2011b) need to be balanced against the large amount of unexplained residual yield variance, even after T_{mean} (and precipitation) variation has been accounted for.

This discussion of yield vs. temperature associations—often empirically determined, with no strong preconceived notions about the underlying physiology of yield response to temperature—progresses in Section 10.3.

10.3 Direct measurements and crop simulation modelling

This section asks whether the reported associations between yield and temperature can be supported by current understanding and measurements from crop physiology.

Introduction to physiology of yield response to warming

Plant and crop processes determining development, growth and yield have been described in general terms in Section 2.6. There is substantial scientific literature covering measured temperature effects on these processes. Much of the research involves pot studies in controlled environments. Although caution is needed when relating their results to the real world, such studies have helped to satisfactorily unravel temperature effects on crop development (phenology), plant growth and leaf photosynthesis. The proviso is that sensible ranges must have been maintained for air temperature, photoperiod and radiation levels, with adequate time for thermal acclimation. Lack of attention to establishing sensible pot (root) temperatures is a weakness in some studies, and many studies fail to consider plant-to-air temperature differences, especially as affected by vpd. However, some effects of temperature can be elucidated only in crop canopies in the field, including yield components (and yield), RUE and the fraction of incident photosynthetically active radiation intercepted by the canopy (F_{PAR} ; see Section 2.6) through effects on leaf area expansion. Needless to

say, independent temperature (and CO₂) manipulation for canopies—especially in the field—has never been easy.

Notwithstanding the above caveats, and assuming other things are equal, across the major crops the **general measured response of yield to temperature** is clear. Above a relatively low growing-season optimum T_{mean} for maximum potential yield (PY; see Chapter 2 on definitions)—as has been identified for the major crops in the second column of Table 10.2—the relationship is always negative. For rate of development, cardinal temperatures are recognised, and as shown in Table 10.2, it is clear that the optimal temperature for fastest development (T_{opt}) is much higher than that for maximum PY. Above T_{opt} , development rate reaches a plateau, so the plant should be considered stressed; higher cardinal temperatures are recognised when development begins to slow, and when it ceases (Connor et al. 2011), but these are not discussed here. A recent collation of all published results suggests that base (T_{base}) and T_{opt} in rice are closer to 13 °C and 28 °C, respectively, and for maize 6 °C and 31 °C, respectively (J. R. Porter, pers. comm. 2012). The cardinal temperatures in Table 10.2 influence the differences in temperature response between crops, discussed below.

Table 10.2 Key growing-season temperature for potential yield (PY), cardinal development temperatures for the determination of development, and high threshold temperature for fertility damage across major crops^a

Crop	Optimal mean temperature (T_{mean}) for maximum PY	Cardinal temperatures for rate of development (°C)			Temperature threshold for onset of heat-induced floret sterility
		Base temperature (T_{base}) for zero rate		Optimal temperature (T_{opt}) for maximum rate ^b	
		Vegetative ^b	Reproductive ^b		
Wheat	15	0	^d 8	26	34
Rice	^c 23	8	8	33	35–36
Maize	^c 18	^e 8	^e 8	34	^f 38
Soybean	^c 22	7	6	26	39

- a Based on estimations by Hatfield et al. (2011) with changes noted
- b These temperatures are used for development rate and duration calculations, where rate is a linear function of temperature between T_{base} and T_{opt} ; most models use daily T_{mean} values, or for greater accuracy, hourly temperatures.
- c Lowest temperature in the range given by Hatfield et al. (2011), referring to whole growth cycle, except for winter wheat when it refers to the spring–summer growth period
- d Raised from 1 °C in Hatfield et al. (2011) in accordance with omitted measurements of Fischer (1985a)
- e Seed trade uses 10 °C for T_{base} and Cicchino et al. (2010a) recently reported a higher T_{base} around silking; other studies suggest that the T_{base} during grain-fill may be 0 °C
- f Raised from 34 °C in Hatfield et al. (2011) to better agree with omitted measurements of Herrero and Johnson (1980)

Of course, problems will be encountered when trying to accurately measure crop responses to temperature on the basis of 'other things equal'. These are 'real world' temperature fluctuations due to time of day, weather on a given date and inter-annual changes—and those arising with climate change—which will always involve changes in other meteorological variables, such as vpd or solar radiation. Furthermore, temperature changes cannot be entirely captured by T_{mean} because the diurnal range and extremes of T_{min} and T_{max} can change independently.

Rate of crop development and temperature

Through quantitative relationships, process-based simulation models of crop yield attempt to bring together all the significant weather factors involved in yield. Of these factors, the most significant is probably temperature, given that **all crop simulation models are built around a fundamental framework driven by the influence of temperature on rate of crop development** (as summarised in Table 10.2 and described in Section 2.6). Connor et al. (2011) provided a clear description of this modelling framework for major crops. Porter and Gawith (1999) also provided useful insights in their comprehensive review of wheat phenological responses to temperature, and White (2003) examined temperature in wheat and maize modelling.

Crop development here—and as described earlier in more detail in Table 2.1—refers to progression of the crop through key events such as germination, seedling emergence, initiation of reproductive organs, anthesis (flowering) and physiological maturity. The duration of individual phenological phases (separating developmental events in the crop life cycle) will depend on the accumulation of given quantities of heat, calculated as thermal time or growing degree-days (GDD) above a T_{base} . GDD is a misnomer because it relates to development (not growth), but is retained here since the measurement is very widely used. GDD is useful because the rate of crop development is approximately linear with respect to temperature between T_{base} and T_{opt} (Table 10.2) and GDD (given in units of °C d) accumulates as demonstrated by equation (12):

equation (12) Accumulation of growing degree-days

$$\text{GDD} = \sum \text{across days of } (T_{\text{mean}} - T_{\text{base}}) \quad (12)$$

where

GDD is growing degree-days (°C day)

T_{mean} is daily mean temperature and T_{base} is the temperature below which development for the period of interest ceases (see Table 10.2). Note if T_{mean} exceeds T_{opt} (see Table 10.2),

T_{mean} becomes T_{opt} in equation (12).

There are, however, elaborations on this simple relationship. Cardinal temperatures refer to observed temperature (not T_{mean}), meaning that when the day temperature exceeds T_{opt} the rate of crop development will plateau or possibly fall. In order to better describe the accumulation of GDD in such instances, more complex functions relating rate of

crop development to temperature are required (e.g. White 2003), and should consider hourly temperatures (easily predicted from daily T_{\min} and T_{\max}). In such functions the linear function between T_{base} and T_{opt} often becomes slightly curvilinear, but T_{base} and T_{opt} remain key parameters. If GDD is calculated by hourly summing of temperature less T_{base} , division of the °C hour sum by 24 gives the °C day sum and the principle of a fixed GDD sum for completion of a given developmental phase remains.

T_{base} and T_{opt} clearly vary among crops and somewhat among stages of development for each crop (Table 10.2); hence so does the duration for completion of any phenological phase. A given GDD means that phase duration, and overall crop growth duration, is inversely related to the prevailing temperature above T_{base} . GDD is the major physiological basis by which higher temperatures generally reduce PY—through shortening of the duration for capture of solar radiation during vegetative, reproductive and grain-filling periods.

There are, however, limits to how much lower temperatures can, by slowing development, increase PY; hence there is **an optimal T_{mean} for maximum PY** (second column of Table 10.2). This limit arises because the benefits of longer duration at cooler locations can be counterbalanced by the depressing effects of low temperature on growth processes such as the early leaf production and expansion necessary for the crop to reach full groundcover. This effect is reinforced by the fact that most crops (including wheat) encounter lower temperatures in the earlier stages of their life cycle, compared with the T_{mean} averaged over the full crop life cycle. Those subtropical crops that grow during the wet season, when temperature is greatest at the beginning of the growing season, are clear exceptions.

Because **wheat** is a long-day plant, shorter days (photoperiods) at any given temperature up to flowering will slow development. In addition, in facultative and winter wheats a requirement for vernalisation (see Section 2.6) can slow development before floral initiation. Models manage this by making the required GDD a function of day length (and vernalisation if necessary) as well as temperature. Of course, genetic differences affect developmental sensitivity to photoperiod, vernalisation and temperature itself (sometimes known as 'intrinsic earliness'; see Section 10.4 on scope for adaptation to climate change). After flowering there is no response to photoperiod but a strong developmental response to temperature remains, and there are usually only small genetic differences in grain-filling GDD (and hence duration).

Depending on the accumulation of encountered cold (hours spent at < 15 °C), warmer temperatures can delay development in the true vegetative stage (i.e. before floral initiation) of vernalisation-sensitive wheats (and canola and sugar beet). Vernalisation sensitivity does not operate after floral initiation, and will thus lengthen the overall crop growth duration by only the extent to which the vegetative stage is extended. This extra duration in winter wheats can mean extra dry matter (DM) and perhaps greater PY, but there are complications (see Section 10.4).

The above description of temperature, development and yield for wheat can be applied to other cereals, such as **rice and maize**, with the difference that these other crops

have higher cardinal temperatures (Table 10.2), do not show vernalisation sensitivity and are short-day plants, meaning that pre-flowering development accelerates in shorter days (Connor et al. 2011). Note that some rice varieties and short duration temperate maizes are almost day-neutral, meaning they are insensitive to day length. The concept of GDD is widely used by the commercial seed sector to describe the duration of maize hybrids from planting to maturity, at least within a given band of latitude—but seed distributors tend to use a T_{base} of 10 °C (not 8 °C presented in Table 10.2) which can cause confusion for readers. In **soybean**, a short-day or day-neutral warm season crop, time to flowering is also controlled by temperature and day length.

Soil and canopy temperature have been incorporated as useful refinements to modelling of temperature-driven crop development. Soil temperature can be a better predictor than air temperature in the early stages of development when the apical meristem (growing tip) is below or close to the soil surface. At later stages, a more accurate predictor can be provided by canopy temperature, determined by stomatal conductance and vpd; this is usually lower than air temperature if the crop is well supplied with water. Despite these additional refinements, **development based on thermal time remains the dominant framework for modelling yield, both for resource acquisition by the crop and for the determination of general temperature sensitivity of yield (especially PY).**

The acceleration of development with higher temperature is particularly critical for yield determination during the phenological phases covering the ~20 days leading up to flowering plus the following ~10 days in wheat (e.g. Fischer 1985a) and rice (e.g. Yoshida and Parao 1976). The effect on PY of variation in temperature and solar radiation can often largely be captured in a simple, positive linear relationship between PY and the photothermal quotient (PTQ) prevailing during this period (Fischer 1985a). PTQ is the ratio of the solar radiation to (temperature minus T_{base}), essentially a prediction of crop growth or DM accumulation per unit of development time.

Rawson (1988) has argued that high-temperature effects on PY can be compensated by high radiation levels, such that PTQ is kept at a high value. Another proviso is that nutrient and water supplies are good enough to meet the resultant high crop growth rates (e.g. 60 g DM/m²/day was recorded in a mini-crop of wheat grown in a growth cabinet at 34 °C T_{max} and 16 °C T_{min} with 24 MJ/m²/d solar radiation equivalent). Following this management strategy, Rawson (1988) achieved a mini-crop yield of 10 t/ha in summer in a glasshouse run at 30 °C T_{max} and 25 °C T_{min} . Unfortunately, the degree of transpirational cooling in these mini-crops was not recorded.

Rate of crop growth or dry matter accumulation and temperature

The preceding paragraph suggests temperature effects on growth process are small. But consideration should be given to these effects, including RUE and the other main determinants of growth—leaf area and F_{PAR} . The early effects on leaf area expansion

and attainment of full light interception (see Section 2.6) have been mentioned. Higher temperature also speeds the rate of leaf senescence, but this is not a clear developmental response, because it is also strongly influenced by other abiotic stresses, especially nitrogen supply, and sink demand.

Temperature effects on RUE are generally small (Sinclair and Muchow 1999), even though temperature is known to markedly increase maintenance respiration (approximately doubling every 10 °C increase). Very low T_{\min} values can also affect photosynthesis, as occurs with frost in wheat, or chilling (<12 °C) in warmer season crops like maize (Connor et al. 2011). Referring to daytime temperature effects, the model Hybrid-maize assumes maximum photosynthesis increases from zero at 8 °C, to plateau at 18 °C before falling again at 30 °C to reach zero at 42 °C.

One recent field study with irrigated maize must be noted. As with many earlier studies, Cicchino et al. (2010b) reported that grain number (GN) and harvest index (HI)—see Section 2.6 for explanation of both—were reduced when temperature exceeded 40 °C on some days, giving several hundred hour-degrees above 34 °C for the 15-day period around silking. However, unlike previous studies, Cicchino et al. (2010b) attributed the reduction in seed number and HI to the estimated marked reduction in RUE during and after the period of higher temperature.

Reduced grain number and grain weight with heat around flowering and grain-filling

In addition to reductions in crop growth duration and its subsequent negative effects, and sometimes negative effects on rate of DM accumulation, the most noted influence of high temperature is its negative impact on HI. This usually arises from direct negative effects on flowering processes resulting in reduced GN through sterility or abortion of the flower buds, young seeds or seed pods. For all four major crops, very high temperatures around the time of flowering will reduce seed number. The effect commences at threshold temperatures, which vary with crop (last column in Table 10.2), and progresses to complete sterility at ~40–45 °C. Threshold temperatures for sterility remain uncertain, especially given the possibility of transpirational cooling of green organs. In rice, T_{\min} values of <15 °C around meiosis (~15 days before flowering) can also cause sterility.

Higher temperature during grain-filling, at least in the case of wheat, has a particularly adverse influence on HI and yield because this developmental stage coincides with either rising temperatures in the crop cycle (spring to early summer at low latitudes) or the one of highest temperatures (mid summer at higher latitudes). Under higher grain-filling temperatures, faster rate of grain development in wheat more than counterbalances the faster rate of grain dry weight accumulation. This inevitably leads to smaller grains for any T_{mean} above a cool 15 °C, with grain weight (GW; see Section 2.6) falling at ~4% per °C rise in T_{mean} during grain-filling (Wardlaw and

Wrigley 1994). In contrast to wheat, GW in rice appears to be insensitive to grain-filling temperature up to a T_{mean} of $\sim 27^\circ\text{C}$ (Tashiro and Wardlaw 1989).

In addition to chronic high temperature during grain-filling, heat waves or hot spells (periods of 1–3 days of T_{max} above $\sim 34^\circ\text{C}$) may affect wheat yield. The reported effect is markedly reduced grain size (Asseng et al. 2011; R.A. Fischer 2011), possibly attributed to widely observed loss of green leaf area reducing grain growth rate. Hot spell effects appear to be largely avoided in irrigated wheat crops because the canopies and spikes can be cooled up to 5°C or more below air temperature, depending on prevailing vpd. However, for rainfed crops there is usually some water stress during grain filling, little or no canopy cooling, and increasing damage from hot spells with increasing water stress (Asseng et al. 2011).

These last two mentioned effects of short bursts of heat seem to have been picked up in some regression modelling already described in Section 10.2—Schlenker and Roberts (2009) and Lobell et al. (2011a) for maize (see Table 10.1), and Lobell et al. (2012a) for wheat in north-west India. For example, the regression modelling for maize points to greater yield sensitivity at $T_{\text{max}} > 29^\circ\text{C}$. However, this threshold temperature could be too low judging by the measured performance of maize in the hot tropics. For example, Muchow et al. (1990) recorded a remarkable average PY of 9.5 t/ha for irrigated maize at latitude 15°S in northern Australia where T_{mean} was 28°C and average T_{max} was 34°C . Similarly the T_{max} threshold of 34°C from the wheat study (Lobell et al. 2012a) could be too low if the wheat is irrigated and transpirationally cooled.

Much uncertainty remains, but to summarise the above discussion, increased temperature relative to ‘normal’ appears to lower yield by two major mechanisms:

1. Chronic warming (higher T_{mean}) speeds crop development: DM accumulation and yield are reduced largely by shorter crop growth duration, and possibly through smaller effects by reduced F_{PAR} and lower RUE (e.g. by higher maintenance respiration).
2. Extreme heat (best seen in high T_{max} values) reduces seed number by direct effects on flowering processes, and can reduce GW perhaps by effects on photosynthesis and senescence of green area. Both responses reduce HI.

Measured yield response to carbon dioxide and ozone

Open-top chambers and free air CO_2 enrichment (FACE) are the two methods for measuring responses to increasing CO_2 in crops in the field. In open-top chambers, air of given CO_2 concentration is passed continuously up through the chamber in sufficient volume to maintain that concentration. The FACE method works with freely growing crops surrounded by a tubular ring of several metres in diameter that injects CO_2 so as to maintain a given concentration in the centre of the ring. According to Tubiello et al. (2007), these two methods produce fairly similar results, but Ainsworth et al. (2008a) assert that FACE gives lower responses under its more realistic conditions. However,

this difference is possibly because the CO₂ concentration at canopy height in the ring centre has been shown to fluctuate widely from minute to minute around the set mean enrichment concentration, with negative effects on photosynthesis relative to that with a relatively steady enrichment concentration (Bunce 2012).

The responses to photosynthesis, DM production and yield to **increasing CO₂** are relatively similar across C₃ crops (see Section 2.4) and almost always positive, but with diminishing returns as CO₂ increases above current ambient level (Horie et al. 2005b; Tubiello et al. 2007). For wheat, Tubiello et al. (2007) summarised many studies to conclude that yield was ~20% greater at a CO₂ concentration of 550 ppm than one of 370 ppm, which is the base level used here unless mentioned otherwise. Ainsworth et al. (2008a) compared wheat yield response to 550 ppm by FACE and an open-topped chamber; the response above the base was ~14% for FACE and 31% for the open-topped chamber.

Horie et al. (2005b) summarised rice responses to a CO₂ concentration of 700 ppm and reported that yield increased by 17% in Indica (warm area) rice and 32% in Japonica (cool area) rice. Hatfield et al. (2011) presented average yield responses of the major crops to a CO₂ concentration of 440 ppm—an increase of 60 ppm or 12.5% over a base of 380 ppm—and reported yield increases of 6.8% in wheat, 6.4% in rice and 7.4% in soybean, while C₄ maize showed only a slight increase of 1%. There is also good evidence (Howden 1992; Ainsworth et al. 2008a) that relative yield responses to CO₂ are greater under conditions of water shortage, and some evidence (Rawson 1995) that the yield response to CO₂ increases with temperature.

The average responsiveness of C₃ crop yield to CO₂ increase from the above reports is about 0.4% yield increase per 1% CO₂ concentration increase. This value is used to predict that if CO₂ is assumed to reach 480 ppm by 2050, **the 100 ppm (26%) rise in CO₂ (from the 2000 concentration of 380 ppm) will increase yields of C₃ crops by about 10%. For C₄ maize the increase is only 2%**, from a sensitivity of 0.1 from (Hatfield et al. 2011). There is some evidence that the yield response of C₃ perennials like oil palm will be greater because both HI and DM are increased (Corley 2012).

Reduced stomatal conductance is an additional effect of increased CO₂, with reductions of 30–40% in all crops (even maize) if CO₂ concentration is approximately doubled (Hatfield et al. 2011). Although reduced stomatal conductance will increase canopy temperature, the net effect is reduced evapotranspiration (ET). Hatfield et al. (2011) estimated a decrease of ~1–4% in ET across a suite of crops when CO₂ concentration increased by 60 ppm, and Asseng et al. (2004) estimated a fall of 6% in wheat when CO₂ concentration increased by 200 ppm. Needless to say, transpiration efficiency rises by about as much as does the yield to ET ratio.

Over the past century, **daytime ozone concentration levels** have increased several-fold in densely populated industrialised areas of the world. From a base mean monthly level of <10 parts per billion (ppb) by volume, by 2000 mean monthly

mid-summer levels had reached 40–60 ppb in these areas (van Dingenen et al. 2009; Hatfield et al. 2011). But unlike CO₂, ozone levels are spatially diverse and vary notably with season and weather such that peak hourly values can exceed 70 ppb. Although there appear to be some abatement of peak hourly levels and stabilisation of mean ozone levels in the USA and Europe, mean levels are estimated to continue to increase to 2030 at least, especially in India and Africa (van Dingenen et al. 2009).

The effect of increasing ozone on crop yield has been studied using the same techniques as for elevated CO₂. Two metrics are used to quantify crop exposure to ozone—either the mean concentration during daylight hours or the accumulation (ppb hours) of ozone concentration above 40 ppb in daylight hours (Wang and Mauzerall 2004; van Dingenen et al. 2009). There is also some evidence that peak ozone values may cause more yield damage than their influence on the mean ozone levels would suggest. The focus is on daylight hours because ozone enters the leaf through stomata, which are open only in daylight.

Sensitivities to ozone appear to be variable, perhaps because of other influences on stomatal conductance (Hatfield et al. 2011). However, soybean appears most sensitive, wheat moderately sensitive, and maize and rice least sensitive (Wang and Mauzerall 2004). One FACE study in Illinois, USA, measured a soybean yield decline of 20% as mean daytime ozone was raised by 23% from 56 ppb (ambient) to 69 ppb (Morgan et al. 2006). Estimates of regional yield losses depend on which metric is used, and the coincidence between the crop growth cycle and the peak months for ozone, which tend to be in summer. Regional estimates present a range of yield losses based on both metrics. Thus Wang and Mauzerall (2004) estimated yield losses in 1990 in East Asia due to ozone to be 1–9% for wheat, rice and maize and 23–27% for soybean. Van Dingenen et al. (2009) estimated that global yield losses as a result of increased ozone in 2000 were 7–12% (wheat), 3–4% (rice), 3–5% (maize) and 6–16% (soybean). The ranges of estimates for each crop reflect uncertainties about sensitivity functions.

Industrial and automobile ozone can be reduced through pollution control, but until this is effected, ozone concentration is projected to increase and will likely exert downwards influence on yield increase. Van Dingenen et al. (2009) calculated additional global yield losses (relative to 2000 yields) due to generally higher mean ozone levels predicted in 2030; these were given as 2–6% for wheat and 1–2% for rice, but <1% for maize and soybean. The predicted losses are especially concentrated in India for which no mitigation is assumed.

The predicted effects of ozone on future yields are not negligible, but the extent of the effect remains uncertain and relatively small, so that **further increases in ozone are ignored here for the estimate of 2050 effects of climate change on yield**. Note that yield progress in the past century could have been slowed by ozone increase, and that effective abatement and adaptation to ozone could bring notable yield increases. Thus a great deal more research is needed on ozone effects on crops as well as implementation of policies for ozone abatement.

Simulating future yield responses to warming and carbon dioxide increase

Process-based crop simulation models attempt to include the individual temperature responses described above, or at least the ones considered most important. They also bring the possibility of considering the yield influence from weather factors independently of each other, thus avoiding collinearity problems of regression models.

White et al. (2011) listed more than 60 crop simulation models—a few of which are mentioned here—that have been used to predict climate change effects on crop yield. Almost all of these models use temperature to drive crop development rate. But beyond this, the inclusion of other temperature effects varies considerably. Further, for all models, because of lack of measurements, uncertainty surrounds consideration of sterility induced by extreme temperature (the threshold temperature in Table 10.2, last column) and the damage from hot spells during grain-filling in wheat. Rötter et al. (2011) noted the inadequacy of all existing simulation models for predicting effects of climate change and urged more research on model development and validation; these authors even suggested the use of suites of models, as is done in the prediction of future climates.

Despite the uncertainties, a large number of reports claim to use simulation modelling to predict sensitivity of crop yield to temperature change. It is useful here to summarise some of the results on temperature sensitivity of yield. This has been done by comparing modelled yields with and without an extra 1–2 °C added each day to temperature in the historic record, while holding all other inputs unchanged (Table 10.3).

Notwithstanding the uncertainties in correctly modelling the response to temperature, there is reasonable agreement across Table 10.3 for reductions in cereal yield per °C increase in temperature, with an average yield response of –7.7% for wheat, –7.4% for rice and –4.1% for maize. The reported responses from soybean to warming are variable, with yield gains in the cooler northern regions in the Mid West of the USA (+2.1% per °C) and yield reductions (–5.7% per °C) in the southern regions; nevertheless, a mean value of –3.1% is taken here. Also in Table 10.3, if hastened development through faster accumulation of GDD were the only effect of chronic warming on yield, then sensitivity to increased temperature should decrease with higher T_{mean} . However, at least with wheat and maize for which several T_{mean} values were available, there is no sign of this. Presumably other negative effects of higher temperature counterbalance such an outcome. The maize data do confirm that the optimal T_{mean} for maize yield is below 20 °C, and close to 18 °C as pointed out in Table 10.2.

The cereal PY results in Table 10.3 are consistently negative for even the smallest increase in temperature, and this agrees with the many simulation results—summarised for the IPCC by Easterling et al. (2007)—which for wheat, rice and maize at low latitudes reveal an almost linear decline in yield with T_{mean} increase. However, at mid to high latitudes, as also summarised by these authors, yields of these three cereals commence with a positive response to extra temperature before turning negative at about +3 °C or +4 °C in a curvilinear response function. This latter trend suggests that currently all these crops are

growing under suboptimal temperatures at these higher latitudes, a result for which this book has found little support (except for rice in north-eastern China and Japan).

Asseng et al. (2011) focused on heat stress during grain-filling in rainfed wheat in Australia. Using historic weather patterns, simulated yields were shown to reduce by ~0.21 t/ha (or about 5%) for every day where grain-filling T_{\max} exceeded 34 °C regardless of rainfall. The Asseng et al. (2011) simulation model excels in attempting to capture all effects of weather (particularly temperature) on wheat yield, but even so, the assumed processes need further validation, particularly in the field.

Table 10.3 Simulated response of potential yields (PY) and water-limited potential yield (PY_w) to temperature rise, derived from the observed sensitivity of simulated yields to small increases (<2.5 °C) in temperature across the full duration of the crop life cycle

Crop	Location and approximate mean temperature (T_{mean}) of growing season	PY sensitivity (%) to +1 °C T_{mean}	Comment and source
Wheat	Yaqui Valley, Mexico ($T_{\text{mean}} = 18.5$)	-12.0	Lobell and Ortiz-Monasterio (2007) table 8, scenario $\Delta T_{\text{min}} = \Delta T_{\text{max}} = 1\text{ °C}$
	San Luis-Mexicali, Mexico ($T_{\text{mean}} = 16.7$)	-6.9	
	Imperial Valley, California ($T_{\text{mean}} = 15.7$)	-7.0	
	Great Plains of the USA ($T_{\text{mean}} = 19.5\text{ °C}$)	-5.5	Linear adjustment of PY sensitivity ^a to +0.8 °C T_{mean} as given in Hatfield et al. (2011)
	Indo-Gangetic Plain, India ($T_{\text{mean}} = \text{about } 21\text{ °C}$)	-6.2	Half of PY sensitivity to +2 °C T_{mean} as calculated with CERES and APSIM models in Lobell et al. (2012a)
	Indo-Gangetic Plain, India ($T_{\text{mean}} = \text{about } 21\text{ °C}$)	-8.3	As above from Lobell et al. (2012a), but with CERES allowing extra effects when $T > 34\text{ °C}$
	Wheat average (n = 6)	-7.7	
Rice	Los Baños, the Philippines ($T_{\text{mean}} = 26\text{ °C}$)	-5.8	Sheehy et al. (2006a), average of two physiological models
	Southern USA ($T_{\text{mean}} = 26.7\text{ °C}$)	-10.0	Linear adjustment of PY sensitivity ^a to +0.8 °C T_{mean} as used in Hatfield et al. (2011)
	China ($T_{\text{mean}} = \text{na}$)	-8.0	Studies summarised by Lobell and Burke (2010b)
	India ($T_{\text{mean}} = \text{na}$)	-5.6	
	Rice average (n = 4)	-7.4	

Continued next page

Table 10.3 Continued

Crop	Location and approximate mean temperature (T_{mean}) of growing season	PY sensitivity (%) to $+1\text{ }^{\circ}\text{C } T_{\text{mean}}$	Comment and source
Maize	Northern Australia ($T_{\text{mean}} = 27.6\text{ }^{\circ}\text{C}$)	-4.5	Half of PY sensitivity to $+2\text{ }^{\circ}\text{C } T_{\text{mean}}$ as used in Muchow et al. (1990)
	Colorado, USA ($T_{\text{mean}} = 18.9\text{ }^{\circ}\text{C}$)	-4.7	
	USA ($T_{\text{mean}} = 22.5\text{--}26.7\text{ }^{\circ}\text{C}$)	-3.1	Linear adjustment of PY sensitivity to $+0.8\text{ }^{\circ}\text{C } T_{\text{mean}}$ given in Hatfield et al. (2011)
	Sub-Saharan Africa ($T_{\text{mean}} = 20\text{ }^{\circ}\text{C}$)	-3.0	Half of PY sensitivity to $+2\text{ }^{\circ}\text{C } T_{\text{mean}}$ as determined in Lobell and Burke (2010a); CERES-Maize for PY and PY_w
	Sub-Saharan Africa ($T_{\text{mean}} = 27\text{ }^{\circ}\text{C}$)	-5.0	
	Maize average ($n = 5$)	-4.1	
Soybean	Mid West of the USA ($T_{\text{mean}} = 22.5\text{ }^{\circ}\text{C}$)	+2.1	Linear adjustment of PY sensitivity to $+0.8\text{ }^{\circ}\text{C } T_{\text{mean}}$ given Hatfield et al. (2011)
	Southern USA ($T_{\text{mean}} = 26.7\text{ }^{\circ}\text{C}$)	-3.0	
	Florida, USA ($T_{\text{mean}} = 24.1$)	-8.4	Linear adjustment of PY sensitivity to $+2.25\text{ }^{\circ}\text{C } T_{\text{mean}}$ response for 1 April sowing, given in Hodson and White (2010)—less sensitivity noted with later sowing
	Soybean average ($n = 3$)	-3.1	

a These sensitivities were measured using field chambers (K. Boote, pers. comm. 2013).

Although Schlenker and Roberts (2009) have done so, it would be incorrect to say that these crop simulation models have not been widely validated with independent data. Nonetheless, they are not validated specifically against temperature increments alone and are still poorly tested against temperature extremes (Rötter et al. 2011). It is thus useful to compare the predicted response to temperature from simulation modelling (Table 10.3) with responses from regression analyses (Table 10.1). Note that the latter relate largely to real FY data, and the former to modelled PY (and PY_w) data, but the relative yield sensitivities should be comparable.

There is large variation among the regression-derived slopes (Table 10.1). But the regression slopes for US wheat and maize agree reasonably with the simulation modelling (Table 10.3), and both approaches suggest soybean is less sensitive to warming. With rice, however, agreement between Table 10.1 and Table 10.3 is not so

good; simulation modelling suggests greater sensitivity to temperature increase. In some cases, both simulation modelling and regression have been used on the same datasets with reasonably similar results. Such was the case for rice, wheat and two maize examples (in Box 10.1 and Lobell et al. 2013a, see below), but not so close for the two approaches with maize and wheat in the USA (Maltais-Landry and Lobell 2012).

One interesting recent coincidence of simulation modelling with regression analysis is that of Lobell et al. (2013a), who used the APSIM-Maize model to determine that maize yield anomalies between 1959 and 2004 in counties of Iowa, USA, were highly significantly related (negatively) to the anomalies in extreme temperatures (accumulated degree-days above 30 °C). This is remarkably similar to the regression analysis result for maize in eastern USA of Schlenker and Roberts (2009) that shows the strong negative effect of temperatures over 29 °C (Table 10.1). This modelling result for Lobell et al. (2013a) has given credence to one mechanism by which elevated temperature affects maize yield in the APSIM-Maize model—that greater temperature will increase potential crop water use or demand (through increased vpd), which in turn will increase the likely degree of crop water stress arising when potential demand exceeds potential supply from the root–soil system. More work is needed to better understand this remarkable coincidence.

CO₂ increase has been incorporated into many recent simulation studies with C₃ crops (e.g. Asseng et al. 2004; Horie et al. 2005a; Tubiello et al. 2007). White et al. (2011) examined more than 200 peer-reviewed crop simulation papers considering temperature plus CO₂ change, finding many inadequacies, especially in clarity regarding exact procedures. Known interactions in key processes were often ignored and results relied on empirical fitting. Little is known about feedbacks that undoubtedly operate when plants are exposed to higher CO₂ over the entire crop life cycle. For example sink capacity feedbacks could limit the extra production of photosynthate per unit solar radiation and per unit transpiration, which might be expected from higher CO₂ in C₃ crops. This book therefore ignores modelling results for CO₂ increase, and uses measurements reported above—a **yield increase of 10% for C₃ crops for the 100 ppm (26%) increase 2000 to 2050, and 2% for C₄ crops (Table 10.4).**

Complications and uncertainties further multiply when simulation models attempt to estimate effects of increased temperature, increased CO₂ and changed water supply. Examples of such simulations include Howden (1992), Lal et al. (1998), Asseng et al. (2004) and Nelson et al. (2009)—discussed further below. Horie et al. (2005b) even included increased susceptibility of floret fertility to higher temperature at elevated CO₂. Worth mentioning for its originality is the effort of 51 wheat crop modellers (Asseng et al. 2013), who used the median response from an ensemble of 27 models applied to four typical wheat-growing locations between latitudes 25° and 55°. The authors predicted a yield decrease of 12% for +3 °C and an increase of 13% for +50% CO₂ (with little or no interaction between heat and CO₂), sensitivities for wheat remarkably similar to the summary estimates shown in Table 10.4.

Conclusion on likely effect of climate change on yields to 2050

Results from regression studies and simulation models are compared, averaged and then rounded off **for a 'best-bet' estimate of sensitivity to temperature increase** in Table 10.4. In this way, yield sensitivity of cereals—whether FY of statistical estimates, or PY (and PY_w) of modelled ones—is around -5% per $^{\circ}\text{C}$ increase in T_{mean} , with some evidence that sensitivity may be greater under drier conditions. Thus if warming to 2050 produces an increase of 2°C , this effect alone would reduce cereal yields by $\sim 10\%$, except in high-latitude rice regions (e.g. Japan and north-eastern China) where warming will likely increase yield. For soybean the average yield sensitivity is -2% per $^{\circ}\text{C}$ warming, but it might also tend positive at higher latitudes.

The effect of the assumed CO_2 rise to 2050 used in Table 10.4 comes from the open-topped chamber and FACE measurements reported above. For the combined effect by 2050, the effects of warming and CO_2 rise are summed, assuming no interaction.

The conclusion here for climate change to 2050 (warming and increased CO_2 only)—without adaptation measures—is that yield effects will be negligible for wheat and rice, negative for maize and slightly positive for soybean.

Note that these 'best-bet' estimations are only that—estimations of the combination of uncertain emission scenarios, uncertain global climate models and uncertain regression and crop measurement and models. Coming from professionals in the climate change field, such results are commonly presented as a range of values reflecting this level of uncertainty.

The above conclusion assumes that the same varieties of crops will continue to be grown in the same locations. Also, a special element of uncertainty with these predictions is a failure to consider possible added negative effects of more frequent hot spells, as have been predicted to occur with warming. Enough is known to suggest that water shortage may amplify negative yield response to higher temperature, while higher CO_2 may have greater positive yield effects under water stress. The last two effects may well cancel each other for C_3 crops.

Both statistical and simulation approaches to predicting future yields under climate change can only be as reliable as the predictions for greenhouse gas emissions and the quality of currently available climate models. To date, climate models tend to be moderately accurate for temperature, but much less so for precipitation—hence precipitation has been omitted from general considerations here. Moreover, both yield prediction approaches suffer from the assumption of 'stationarity' whereby recent observed (statistical models) or assumed weather (simulation models) anomalies are expected to correctly mimic the intricacies of future weather under climate change.

Table 10.4 Yield sensitivity to warming, and estimates of the effect of warming and CO₂ increase on crop yields to 2050^a

Crop	Yield sensitivity to 1 °C rise relative to 2000 yield (%)				Overall yield response by 2050 relative to 2000 yield (%)		
	From regression studies (Table 10.1)	From simulation models (Table 10.3)	Average regression and simulation	'Best bet' after rounding	2 °C warming	+100 ppm CO ₂	Sum
Wheat	-4.1	-7.7	-5.9	-5	-10	+10	0
Rice	-2.3	-7.4	-4.8	-5	-10	+10	0
Maize	-4.9	-4.1	-4.5	-5	-10	+2	-8
Soybean	-0.3	-3.1	-1.7	-2	-4	+10	+6

a Assuming growing-season mean temperature (T_{mean}) warming is +2 °C and CO₂ increase +100 ppm (+26%)

Source: estimations developed in text

The approach used here to estimate yield effects of climate change contrasts in sophistication with the multitude of published climate models and crop simulations on this question. Although many of these studies provide plausible answers, White et al. (2011) and others mentioned above have noted that inadequacies persist because of many assumptions, lack of clarity and poor validation. These problems increase when simulation is used to assess climate change effects for crops right across the globe at high spatial resolution (e.g. Nelson et al. 2009; 2010; Deryng et al. 2011). It has recently been shown that this use of 'gridded' weather data for complete terrestrial coverage leads to large errors and biases relative to modelling with good-quality data from weather stations (van Wart et al. 2013a). Thus, in the light of weather data and crop modelling uncertainties, this chapter has opted for simplicity and transparency to develop predictions, staying within the bounds of current limited crop knowledge.

Notwithstanding the above uncertainties, well-validated crop simulation models can help the exploration of agronomic, and possibly breeding, adaptations to warming. There is some merit in using simulation to identify those regions in which crops are at greatest risk (or benefit) in order to target adaptation action and research. This is especially so for altered phenology, the first step in adaptation and fortunately the most reliable component of crop modelling. Importantly, the big advantage of simulations is that they are process-based, meaning they might be improved with more crop physiological research.

10.4 Scope for adaptation to climate change, especially warming

Much has been written on adaptation to climate change. Leading examples for cropping in general are provided in books edited by Reynolds (2010) and Hillel and Rosenzweig (2012), while for regional perspective, Wassmann et al. (2009) examined rice in Asia and Stokes and Howden (2010) considered cropping in Australia. Meanwhile, breeding for better adaptation across crops was reviewed by Chapman et al. (2012), and for heat tolerance in wheat by Cossani and Reynolds (2012).

A growing number of papers use simulation to test proposed adaptive cropping changes in the face of changed climates. Most suffer from the criticism noted above—too many assumptions and too little validation for what they are trying to achieve. It is worth mentioning one apparent exception (Zheng et al. 2012), which evaluated effects of warming across the Australian Wheat Belt. First, effects were examined on the spring flowering window that exists between the risk of late spring frost and that of early summer heat, and second, on the autumn sowing window for early, medium and late maturity wheat varieties. The flowering window, of course, will likely become earlier with warming, bringing changed sowing dates that were estimated for each variety type. Simulation of yield effects and of the most adaptive maturity strategy will no doubt follow, but these face greater uncertainties arising from inadequate understanding of both the crop physiology and climate change.

Much of the climate adaptation literature simply reports on avenues for yield increase that are well known even in the absence of climate change. Little effort is made to identify new pre-emptive research on adaptation that may be warranted given likely warming and associated CO₂ rise. There are frequent calls for more drought research, but because drought has always been an issue, and because of the uncertain direction of future rainfall predictions, extra weighting for drought research seems hard to justify. A case perhaps could be made for extra effort on submergence and salinity tolerance in rice for which the threat of sea-level rise looms largest (Wassmann et al. 2009). Warming may also increase vpd levels, but adaptation to this added complication is not considered here, given uncertainties.

Across the globe, research managers and policymakers need to be careful that the upsurge of 'climate change' initiatives does not distort allocation of scarce research resources. Thus the focus of the brief discussion below is on plausible specific genetic and agronomic adaptations to warming and to increases in CO₂ and ozone.

Plant breeding

There is little evidence for varietal differences in sensitivity of yield to higher temperature alone; such analyses are difficult to make due to the frequent presence of other complicating environmental factors such as water stress. CIMMYT has been targeting

wheat selection for high-temperature environments across the globe since the late 1980s. Attempts have been made to measure their progress in specific adaptation to heat (Lillemo et al. 2005; Gourdjji et al. 2013). To date progress has been limited and/or unclear, perhaps because special diseases dominate many hot sites. However, it appears that the CIMMYT activities represent the only major effort to breed for specific heat tolerance, and such research should be expanded.

Since the general increase in crop development rate with chronic heat (warming), and consequent reduction in crop growth duration and yield, appear to be at the heart of PY reduction with warming, one obvious question is whether there is useful **genetic variation in the response of development rate to warming**. This question implies that there is genetic variation in the cardinal temperatures for developmental processes in Table 10.2, since they control the sensitivity of duration to temperature. White (2003) and Parent and Tardieu (2012) found no varietal differences across 17 crops, including all the major ones, although there were differences among species, which tended to accord with their origin (tropical vs. temperate). Moreover, Parent and Tardieu (2012) argued that the sensitivity of developmental processes to temperature is a fundamental property that will be difficult to alter, since it appears not to have been affected by plant breeding even when comparing varieties from very different environments (e.g. Japonica vs. Indica rice varieties).

The conclusion of the previous paragraph does not imply that **genetic variation in duration of developmental phases at a given temperature** does not exist; thus the possibility of a genotype with a long phase under normal temperatures accelerating to an optimal duration under warmer temperatures cannot be ruled out. Certainly genetics can slow overall development through altering vernalisation and photoperiod requirements, or lengthening the minimum vegetative period (often known as the minimum number of stem nodes to flowering, or the basal vegetative period in determinate cereals). Breeders have sometimes increased PY by causing development to slow and delaying flowering to permit more vegetative growth, as demonstrated in situations where photoperiod drives very rapid development, such as for spring wheat at high latitudes (Section 3.6) and soybean at lower ones (Sections 6.2 and 6.3). In maize, PY appears to be positively related to the overall GDD of the hybrid (discussed below). However, in other examples with wheat and rice, breeders have increased (or at least maintained) PY while shortening duration, clearly increasing PY per day (of overall crop growth duration) in either crop.

As discussed in Section 9.3 on increasing PAR_i , physiological understanding explains the **apparent independence of PY and overall crop growth duration** in such examples as above by relating grain number (GN) to crop growth in a key, short developmental period around flowering. In turn, PY is related to GN, and (to some extent) grain-filling duration by its influence on GW. In other words, and as explained in Section 2.6, overall crop growth duration is the sum of a vegetative period (before floral initiation), a reproductive GN-determining period and a grain-filling period. These durations may be unrelated, since most genetic variation in overall crop growth duration arises because of variation in the length of the vegetative period, exemplified by a comparison of winter and spring wheats (R.A. Fischer 2011).

Vegetative duration is related both to the number of vegetative (leaf) nodes on the main stem before floral initiation and the rate of appearance of these leaves (phyllochron). The former is under genetic controls (as used to date by breeders), while the latter appears to be fundamentally linked to temperature (probably by the rate of cell division) with only small genetic variation. The negative influence of higher temperature on overall duration might arise from shortening of all three periods, but the negative influence on yield probably arises more from shortening the duration of the critical GN-determining period, provided that the vegetative period has been long enough for full light interception to have been reached. For this reason, any effort to counter the generally negative effect of warming on yield will require particular attention to the GN-determining period. Some genetic effects on duration of this period (e.g. operating by photoperiod sensitivity genes), and small genetic effects on the GDD duration of grain-filling, are reported, but their value for maintaining duration under warmer conditions has not been adequately studied.

As alluded to in Section 9.3, **maize may behave differently in terms of the lack of independence of its developmental phases.** In the US Corn Belt and in temperate Argentina, there appears to be a strong positive relationship between total GDD from emergence to maturity (GDD_t) and PY across hybrids of differing duration, even after exclusion of early hybrids that do not reach full light interception (see also Section 9.3). This effect may arise because grain-filling duration appears to increase as the duration from seedling emergence to silking increases across these hybrids, with duration of the former increasing by 1.2 days for each increase of 1 day in the latter for the USA (Yang et al. 2004) and 0.7 d/d for Argentina (Capristo et al. 2007). Yang et al. (2004) incorporated the relationship into the model Hybrid-Maize, leading to a relative relationship between PY and GDD_t (and GDD emergence to silking) such that a 1% increase in duration gives a 1% increase in PY, other things equal and as seen for example in Cassman et al. (2010). Assuming no effects on RUE, it seems that, in the face of warming, simple selection of hybrids with greater GDD_t would maintain production levels of DM and PY.

The above suggestion that maize yield may be maintained with genetic systems to increase GDD_t , thus holding the temporal duration and balance between pre- and post-tasseling periods steady despite warming, needs further research. However, yield maintenance would surely require that the effect of warming on the duration of the short critical GN-determining period around silking be similarly countered. A similar doubt arises with rice, in the case of the 1:1 relationship between GDD_t and PY that Timsina et al. (2011) showed using ORYZA2000 to model the response of PY to proposed genetic change in GDD_t .

As mentioned, there has been little study of genetic variation in duration of the key development stages directly linked to yield (i.e. flowering and grain development)—stages that are presumably accelerated by warming. Therefore longer duration (i.e. longer GDD) for these key stages certainly merits further exploration as a mechanism to counter yield loss from warming. At the same time, exploiting the earliness that comes with warming by producing more crops per year is another worthwhile strategy for maintaining grain production per year.

An entirely different negative aspect of warming is **the response of flowering effectiveness to heat stress**, one for which some useful genetic variation in crops is available. In controlled temperature glasshouses, Wardlaw et al. (1989) showed large varietal differences in wheat in response to exposure to chronic heat of 30/25 °C (T_{\max}/T_{\min}) compared with 18/13 °C from flag leaf emergence to spike emergence (booting period). The reduction in grains per spike ranged from 10% to 80% across varieties. With separate but similar heat treatments during grain-filling, the GW reduction ranged from 15% to 55%, but varietal sensitivities were not correlated between the two stages, even though reductions appeared to be lower in varieties from warmer locations. This work, by far the most extensive investigation in any crop plant—and one that made a special effort to sample reputedly high-temperature tolerant materials from CIMMYT—has unfortunately not been further pursued.

Rice provides perhaps the clearest example of brief heat causing sterility, and of genotypes differing in sensitivity to this stress (Prasad et al. 2006; Wassmann et al. 2009). Although sterility can arise from temperatures above ~35 °C at male meiosis (some days before flowering), even greater sensitivity is seen at anthesis (flowering) where, for example, fertility ranged from 18–71% across genotypes after 6 hours at 38 °C (Jagadish et al. 2010). Several aspects of anther and pollen physiology, including the time of day when pollen is shed, seem to be involved in this heat-induced male sterility. Thus flowering effectiveness in rice under high temperature seems complex; unravelling its genetic basis (starting with molecular markers for this quantitative trait) could be useful in breeding (Wassmann et al. 2009).

Brief heat at anthesis when the temperature exceeds ~35 °C (such as hot spells) is also well known to induce sterility in wheat. Remarkably, however, there appear to be no reports of varietal differences in hot spell – induced sterility, although some wild relatives appear to be more tolerant than cultivated wheat (Pradhan et al. 2012). The situation is little better with maize, although 30 years ago, Herrero and Johnson (1980) suggested that pollen viability under heat differed among varieties. Also, Rattalino Edreira et al. (2011) reported that GN in a tropical maize hybrid was less sensitive to heat around silking than was a temperate hybrid.

One of the clearest examples of breeding based on a heat tolerance trait is that of cowpea in southern California, USA (Hall 2004). Targeted selection under heat was able to overcome the suppression of floral bud development by heat and the induction of sterility by high night temperatures (>16 °C), leading to the release of an adapted variety for the hot summer environment of the San Joaquin Valley.

A great deal has been published about plant heat stress **responses at the metabolic and molecular levels** in the past 25 years. Researchers attempt to relate these responses—often involving membrane disruption—to heat damage in key physiological processes such as photosynthesis, respiration or seed setting (identified above). Whenever there is heat stress, it seems that a multitude of genes change activity, with many heat shock and other new proteins and reactive oxygen molecules produced. Through gene manipulation, some of these changes have been linked to the improved

heat tolerance that occurs normally when plants acclimate to heat (e.g. Wahid et al. 2007; Barnabas et al. 2008). However, very few changes (if any) have been linked to the sort of genetic variation in heat-induced sterility discussed above. This effect is probably explained by three considerations:

1. Heat tolerance is likely to be multigenic and complex.
2. Simple screening for heat tolerance is difficult, although electrolyte leakage from the leaf disc is an example of one such test showing some promise (Reynolds et al. 1994).
3. Not many genetic differences have been characterised by physiologists.

Molecular markers for heat tolerance in key processes may eventually be developed and prove useful in breeding, but progress seems very slow (Wahid et al. 2007). Similarly, some targeted genetic engineering (GE) has increased heat tolerance in laboratory systems, but this work is in its infancy. Wahid et al. (2007) suggested that there may be scope to use certain chemicals to induce heat acclimation and improve tolerance by pre-treating seeds and plants of otherwise desirable varieties, but again progress is limited. Empirical selection, facilitated by smart screening, plus targeted searches among crop genetic resources from hot locations, may offer the best prospects for what is essentially (at this early stage) pre-breeding for heat tolerance.

Given concerns about heat it is surprising how little knowledge there is about the physiological basis of genetic differences in heat sensitivity at flowering—noting that the cowpea example mentioned above is a clear exception. Perhaps it is because sterility differences at moderately high temperatures have been eliminated during breeding by natural selection, and are only now revealed with extreme heat stress.

Genetic differences in dark respiration rate were reported in perennial ryegrass by Wilson and Robson (1981) to be associated with more plant growth in low respiring lines. This finding is intriguing given that accelerated maintenance respiration (see Section 2.6) is often ascribed a role in reducing growth at higher temperatures. Although the research into respiration genetics appears to have lapsed, it may point to useful varietal differences when there is a high cost of maintenance respiration at higher temperatures.

In concluding this discussion of genetic variation in response to heat stress, note that investigators have not been sufficiently aware of the **transpirational cooling of the organs affected by heat stress**, which is a simple function of stomatal conductance and vpd. Canopy cooling may be a possible indirect route to heat tolerance. For example Lu et al. (1994) claimed that modern varieties of cotton have less heat-induced floral bud abortion than older varieties because their stomata are more open and consequently their canopies are cooler. Similarly, Amani et al. (1996) reported that the crop canopy was easily cooled by 6 °C (relative to air temperature) in irrigated wheat when vpd was ~4 kPa; the cooling effect differed by >2 °C across varieties, and was strongly correlated with yield under warm conditions. The cooling depends on an abundant water supply and high vpd. Partial stomatal closing induced by further CO₂ increase could lessen the chances for such heat escape.

We might expect plant breeding to have unintentionally built **adaptation to higher CO₂** in more recent crop varieties. In Section 9.4 on increasing RUE, varietal differences in response to higher CO₂ in canopies in the field are mentioned for rice (Moya et al. 1998), soybean (Ziska and Bunce 2000) and wheat (Ziska 2008). Older varieties seem more responsive, which is quite surprising.

Ainsworth et al. (2008b) realistically reviewed adaptations to higher CO₂ at the physiological level and pointed out that plants evolved at much lower CO₂ levels (~200 ppm), to which they may still be attuned. Possible adaptations for improving photosynthetic performance at higher CO₂—which are not exactly the same as adaptations for higher P_{max} discussed in Section 9.4—include:

- optimisation of the properties of Rubisco (the enzyme involved in the first major step of carbon fixation)
- faster regeneration of the CO₂-acceptor molecule, ribulose-1,5 biphosphate (RuBP), through increasing key enzymes in its synthetic pathway
- better utilisation of carbohydrate, which tends to accumulate in leaves at higher CO₂.

Genetic engineering may be able to realise the opportunities that higher CO₂ seems to offer C₃ crops, but the task will not be easy. Much more pre-emptive research in this area is warranted because CO₂ levels continue to rise.

Crop variety differences in **sensitivity to ozone concentration** are well recognised, having been reported in wheat (Biswas et al. 2008; Feng et al. 2011), rice (Pang et al. 2009; Shi et al. 2009) and soybean (Robinson and Britz 2000). In wheat, damage from ozone is greater with more modern varieties, and this seems closely related to greater stomatal conductance (Biswas et al. 2008). Fortunately not all variation in sensitivity can be explained by stomatal conductance (Feng et al. 2011), offering some prospect for increased tolerance without a yield penalty. Increased leaf antioxidant capacity could be important in detoxifying ozone which enters leaves (Ainsworth et al. 2008b); again plants have not evolved with elevated ozone concentrations, but biotechnological solutions require much more research.

10

Crop agronomy

There are a multitude of possible agronomic adaptations to warming. Many adaptations will interact with change in crop variety, especially adaptations related to crop growth duration. This difference is very much a question of crop and region, but the overall result in many situations is heartening, at least for warming out to 2050. Agronomic adaptation options for each major crop—wheat, rice, maize and soybean—are discussed briefly below.

For **wheat** at lower latitudes, warmer winters would produce more winter growth from a given sowing date in the autumn, accommodating earlier flowering (especially if frost risk also declines), and probably maintaining (or even improving) yield levels for both

rainfed and irrigated crops (assuming other things equal). For wheat (and barley) at intermediate latitudes, it may seem counterintuitive that improved genetic tolerance of frost around flowering could protect yields against warming by permitting flowering in the earlier, cooler part of the spring. This advantage could apply even if global warming causes less-frequent spring frosts, something which is not at all certain. For the first time, researchers in Australia have clearly demonstrated genetic differences in flowering frost tolerance in wheat (B. Biddulph, pers. comm. 2012).

Winter wheats could be sown later to deal with excessive winter growth in warmer winters, and the optimal flowering date could move earlier, which would improve water supply but perhaps lessen solar radiation in later critical phases. A big benefit, however, would be displacement of lower yielding spring wheats by winter wheats that spread to more northern latitudes as the risk of winter-kill declines (see Section 3.6). At higher latitudes, where winter wheats still do not survive, earlier planting of spring wheats of longer duration would likely lead to yield gains. Also new agronomy will likely be needed if the northern limit for spring wheat moves further northwards.

Speculation about greater summer rainfall (and less winter rainfall) with climate change in the southern Australian rainfed Wheat Belt has stimulated efforts to increase opportunities for earlier sowing—with generally better yield prospects—by, for example, more efficiently storing fallow water from the summer (Kirkegaard and Hunt 2010). Steady improvement in seasonal climate forecasts, based on global circulation models, for cropping in Australia (and potentially elsewhere) have given farmers a significant advantage to strategically and tactically manage rainfed cropping in the face of variable weather—even as influenced by climate change.

Compared with wheat, **rice** is grown in especially complex cropping systems. Thus, warming opens various opportunities by also shortening the duration of other crops in the rotation. This may mean earlier planting of rice to avoid heat at flowering, and could facilitate double- or triple-rice cropping. Even where (at high latitudes) there is no winter crop, earlier planting of the summer rice crop could be advantageous to yield if the risk of chilling damage to seedlings or at meiosis is also reduced.

The effect of climate warming on **maize** will be a continued poleward spread of this crop at high latitudes. Through use of longer GDD_t maize hybrids—with possibly higher PY, and/or less risk of frost damage or high grain drying costs at the end of the season—warming will permit earlier planting and the accompanying yield benefits. Warming will also facilitate conservation agriculture in high-latitude maize by increasing soil warming in the spring under retained crop residues. At lower latitudes, scope will increase for 'winter' maize in situations like the lower Indo-Gangetic Plain of India and Bangladesh (see Section 5.6), resulting in higher grain productivity and less water use than wheat and winter rice.

In Sub-Saharan Africa and Latin America, rainfed summer maize dominates in the summer wet season. Most maize crops there already encounter T_{mean} values above the optimum for maximum yield (Lobell et al. 2011a) so options for agronomic adaptation are more limited. Moreover in Sub-Saharan Africa, agronomic adaptation to climate

change is not a high priority given other major agronomic limitations—poor soil fertility, weeds, unnecessary tillage and shortage of draft power (as described in Section 5.4). In South America, these problems hardly exist, and (depending on rainfall distribution) the flexibility permitted by mechanisation enables adjustment of planting dates (earlier or later) and switching to varieties of different duration to shift flowering away from the hottest time of year, if warranted with climate change.

The situation for **soybean** is positive. At intermediate latitudes with good moisture (e.g. Argentina or south-eastern USA), double cropping with summer soybean is often restricted by delayed harvest of winter crops, as seen, for example, with lower yields from planting after wheat harvest than planting 1 month earlier. Warming will therefore facilitate double cropping, and make unnecessary the elegant (but scarcely practical) solution of precision mechanised relay cropping of soybean into unharvested wheat, as proposed by Calviño and Monzon (2009). At higher latitudes (such as the Mid West of the USA), soybean planting is often delayed with yield penalties until maize planting has been completed (see Section 6.2). Warming should permit on average earlier planting of both crops, and just as with maize, soybean could spread poleward with warming.

A complete change of crop species represents the best agronomic response to climate change. Current examples are where maize and soybean replace wheat and canola in the southern parts of the Canadian province of Manitoba, and where wheat replaces barley at higher latitudes. But temperature increases in those middle and low latitude areas already growing maize and soybean pose a greater challenge. Here sorghum and millet, mungbean and cowpea are probably more heat tolerant than maize and soybean, but other things equal, are less productive. Thus there is scope for rebalancing breeding investments. Cassava is clearly more heat tolerant than maize or soybean, but its long-term future depends on the development of mechanised systems for harvesting.

Conclusion on adaptation

Despite considerable uncertainty about the rate of warming—and especially precipitation and ozone change—there is some certainty about a negative yield effect of warming, and the benefits of increased CO₂ for C₃ crops. Fortunately, there is large scope out to 2050 for adaptation to lessen these potential negative influences.

Important adaptations can be expected from conventional plant breeding, especially if resources permit targeting of tolerance to specific heat stresses. It is difficult to list distinct agronomic changes that might arise in response to climate change because such changes are so intimately linked to local cropping systems. Changes are also tied to many agronomic adaptations for 'normal' crop improvement, as conducted by researchers and farmers in the face of 'normal' weather fluctuations and trends. Moreover, agronomic adaptation to climate change will undoubtedly be substantial. Taken along with possibilities for breeding to supplement adaptation, PY and PY_w may not be greatly affected by the predicted climate change out to 2050—this even applies to the drying predicted by some models for some rainfed cropping regions.

10.5 Greenhouse gas emissions from cropping and their mitigation

Global warming potential (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. In Table 10.5, total annual GWP figures from IPCC (2007) are shown for land clearing and agriculture in 2004; agriculture comprised 13% of the GWP of total global emissions. The GWP figures combine emissions of the three major greenhouse gases, measured in terms of CO₂ equivalent mass (CO₂-e), applying a 100-year view of the atmospheric residence time of the particular gas (IPCC 2007):

- carbon dioxide (CO₂)
- nitrous oxide (N₂O); mass multiplied by 296 to determine CO₂-e
- methane (CH₄); mass multiplied by 23 to determine CO₂-e.

In addition, a multiplier of 3.67 is used to calculate the CO₂-e when emissions are expressed as the mass of elemental carbon (as is the case in some reports).

Atmospheric concentrations of the three major greenhouse gases (listed above) have been steadily increasing since pre-industrial times. However, much uncertainty surrounds the estimated annual rates of emission, including those in Table 10.5. Thus Tubiello et al. (2013) recently suggested that total global emissions in 2010 were only 4,400 Mt CO₂-e from land clearing and 5,600 Mt CO₂-e from agriculture—a notable decrease from the 2004 values shown in Table 10.5. While land clearing has probably decreased since 2004, it is surprising to see a reduction in agriculture emissions, and thus the difference in results may point to differences in estimation methodology.

On a global scale, if total harvested crop area is taken to be 1,400 Mha (Section 1.4), then the total annual cropping emissions shown in Table 10.5 (4,225 Mt CO₂-e) amount to an annual figure of ~3 t CO₂-e/ha. The greenhouse gas contribution from agriculture is annually increasing, although the contribution is decreasing as a fraction of global GWP emissions from all sources, which are increasing even faster. In the USA, agriculture now contributes only 7% of total US greenhouse gas emissions (USDA 2011) and the recent worldwide figure is similar (Tubiello et al. 2013).

Microbial production of N₂O in soils and manure is the dominant source of global N₂O emissions from agriculture (Table 10.5). For cropping, the largest source of GWP is also N₂O emission from soils, amounting to almost 50% of the cropping total in Table 10.5, followed by methane from rice. Finally, the last four components in Table 10.5, including fertiliser manufacture, all contribute CO₂-e emissions derived from the fossil fuel consumed in manufacture, transport and on-farm operations.

Table 10.5 Annual global greenhouse gas emissions related to agriculture, estimated for 2004 and including carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄)

Source of emissions	Total annual emissions (Mt CO ₂ -e GWP) ^a	Emission contribution from agriculture (%)	Comment
Land clearing	8,500	na	17% of world emissions
Agriculture	6,500	100	13% world emissions
Animal agriculture			
Ruminants	1,690	26	CH ₄
Manure (all farmed animals)	585	9	Includes CH ₄ and N ₂ O
Total	2,275	35	
Cropping			
N ₂ O from soils	2,080	32	Includes N ₂ O from fertiliser ^b
CH ₄ from rice	715	11	High because of anaerobic flooded soils
Fertiliser	455	7	Manufacture and transport
Machinery	390	6	Manufacture and use
Irrigation	390	6	Pumping water
Pesticides	195	3	Manufacture and use
Total	4,225	65	

a GWP = global warming potential measured in megatonnes (Mt) of CO₂ equivalent mass (CO₂-e)

b Much uncertainty surrounds this, but IPCC (2007) assumes 1% of fertiliser nitrogen is directly lost from the soil as N₂O (see text).

Source: IPCC (2007) for land clearing and agriculture (to the farm gate); Connor et al. (2011) for breakdown into percentage of agricultural emissions

The real issue for greenhouse gas mitigation in agriculture, however, is how much GWP is released per unit of agricultural product at the farm gate. Such a metric is referred to as **yield-scaled emissions** (Linguist et al. 2012), and the question is how this metric can be affected by yield increase. If the cropping emissions in Table 10.5—net of rice CH₄, which is a special case—are equated to non-rice (wheat) grain equivalents (calculated from calories) produced in 2004, the yield-scaled emissions are ~1.4 kg CO₂-e/kg grain. For rice, the CH₄ component alone is ~1.1 kg CO₂-e/kg of paddy rice.

Just as the energy used per unit of product has fallen over the past 20 years in modern agriculture (Section 11.4), it is likely that yield-scaled GWP emissions have fallen also. Unfortunately, however, additional complications arise, especially with uncertainties about N₂O emissions from nitrogen fertiliser use. Nevertheless, Keystone Center (2009) estimated changes in GWP emissions associated with maize, soybean and wheat in the USA. These authors considered greenhouse gases from all energy and nitrogen fertiliser inputs, adding an estimate of net soil sequestration of CO₂ (i.e. a build-up of soil carbon of 1.24 t CO₂-e/ha/yr, but only for land under continuous zero-till). The changes in yield-scaled GWP emissions between 1987 and 2007 (shown as CO₂ equivalent per kilogram of grain yield in 2007) for each crop were:

- +14% to reach 0.34 kg CO₂-e/kg wheat grain
- -23% to reach 0.18 kg CO₂-e/kg maize grain
- -37% to reach 0.11 kg CO₂-e/kg soybean grain.

The increase in yield-scaled emissions for wheat suggests that increased use of nitrogen fertiliser later in the study was not balanced by proportionate FY increases. Yield-scaled GWP for wheat in 1987 could be artificially low because more nitrogen was being supplied by breakdown of the native soil organic carbon, and calculations did not allow for this.

The Keystone Center (2009) numbers for US grain crop GWP intensity are much lower than the global figure of 1.4 kg CO₂-e/kg of grain mentioned previously in relation to Table 10.5. This figure likely reflects the high efficiency of modern farming as practised in the USA, but could also partly be because the Keystone Center (2009) analysis omitted soil N₂O losses that were not directly linked to fertiliser nitrogen emissions (see below). However, the Keystone Center (2009) numbers are confirmed by a central Nebraska (USA) study of irrigated maize (Grassini and Cassman 2012). Under a very high input system across many farmer fields, and including estimation of N₂O losses associated with nitrogen fertiliser and other nitrogen sources, these authors recorded a median GWP intensity of 0.22 kg CO₂-e/kg of maize. This value was reduced by 15% for sprinkler irrigation (compared with flood irrigation) due to lower water use, and hence pumping, and reduced by 10% in a rotation of maize after soybean (compared with maize after maize) due to lower nitrogen fertiliser and higher maize yields.

In a detailed 18-year study of wheat rotations in the dry conditions of Alberta, Canada, with wheat yields ~2 t/ha, Bremer et al. (2011) calculated that GWP intensity (from energy use plus N₂O emissions) increased from 0.12 to 0.18 kg CO₂-e/kg as nitrogen rate increased from zero to 40 kg of nitrogen per hectare (kg N/ha). However, SOC loss was also measured, and when this factor was included in the GWP calculation, the effect of the nitrogen fertiliser was reversed. Average GWP for fallow wheat fell with nitrogen from 0.41 to 0.33 kg CO₂-e/kg, and similarly for continuous wheat from 0.15 to 0.03 kg CO₂-e/kg. This decrease occurred because nitrogen fertiliser, as well as increasing grain yield, reduced the SOC loss.

Efforts to reduce the yield-scaled GWP emissions of crop production relate partly to energy efficiency, which is discussed in Chapter 11.⁴⁸ However, four other important avenues for greenhouse gas mitigation exist with cropping:

1. reductions in N_2O emissions from agricultural soils in general, and by reductions in emissions from applied nitrogen fertiliser (and/or manure) in particular
2. reductions in CH_4 emissions from flooded rice and other agricultural systems
3. net carbon accumulation or sequestration in cropping soils
4. reductions in land clearing for cropping.

These will be discussed briefly below, noting that N_2O emission can also be affected by many agronomic practices that influence carbon sequestration.

Emissions from nitrogen fertiliser manufacture and nitrous oxide emissions from soil

When considering the overall GWP associated with nitrogen fertiliser, **energy costs for manufacture are high**. Lal (2004) considered manufacturing costs of urea fertiliser, $CO(NH_2)_2$ —the most common form of nitrogen fertiliser—in CO_2 equivalent per kilogram nitrogen applied, and arrived at a figure of 4.8 kg CO_2 -e/kg N. Snyder et al. (2007) reported CO_2 equivalent per kilogram for production of ammonia (NH_3) fertiliser nitrogen—another form of nitrogen fertiliser—and used an average figure of 2.5 kg CO_2 -e/kg N. Snyder et al. (2007) went further than Lal (2004) and argued that full GWP accounting should also include CO_2 released directly from:

- the amount of lime needed to balance acidification caused by most nitrogen fertiliser forms (reported as 0.84 kg CO_2 /kg N applied)
- the fertiliser molecule when urea is used as the nitrogen source (reported as 0.80 kg CO_2 /kg N applied).

On this basis, the full GWP account from Snyder et al. (2007) totals 5 kg CO_2 -e/kg N applied (from urea), which is similar to the number derived by Lal (2004); the figure is somewhat less, at ~ 3.5 kg CO_2 -e/kg N applied, if ammonia fertiliser is used. When ammonium nitrate (NH_4NO_3) fertiliser is used, the value is closer to 10 kg CO_2 -e/kg N applied, because N_2O is released during manufacture with current technology (Snyder et al. 2007).

The other major GWP cost associated with use of nitrogen fertiliser is the **N_2O emissions when nitrogen fertiliser is mineralised in the soil**. These emissions occur through small amounts of leakage during the microbial processes of both:

48 Conversion of energy consumption to CO_2 depends on the energy source: 1 MJ from diesel is accompanied by the release of 77 g CO_2 ; from petrol, ~ 70 g; and from liquid petroleum gas (LPG), only ~ 50 g (Lal 2004; Smil 2008). Lal (2004) lists estimated carbon emissions associated with various farm operations.

1. **nitrification**—the process through which ammonia (NH_3) is converted to nitrate (NO_3^-) under aerobic conditions
2. **denitrification**—the process through which NO_3^- is converted to nitrogen gas (N_2) under anaerobic conditions.

Denitrification is clearly the more important of the two processes for N_2O emissions, and hence waterlogging arising from heavy rain and poor internal drainage are important predisposing factors.

IPCC (2007) calculates direct losses of N_2O emission through mineralisation as 1% of fertiliser nitrogen and/or nitrogen from other inputs (such as compost, manure and nitrogen in irrigation water).⁴⁹ Because of the large GWP of N_2O —recall the CO_2 equivalent multiplier of 296 for N_2O mass—direct losses of N_2O from fertiliser use amount to 4.65 kg $\text{CO}_2\text{-e/kg N}$ applied. Thus, by adding the GWP of 1% N_2O emissions from fertiliser mineralisation in the soil (IPCC 2007) to the GWP of 5 kg/ha $\text{CO}_2\text{-e}$ from the full GWP costs of making urea fertiliser (Lal 2004; Snyder et al. 2007), the **total GWP for urea amounts to ~10 kg $\text{CO}_2\text{-e/kg N}$** applied. This is similar to the figure of 9 kg $\text{CO}_2\text{-e/kg N}$ used by Tilman et al. (2011) in their general global study of the GWP costs of closing yield gaps with nitrogen fertiliser (see below).

Using the 1% figure for losses, Snyder et al. (2007) in turn estimated that in 1995 only 35% of the estimated agricultural N_2O emissions in the USA came from nitrogen fertiliser, and the figure for the world was 23%. In 2004 when ~90 Mt nitrogen equivalent fertiliser was used globally (FAOSTAT 2013), a 1% N_2O loss of fertiliser nitrogen represented only 20% of the world's total cropping soil N_2O emissions (2,080 Mt $\text{CO}_2\text{-e}$; Table 10.5). This calculation raises questions as to the origin of the other 80% of N_2O emissions, or alternatively, suggests that the 1% figure—calculated by IPCC (2007) as the mean of many wide-ranging estimations and measurements—is underestimated. For example, estimates of N_2O losses from nitrogen fertiliser use in 2008 in China were higher at 1.4% (Tian et al. 2012).

Geochemists working down from annual global atmospheric N_2O changes in relation to changes in manure and fertiliser production have also calculated higher numbers for fertiliser nitrogen loss, including a 2.5% figure from Davidson (2009) who estimated also a 2% loss from all manure nitrogen. Other sources of nitrogen in the cropped soil could also be involved in N_2O emission, such as biological nitrogen fixation or organic matter breakdown (much of which could contain fertiliser nitrogen from earlier years). Further, sources of N_2O outside of cropped soils (but linked to them) could include fertiliser nitrogen escaping the system through ammonia volatilisation and nitrate leaching; IPCC (2007) assumed that these losses add 0.33% of nitrogen from N_2O (N_2O -nitrogen) to their previous 1% figure. Obviously uncertainties abound, and as such, this chapter keeps to the IPCC method (based on 1% direct loss from inputs), or preferably when

49 Under drier conditions losses are likely to be lower; for example in western Canada, a figure of only 0.16% nitrogen loss as N_2O is assumed (Bremer et al. 2011).

measurements permit, the nitrogen-surplus method based on field-level measurement of emissions (see below).

Many have considered **whether nitrogen fertiliser can be better managed to reduce greenhouse gas emissions**. Snyder et al. (2007) summarised scores of experiments on nitrogen fertiliser management and N_2O emission measurement. Unfortunately, N_2O emission studies on the source and placement of nitrogen fertiliser, and/or interaction with tillage systems, have not yielded consistent results. It is, however, safe to conclude that good strategies to maximise nitrogen use efficiency by crops (see Section 11.3) will also minimise emission of N_2O , and will always include:

- timing nitrogen fertiliser application to match that of crop uptake
- ensuring application rates do not exceed the optimum
- maintaining an appropriate balance between nitrogen, phosphorus and potassium (the N:P:K ratio)
- for rice, continuous flooding immediately after nitrogen fertiliser application.

Use of slow-release forms of nitrogen fertiliser, and nitrification inhibitors, for situations where application precedes peak crop demand—for example, the common autumn application of NH_3 fertiliser for spring-planted maize in the US Corn Belt—have given variable results (e.g. Parkin and Hatfield 2010). Biochar (apparently inert charcoal, see Section 10.5) is reported to reduce N_2O emissions from denitrification in many soils, but the required quantities appear to be very large (Cayuela et al. 2013). Moving application timing closer to that of crop demand—for example, less pre-planting NH_3 and more post-planting urea for irrigated wheat in the Yaqui Valley (Matson et al. 1998)—can reduce N_2O emissions. Nitrogen in manure applied to cropping soils behaves much as it does in fertiliser, and is subject to similar (and equally uncertain) losses and management rules for reducing losses.

A breakthrough came when van Groenigen et al. (2010) conducted a meta analysis of 19 studies, grouping results by nitrogen rates to reveal that average measured N_2O emissions fluctuated between 1 kg and 2 kg N_2O -nitrogen per hectare. No trend was seen as applied nitrogen rose from zero to 200 kg N/ha, but above that, N_2O emission rose dramatically. The van Groenigen team scaled N_2O emissions to crop nitrogen uptake and noted that emissions were lowest (~ 10 g N_2O -N/kg N uptake) when the nitrogen application rate was less than or close to 200 kg/ha—the approximate economic optimum. Around this point, crop nitrogen uptake was about equal to nitrogen applied, but above this point, N_2O emissions per kilogram of crop nitrogen uptake rose sharply. Additional nitrogen applied beyond the economic optimum was presumably surplus to crop need and more susceptible to loss by denitrification (and hence more N_2O emissions). This reasoning became the basis of the nitrogen-surplus method for estimating N_2O emissions from nitrogen fertiliser.

Grassini and Cassman (2012) used the nitrogen-surplus method to estimate N_2O emissions in their maize study in Nebraska, USA (see Section 11.3), estimating that emissions could be reduced by 20% of estimated values with current practices across

their studied fields if nitrogen could be managed to avoid surplus. In another recent meta analysis, Linquist et al. (2012) reported N_2O emissions from rice, wheat and maize crops at 62 study sites involving little overlap with the van Groenigen et al. (2010) study. Individual observations showed N_2O emissions significantly increased with rate of nitrogen applied. Slopes for mass of N_2O -nitrogen emitted per kilogram of fertiliser nitrogen applied were:

- 0.7% for rice (or 0.007 kg N_2O -N/kg N)
- 1.2% for wheat
- 1.1% for maize.

However, the relationship between N_2O emissions and rate of nitrogen application did not explain more than one-third of variation in emissions.

Following van Groenigen et al. (2010), Linquist et al. (2012) also reported that average yield-scaled N_2O emissions rose sharply in wheat and maize when nitrogen application rate exceeded 200 kg N/ha, with the lowest average values for each crop occurring at ~92% of maximum yield (when nitrogen application rates were 125–200 kg N/ha). Reported as CO_2 equivalent, yield-scaled emissions of N_2O at maximum yield were:

- 0.03 kg CO_2 -e/kg paddy rice grain
- 0.15 kg CO_2 -e/kg wheat grain
- 0.17 kg CO_2 -e/kg maize grain.

These and other studies establish that optimised rates of nitrogen fertiliser application can maintain high yields while minimising yield-scaled N_2O emissions. However, observed optimal rates vary greatly (e.g. with field history and weather), indicating that substantial local research is needed to improve prediction of optimum rates.

In the absence of recent nitrogen fertilisation, Linquist et al. (2012) reported nil N_2O emission from flooded rice, but ~1 kg N_2O -N/ha/season for wheat and maize. These substantial background emissions for aerobic crops are undoubtedly the consequence of cropping soils maintained at relatively high mineral nitrogen levels for high productivity. In this case much mineral nitrogen comes from nitrogen application in previous years (including manure) or from prior use of legumes. **Soil management that can reduce any large build-up of mineral nitrogen, and reduce the duration of waterlogging periods, will reduce N_2O emissions linked to denitrification.** In some European systems, catch crops are planted in the autumn to take up surplus soil mineral nitrogen and thereby reduce emission (and leaching) losses.

Legumes fix atmospheric nitrogen into NH_3 which then becomes directly available to the growing plant. Peoples et al. (2009) reported that the contribution of respiratory CO_2 to the atmosphere from biological nitrogen fixation is ~1–5 kg CO_2 /kg N fixed. This figure is more uncertain than—but not dissimilar to—the energy cost of manufacturing nitrogen fertiliser, but the energy derives from a renewable solar source. Thus, provided that no additional land is cleared to accommodate legumes in crop rotations—see

reference to Tilman et al. (2011) below—**legumes can save the energy associated with the manufacture and application of fertiliser nitrogen.**

Less clarity, however, surrounds emission of N_2O from legume-fixed nitrogen. During legume growth, emission of N_2O tends to be low, and is usually notably lower than any adjacent non-legume crop using nitrogen fertilisation (Jensen et al. 2011). However, significant soil emissions of N_2O can follow legume crops. Breakdown of legume residues results in higher soil mineral nitrogen levels—especially from residues with low carbon to nitrogen ratios. The extent of N_2O emission will depend on the timing of legume breakdown relative to denitrification events (e.g. waterlogging) and to the nitrogen demand of subsequent crops (Peoples et al. 2009; Jensen et al. 2012). While it is possible that a legume–cereal rotation (with nitrogen fertiliser on the cereal) may reduce N_2O emissions compared with continuous cereal with more fertiliser nitrogen every year (Jensen et al. 2011; Grassini and Cassman 2012), this is not always the case (Snyder et al. 2007).

In summary much uncertainty surrounds the substantial N_2O losses from soils—those linked directly to nitrogen fertiliser and manure use, and substantial other losses—which together amount to ~50% of the GWP of global cropping. Better management of nitrogen fertiliser and manure application—in particular, avoiding nitrogen applications in excess of crop demand—can significantly reduce losses directly linked to these sources, improve the all-important metric of yield-scaled emissions and save fertiliser costs. Research may reveal better strategies for reducing emissions, even as cropping systems operate at the higher levels of soil nitrogen fertility that are probably essential for higher yields. Other possible strategies to improve nitrogen fertiliser efficiency (and hence reduce N_2O emissions) are discussed in Section 11.3.

On a positive note, there is scope for progress to be made. For example, between 1985 and 2009, Denmark reduced total agricultural greenhouse gases by 28% (Danish Agriculture and Food Council 2011); this was especially due to a 32% reduction in N_2O emissions, which in 2009 represented 41% of total emissions. Mikkelsen et al. (2011) presented the calculations with clarity and detail, showing that N_2O savings particularly arose from:

- switching from solid to slurry manure management
- reducing applications of fertiliser nitrogen (now about equivalent to the amount of nitrogen applied as manure)
- reducing the fraction of total applied nitrogen that is leached from the soil (from 43% to 33%).

Reducing methane emissions from flooded rice

According to the review by Linquist et al. (2012), the anaerobic conditions of flooded rice facilitate CH_4 production from fresh crop residue. In that report, emissions ranged from zero to ~850 kg CH_4 /ha/crop, with an average of 134 kg CH_4 /ha/crop; using the

multiplier of 23 (identified earlier) to calculate the CO₂ equivalent mass, the average equates to 3.1 t CO₂-e/ha. These authors offered no explanation for the wide range, except that CH₄ emissions did not appear to be affected by rate of nitrogen application.

For crops yielding 6 t/ha paddy rice, Linquist et al. (2012) determined that yield-scaled CH₄ emissions equated to 0.57 kg CO₂-e/kg—a figure that is much greater than the GWP of N₂O from flooded rice, given earlier as 0.03 kg CO₂-e/kg. Yield-scaled emissions of CH₄ were clearly lower when yields were higher. In contrast, CH₄ emissions contributed <2% of GWP for upland crops (wheat and maize), and when Linquist et al. (2012) added GWP from CH₄ to that from N₂O, average total yield-scaled GWP from rice (0.66 kg CO₂-e/kg) was four times that of wheat (0.17 kg CO₂-e/kg) and maize (0.19 kg CO₂-e/kg) in their sample of crops.

The average CH₄ emissions from the rice experiments summarised by Linquist et al. (2012) accumulate, on an area basis, to approximately match the IPCC (2007) global figure for rice given in Table 10.5 (715 Mt CO₂-e). This figure is also reasonably close to a revised annual global figure for CH₄ from rice of 590 Mt CO₂-e calculated by Yan et al. (2009). These are large numbers in the global GWP account, amounting to ~15% of cropping emissions.

Mid-crop drainage of flooded rice reduces CH₄ emissions by ~16% (Yan et al. 2009), often without yield loss, while the increase in GWP from extra N₂O emissions is small relative to emission savings from CH₄ reductions. Yan et al. (2009) also estimate that removing straw of the preceding crop could lead to reductions in CH₄ emissions that are similar to those with mid-crop drainage.

Only modest varietal differences in CH₄ emissions are known. One study in China showed a high-yielding hybrid variety to have lower emissions when grown alongside lower yielding inbreds, in part because the hybrid appeared to have more CH₄-oxidising bacteria in its root zone (K.E. Ma et al. 2010). It is intriguing to note that some of the rice CH₄ emissions come from metabolism of root exudates in the rhizosphere, that all CH₄ emitted by flooded rice passes through the plant from soil to the atmosphere and that a large portion is oxidised during passage (Linquist et al. 2012). Each observation suggests plausible plant modifications by which CH₄ emissions could be reduced.

Increasing soil carbon sequestration

Soil carbon sequestration has become a popular subject, and change in SOC is often a big item in the GWP balance of cropping and/or tillage systems. However, soil carbon is difficult to accurately measure over short to medium periods, and many comparisons of tillage systems fail to sample deeply enough (at least to 50 cm), allow for differences in bulk density between treatments and/or properly separate plant material from SOC (Baker et al. 2007).

Despite discrepancies in analysis, at least one general observation is possible. Large decreases in SOC are seen when land—grassland, woodland or improved pasture—is

brought into cropping, until a lower SOC equilibrium is reached. At the new equilibrium, inputs will balance outputs at a level largely influenced by the cropping system, prevailing temperature and humidity, the amount of mechanical disturbance (tillage) and the level of fertilisation. Even in well-managed modern cropping systems, the new equilibrium SOC will be below the original indigenous level if native soils were not deficient in one or more essential nutrients, which can be the case.

Management options to increase equilibrium SOC in cropping soils are limited and operate slowly, although well-recognised strategies include reversion from cropping to grazed pasture, and increased soil fertility through fertilisation and/or legume green manures. The effect is undoubtedly linked to increased production and return of plant residues accompanying greater fertility. Conservation agriculture, with zero-till and crop residue retention, is also often promoted for increasing SOC.

To the extent that conservation agriculture reduces soil erosion, SOC can be conserved. However, much uncertainty surrounds the other carbon-sequestration benefits that are often invoked with switching from conventional cultivation to reduced and/or zero-till—with the associated retention of crop residue—partly because of the sampling problems for SOC mentioned. In general, however, SOC appears to somewhat increase with adequate fertilisation and reduction (or elimination) of tillage, while N_2O emissions from the system are reduced (Snyder et al. 2007). For example, Keystone Center (2009) used a figure of 1.24 t CO_2 -e/ha/yr sequestration for SOC build-up in continuously cropped zero-till fields in the USA. In contrast, USDA (2011) estimated soil carbon sequestration in 2008 to be 42 Mt CO_2 -e in the 166 Mha of cropped mineral soils in the USA, giving an average of ~ 0.25 t CO_2 -e/ha/yr—a figure much lower than the Keystone Center figure because only a small proportion of these soils are subject to continuous zero-till. In the drier Australian environment, a meta analysis of scores of studies between 1980 and 2012 found net sequestration to range widely but average about 0.5 t CO_2 -e/ha/yr in the first 10 years following the adoption of reduced tillage, residue retention or return to pasture, after which SOC build-up slowed (Lam et al. 2013).

USDA (2011) also estimated the SOC breakdown due to cultivation of the 1 Mha of drained so-called 'organic' or peat soils; this loss was a massive 30 t CO_2 -e/ha/yr for a total of 30 Mt CO_2 -e, almost as much as the total losses from all other cropped soils in the USA. Draining and cultivating peat soils in South-East Asia for oil palm is likely to involve even greater per-hectare losses of SOC.

Reviewing the role of legumes in reduced tillage systems, Jensen et al. (2011) suggested that SOC can accumulate (including at depth in the soil profile) if legumes, adequately fertilised with phosphorus and sulfur, return large amounts of fixed nitrogen to the soil. This effect is seen with cover crops, green manures and pulse grain crops with low nitrogen HI. But SOC will eventually reach a new equilibrium, and can quickly decline if tillage is increased. Finally, global warming (and hence soil warming) is likely to reduce SOC equilibrium levels, other things equal, and evidence suggests that this is already happening (e.g. Sentilkumar et al. 2009). Again it is an issue demanding more research, particularly in subtropical and tropical environments.

All the above plans to sequester more soil carbon rely on increasing soil humus (the major component for SOC). Humus will increase only when the relatively fixed ratio between its carbon–nitrogen–phosphorus–sulfur components of 100:8:2:1.4 has been met (Kirkby et al. 2011). Thus in order to increase SOC in many soils, it is important to also provide an external supply of phosphorus and sulfur (as well as nitrogen) through fertiliser, manure or legumes. Together these three additional elements add considerably to the opportunity cost of SOC build-up. For example, even the nitrogen associated with one tonne of carbon as humus would cost as fertiliser more than US\$100, a point strongly made in the Australian study (Lam et al. 2013).

Also—to truly complete the equation for soil carbon sequestration—note that application of lime (CaCO_3) is accompanied by the rapid loss of its carbon as CO_2 . The practice of liming remains an essential counter to the unavoidable soil acidification that occurs with intensive cropping through removal of alkaline crop products and leaching of NO_3 and cations. USDA (2011) estimated that 11 Mt of lime (5 Mt $\text{CO}_2\text{-e}$) was used in US cropping in 2008, an amount loosely linked to nitrogen fertiliser use (~11 Mt N/yr), but small relative to GWP directly related to this fertilisation (~110 Mt $\text{CO}_2\text{-e/yr}$) as discussed earlier.

Sequestration of carbon as biochar (the carbonaceous charcoal product obtained from burning organic materials under low oxygen) in agricultural soils is currently receiving attention from researchers because biochar appears to be very resistant to microbial decay and it carries no nutrient cost. However, it is too early to say whether biochar will play a significant role in greenhouse gas abatement.

Reducing future land clearing for cropping

New cropping technologies reduce yield-scaled GWP—the rate that existing croplands produce greenhouse gases relative to the amount of yield produced. In addition, several researchers have pointed out that reduced demand for land clearing (and associated greenhouse gas emission) is an additional indirect GWP benefit from yield progress. For example, Tilman et al. (2011) explored cropping intensification vs. land-clearing trajectories needed to meet world calorie demand, which they estimated to increase by 100% between 2005 and 2050. Note that this prediction of increased quantity of demand is somewhat larger than most other estimates (see Table 1.6).

Tilman et al. (2011) weighted future clearing by vegetation type (e.g. grassland, savanna and forest) and calculated average emissions of 308 t $\text{CO}_2\text{-e/ha}$ of land cleared, from a range spanning 18 t $\text{CO}_2\text{-e/ha}$ for grassland to 510 t $\text{CO}_2\text{-e/ha}$ for forest. SOC mineralisation over the first 20 years following clearing was also calculated to have released a further 95 t $\text{CO}_2\text{-e/ha}$, for a total average GWP of 403 t $\text{CO}_2\text{-e/ha}$.

The alternative to increasing crop area through land clearing is intensification on existing cropland; this can be achieved, for example, with increased nitrogen fertiliser use and new technology, especially in gap closing situations where current nitrogen use is low. Tillman et al. (2011) estimated that cropland intensification, which limited

land clearing to just an additional 200 Mha (+14% or 4.4 Mha/yr), would minimise extra annual greenhouse gas emissions in 2050. They projected the emissions would amount to 3,670 Mt CO₂-e from land clearing plus the extra nitrogen fertiliser required to increase cropping intensity. Lesser cropping intensification and lower yield trajectories greatly boosted land clearing and annual greenhouse gas emissions; note that Tilman et al. (2011) worked with carbon equivalents (C-e), which have been multiplied here by 3.67 to provide CO₂-e for consistency.

There are challenges to the favoured option promoted by Tilman et al. (2011). The optimal 'land sparing' strategy relies on very high annual increases in global crop yield; these authors reported an 80% increase in yield in 2050 (compared to 2005) with this strategy which, over the 45-year study period, equates to 1.8% p.a. linear relative to 2005 yield—something very difficult to achieve across the globe. But in addition, the optimal strategy requires the global average application rate for fertiliser nitrogen to reach 160 kg N/ha—a marked increase from the 2005 average of 94 kg N/ha. This amount of nitrogen use and yield increase is probably beyond the biological optimum considering the moisture limits to PY (more correctly, PY_w) of many cropping locations (e.g. semi-arid and sub-humid rainfed cropping).

Despite these difficulties the conclusions of Tilman et al. (2011), which highlight the GWP benefits that can be achieved through cropping intensification as opposed to land clearing, appear valid and confirm earlier calculations (e.g. Burney et al. 2010). But there is an easier way to appreciate the interaction between intensification and clearing. Assume a modest partial productivity for nitrogen fertiliser of 20 kg grain produced per kilogram of nitrogen applied (see Section 11.3) vs. a yield of, say, 5 t/ha/yr over 20 years following land clearing. Taking GWP from CO₂ and N₂O emissions (as discussed above) to be 10 kg CO₂-e/kg nitrogen fertiliser applied, the nitrogen fertiliser scenario produces emissions of just 0.5 kg CO₂-e/kg grain—one-eighth of the figure for land clearing with 403 t CO₂-e/ha for 100 t of grain, or 4 kg CO₂-e/kg grain.

While land clearing is clearly bad for GWP emissions, planting land to forestry or even allowing it to remain in forestry is beneficial. USDA (2011) estimated that in 2008, US forests contributed an annual net reduction in GWP of 886 Mt CO₂-e, almost twice the figure of 472 Mt CO₂-e GWP emissions from all agricultural sources (animal plus crops).

Conclusion on greenhouse gas mitigation and yield increase

Crop yield improvement—even as input levels have increased—has reduced GWP emissions per kilogram of grain in developed countries, and there is scope for this to proceed further in developing countries. Economics have driven energy and nitrogen fertiliser efficiency with linked GWP benefits.

However, concerns remain for N₂O emissions associated with higher nitrogen fertiliser application (especially excessive application, as occurs in China) and, more generally, with desirable increases in the fertility of cropping soils. In part, this concern is related

to variable and poorly understood estimates of N₂O emissions. A corollary benefit from economically driven practices to maximise nitrogen use efficiency (see Section 11.3) will be a reduction in yield-scaled N₂O emissions.

Positive changes in soil carbon sequestration should come about with greater fertilisation and higher soil fertility—especially if combined with reduced tillage and residue retention—but the gains cannot continue forever, carry a substantial opportunity cost in nutrients (N, P and S) necessarily sequestered with the soil organic carbon, and are easily lost with tillage. Increasing N₂O emissions from general soil microbial activity as soil fertility rises could also counter some of the gains, and rising soil temperatures could reduce new SOC equilibrium levels. Possibilities exist to reduce the large GWP from CH₄ in flooded rice, but again results are highly variable.

A great deal more research is needed in all areas before the further reductions in yield-scaled GWP glimpsed here can become reliable practices for farmers under pressure to cut GWP emissions. However, it has to be stated that even if the yield-scaled GWP of crop production can be further improved, the overall possibilities for reducing the current total net cropland greenhouse gas emissions of ~4,225 Mt CO₂-e/yr (Table 10.5) are quite limited. This view contrasts with the joint statement of the American Society of Agronomy (ASA), the Crop Science Society of America (CSSA) and the Soil Science Society of America (SSSA), which proposed that agriculture can offer a global mitigation potential of 5,500–6,000 Mt CO₂-e/yr (~4 t CO₂-e/ha/yr) (ASA/CSSA/SSSA 2011). The prediction appears to apply to only cropland—since it lists improved productivity, reduced greenhouse gas emissions and conservation of soil as the key mechanisms for extra sequestration—but even if it includes grazing lands, it would appear unrealistic in light of the review of possibilities discussed in this chapter. The report does list priority areas for mitigation research in cropping. However, only massive tree planting can deliver the amount of sequestration proposed. Similarly, avoiding land clearing is the most effective way to limit further emission growth caused by cropping.

Resource use efficiency, sustainability and environment

11



Key points

- Yield increase has been associated with improved water use efficiency in both rainfed and irrigated cropping; in the latter case, there is good scope for further gains.
- Yield increase and better management have lifted nitrogen and phosphorus use efficiencies, but limits are being approached under good management. In some developing countries, excessive nitrogen fertilisation has seriously lowered efficiency and added to pollution.
- The total life cycle energy cost to produce a given weight of grain has also improved with yield increase and better management, but limits are being reached in developed countries.
- Sustainable intensification is the only realistic path for efficient cropping and greater food security. This refers to greater management skills as well as more physical inputs. It is essential that all key soil properties and agricultural biodiversity should be sustained; this can be achieved.
- The biggest risk to the sustainable intensification of cropping is evolution of resistance to biocides and to host-plant resistance, where the resistance genes are either naturally present or added by breeders. Protection against this risk will come from integrated management using all available tools, including genetic engineering and greater cropping diversity.
- Organic farming has no scientifically proven benefits, and promotion of this system as a means of ensuring world food security is misguided. The inadequate crop nutrition that results without recourse to nutrients indirectly supplied from fertilisers will reduce yield over time.
- The biggest environmental threat from intensive cropping is probably nitrate (NO_3) transfer to waterways in humid areas, and nitrous oxide (N_2O) emissions (covered in Chapter 10).
- The greatest contribution from intensified cropping to non-agricultural biodiversity is the land saving that can arise from crop yield increase.

Resource use efficiency, sustainability and environment

11.1 Introduction

Crop yield—the major consideration for this book thus far—measures production per unit land surface. To further pursue yield progress, it is important to seek productivity gains against other essential inputs. Use of most inputs (or resources) increases as cropping modernises, leading to the common perception of excessive dependency on natural resources. No input is free or unlimited, and global shortages of several inputs loom large in discussions of world food security and the sustainability of agriculture. Such inputs include the supply of water, nutrients, energy, human effort and capital invested in machinery and/or land improvement.

This chapter considers crop production relative to each of the three physical inputs (water, nutrients and energy). **Input efficiency is defined as the amount of output per unit input.**⁵⁰ Labour and capital are also important agricultural inputs, but are considered in Chapters 12 and 13, along with total factor productivity (TFP), which measures crop output against the sum of all inputs.

Sustainable crop production looks beyond the efficient use of resources by crops in the short term, to consider long-term maintenance (or improvement) of the agricultural resource base and the minimisation of off-farm environmental damage. The subject has been prominent in the discussion of modern agriculture for the past 30 years, again with much critical comment. The resource base is defined here as the soil, water supply, and relevant aspects of agricultural biodiversity, which is discussed in Section 11.5. Section 11.6 is a brief reference to the off-site effects of modern cropping. It is also critical to sustain the human resource base of cropping, in particular the knowledge and

⁵⁰ Strictly speaking this definition should be termed a 'partial factor productivity' measure and 'efficiency' refer to the amount produced relative to some attainable productivity. However, the term 'factor use efficiency' is retained here because of its widespread use.

skills possessed by farmers; this subject is included briefly with other socioeconomic issues in Chapter 13 'Policies and people'. Finally, while climate can be considered part of the resource base in the agricultural sustainability debate, the subject of climate change, including the contribution of cropping, is covered in Chapter 10.

11.2 Water use efficiency

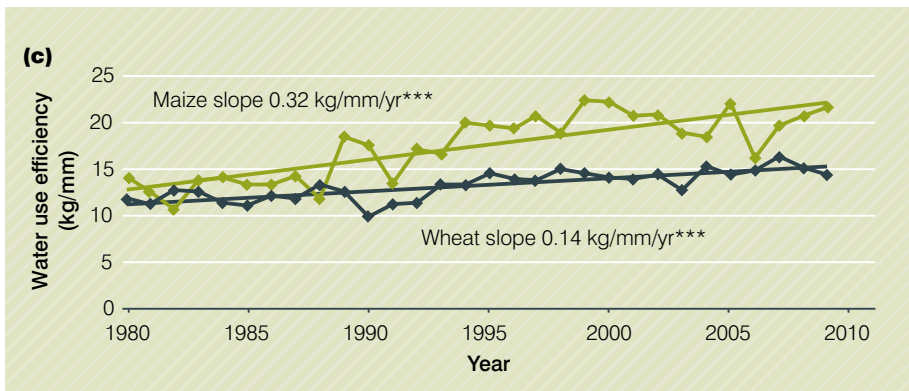
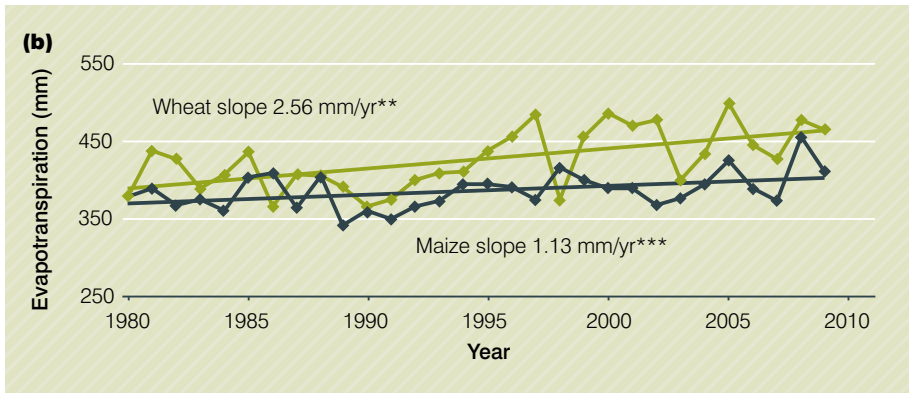
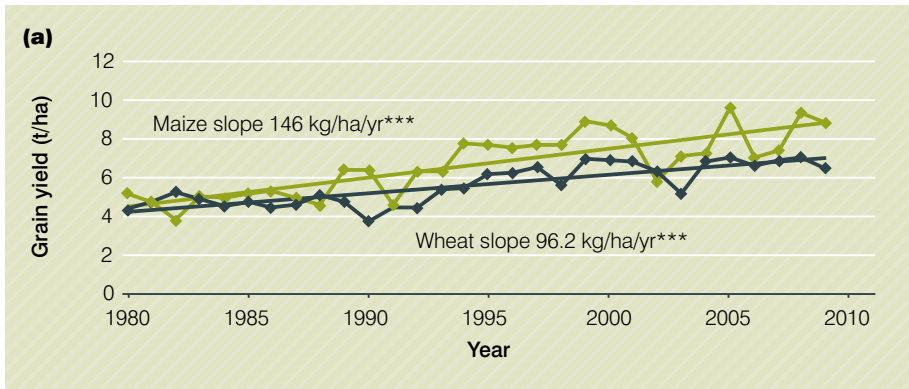
General observations about irrigated cropping

Water use efficiency (WUE) is measured as yield (harvested grain) in kilograms per hectare, divided by water use (crop evapotranspiration) in millimetres (shown as kg/ha/mm).⁵¹The principles surrounding WUE are introduced in Section 2.6 and expanded in Section 9.6 in the context of advancing water-limited potential yield (PY_w). These same principles also apply to water-abundant situations (irrigated or high in-crop rainfall) where potential yield (PY; see Chapter 2) prevails. With irrigated cropping there is often in-crop rainfall, so it is also useful to distinguish **the marginal irrigation water-use efficiency (WUE_i), defined as the yield increase over non-irrigated cropping relative to the irrigation applied** (also given in units of kg/ha/mm). Water used in irrigated cropping is usually scarce (see Section 11.5 on sustainability) and always involves a cost; thus, WUE_i has become an important consideration.

For irrigated crops in the United States of America (USA) the Keystone Center (2009) estimated WUE_i by dividing the yield difference between irrigated and non-irrigated crops on the same farm by the farm's irrigation water use. Between 1987 and 2007, WUE_i rose approximately by 40% for maize and 21% for soybean (and 73% for cotton lint, which is also an irrigated crop), but fell by 7% for wheat. Since farmers may choose to irrigate more favourable portions of their farms, there may be some bias in these WUE_i estimations, but there should be little or no bias in the above changes in WUE_i over time. Similar to this study, a non-grain crop example from Hanson and May (2006) clearly showed that yields of irrigated processing tomato in rainless central California, USA, increased by 50% over the past 30 years because of improved agronomy and varieties, without increase in crop evapotranspiration (ET)—meaning that WUE_i also rose by 50%.

For irrigated, double-cropped wheat–maize systems in the North China Plain, X. Zhang et al. (2011) reported a detailed PY experiment using the best agronomy and varieties available each year over the 30 years from 1979 to 2009. Grain yield increased in wheat by 66% to reach 6.9 t/ha, and in maize by 97% to reach 8.8 t/ha (Figure 11.1a). At the same time crop ET rose only 20% in wheat to 465 mm, and 10% in maize to 402 mm (Figure 11.1b). Thus WUE rose by 38% in wheat and by 70% in maize, to give maize a 53% advantage over wheat in WUE (Figure 11.1c).

⁵¹ Water use efficiency of 10 kg/ha/mm is equal to 1 kg of grain per tonne of water, or 1 tonne of grain per megalitre (ML) of water (equivalent to 100 mm over 1 ha).



0.01 < P < 0.05, *P < 0.01

Figure 11.1 Effect of improvements in agronomy and variety between 1980 (first harvests) and 2009 in an irrigated wheat–maize double-crop system in the North China Plain (a) grain yield (t/ha), (b) evapotranspiration (mm) and (c) water use efficiency (kg/mm). Source: Adapted from X. Zhang et al. (2011)

X. Zhang et al. (2011) attributed greater WUE to improved varieties and higher soil fertility, leading to higher final total dry matter (DM)—seen in increases of 30% DM for wheat and 6% DM for maize—and increased harvest index (HI), especially in maize (see Section 2.6 for definitions of DM and HI). Weather-driven potential evapotranspiration (ET_p ; see also Section 2.6) did not change and crop growth duration did not increase for either crop, meaning that increases in crop ET per day were somehow linked to greater crop growth rate. With maize, the smaller ET increase was partly caused by retention of the wheat crop residue, which reduced soil evaporation under maize by 30–40 mm when direct seeding of maize was introduced in 1991.

The general improvement in WUE over time, as mentioned above, is easily explained. As discussed in Section 2.6, ET of irrigated field crops is driven more by weather and crop growth duration, and is only weakly dependent on crop leaf area index (LAI). ET is the sum of crop transpiration plus soil evaporation, such that when LAI is low ET is insensitive to LAI because under relatively frequent irrigation (or frequent rains) evaporation from the wet soil surface will largely compensate for lower transpiration from fewer crop leaves. Agronomic management and breeding advances, **which can increase early growth rate (but not overall crop growth duration), will increase crop transpiration at the expense of soil evaporation**, and thereby increase total DM per unit ET. If HI simultaneously increases (as has often been the case with variety improvement), WUE will further benefit.

There are additional considerations with irrigated cropping, although none contradict the general conclusion that improvements in PY, through better agronomy or greater HI, have improved WUE and WUE_c. First, heavy **surface mulch or buried drip irrigation** can potentially reduce soil evaporation. Buried drip irrigation, although uncommon for field crops because of the expense, can reduce soil evaporation compared to flood or sprinkler irrigation when there is little rain in early stages of crop growth. Sometimes buried drip irrigation offers additional (but poorly understood) benefits for crop growth. Second (and surprisingly), HI and grain yield can on occasions be increased in indeterminate broadleaf irrigated crops (such as cotton) through a managed degree of water stress at defined stages of development (**deficit irrigation**) despite reductions in crop ET and DM production. In Asia, alternate wetting and drying of irrigated rice is a widely practised technique related to short periods of managed surface soil drying. However, the largest benefits are (usually) reduced deep drainage losses and (sometimes) stimulated growth (e.g. Xue et al. 2013), as rice cannot tolerate reductions in crop ET below the maximum crop ET without proportional yield loss.

Although beyond the scope of this chapter, it is important to note that better management of **irrigation systems and the field water supply** can enable large water savings in irrigated cropping. In this discussion, 'better management' refers to an increase in crop ET per unit of irrigation water supplied from reservoirs or wells, which can be derived through reducing canal seepage, ceasing or reducing wasteful pre-crop irrigation for land preparation, and minimising deep drainage and/or un-trapped run-off from the cropped field. The latter occurs when irrigation exceeds crop demand and/or when there are unanticipated rains. Moreover, more timely supply of water by the system to farmers can improve WUE_c.

The ratio of crop ET to total water supply is often very low (0.1) in existing irrigation systems, when it could reach 0.6 or better under best management (Hsiao et al. 2007; Fereres and Gonzalez-Dago 2009). This ratio tends to be higher for tube wells because water is pumped close to the crop, which reduces potential for off-field losses. Further, more scope exists to reduce on-field losses because farmers usually have better control over pumped water than they have over canal water from shared irrigation. Moreover, in these tube wells, deep drainage often returns water to the source aquifer, thus incurring only a pumping energy cost.

Transpiration efficiency (TE) refers to DM produced per unit of transpiration, and can be measured either in units of kilograms per hectare per millimetre or as a dimensionless ratio (see TE₁ and TE₂, respectively, in Section 2.6). **WUE at the canopy level** (at least for DM production) is dominated by the TE effects of the prevailing vapour pressure deficit (vpd)—to which TE is inversely related—and to the plant photosynthetic system (i.e. TE is lower for C₃ crops than for C₄ crops; see Section 2.6). Thus strategies to increase WUE_c when irrigation water is scarce would be to grow crops where (or when) vpd is lowest (such as in winter and/or spring) and to switch from C₃ to C₄ crops where possible. This strategy is the focus of current research in the water-scarce North China Plain, where wheat and maize are both currently grown but maize has a higher WUE (e.g. X. Zhang et al. 2011). For this reason, in Bangladesh, maize (a C₄ crop with greater WUE) is better than wheat or rice (C₃ crops) as an irrigated winter–spring cropping alternative (Timsima et al. 2010).

Water use efficiency values and limits

The Keystone Center (2009) surveyed US farm WUE_i in 2007 and reported values of **5 kg/ha/mm for wheat, 8 kg/ha/mm for soybean and 13 kg/ha/mm maize**. These values appear low when compared with the modern tomato varieties studied by Hanson and May (2006), which achieved dry fruit yield values of **~6 kg/ha/mm** in the hot, dry Californian summer. Similarly, higher values were seen in the above North China Plain irrigation study (X. Zhang et al. 2011), when WUE under the leading technology reached **15 kg/ha/mm for wheat and 22 kg/ha/mm for maize**. Additionally, in a comprehensive study of irrigated maize in the central part of southern Nebraska, USA, Grassini et al. (2011b) measured WUE_i to be **19 kg/ha/mm for surface irrigation and 32 kg/ha/mm for centre-pivot irrigation**. The average of these two figures is 26 kg/ha/mm, which agrees with results for other studies of maize under optimal management, such as in Texas, USA (Howell 2001).

It is difficult to determine why the Keystone Center (2009) WUE_i values are so low. It is possible that the data include ex-field losses, or that the farmers in the study of Grassini et al. (2011b) are better managers, perhaps helped by the huge water-holding capacity of Nebraskan soils (where plant available water-holding capacity for maize is >300 mm). Regardless of the reason for the difference in results, simulation modelling by Grassini et al. (2011b) suggests that **Nebraskan maize could attain a WUE_i of 42 kg/ha/mm** under the prevailing vpd of the region, if excess irrigation were eliminated

(saving on average ~60 mm) and practices of soybean–maize rotation, zero-till and pivot irrigation were adopted. A further 31 mm could be saved (with only 4% yield penalty) if deficit irrigation was also practised, thus lifting WUE_i to 46 kg/ha/mm. Deficit irrigation is, however, difficult to manage, and irrigation water would have to be very expensive to justify the small gains in WUE_i that might be achieved. The Grassini et al. (2011b) study indicates, however, that the current good management of pivot-irrigated maize achieves a WUE_i well above that reported by the Keystone Center (2009) and only 30% below that from modelling PY and ET_p in Nebraskan maize (Grassini et al. 2011b).

While Grassini et al. (2011b) demonstrated how good crop management could close the WUE gap (at least for maize in the USA), the study did not evaluate the scope to increase the current upper WUE limit in a given environment and for a given HI—a feat that would require TE at the leaf level to be raised for a given vpd regime. Some genetic variation has been found in TE within several crop species over the past 20 years (e.g. Richards 2006). Most of the research has related to performance under water scarcity (i.e. related to PY_w) as discussed in Section 9.6, but the findings are also relevant to irrigated crops (i.e. PY). Other research (see Section 9.4) has shown that genetic improvement in radiation use efficiency (RUE) and/or maximum photosynthesis (P_{max}) is associated with PY increases in several situations. Thus, it is logical to ask whether these changes have consequences for WUE , should they continue.

It might be expected that WUE increases proportionally with increases in RUE that occur through better canopy light distribution, or through greater P_{max} attained by greater internal photosynthetic activity of the leaves, because such changes in P_{max} and hence RUE should not increase ET. However, observed RUE increases are more commonly associated with increased stomatal conductance such that TE at the leaf level falls because transpiration of leaves tends to increase more than photosynthesis in response to stomatal opening. However, the consequences of **increased stomatal conductance for TE of crop canopies** is subject to complex micrometeorological feedbacks within the canopy, dependent largely on wind speed and canopy roughness, which determine ‘coupling’ of canopy and atmosphere.

Understanding the relationship between stomatal conductance and canopy TE is further complicated by stomatal sensitivity to increasing vpd, a trait recently shown to be common among crops and which appears to show genetic variation within crop species (Section 9.6). Heightened sensitivity—as in midday or early afternoon stomatal closure when vpd is close to peak diurnal value—is an obvious way to increase TE, but this occurs at the expense of photosynthesis and growth. Conversely, stomatal insensitivity would boost photosynthesis and growth, but by increasing canopy transpiration, it may lower canopy TE depending on the prevailing micrometeorology.

In their wheat study for the North China Plain, X. Zhang et al. (2011) suggested that the 21% increase in wheat ET may have been due to greater stomatal conductance, which increased 30% over the 30-year period of variety release. However, these authors measured stomatal conductance on only one date, and edge effects from the relatively

small (40 m²) plots may have distorted micrometeorological features of the trial crops. By comparison, in a mid-sized 200-m² plot study of irrigated wheat by Pinter et al. (1990), **the relationship of ET to stomatal conductance** (although much attenuated across varieties) was still highly significant with ET increasing by 9% for a doubling of stomatal conductance; TE was not reported. At an even larger scale, a wheat field study using 5-ha plots indicated that variety differences in stomatal conductance affecting leaf TE affected growth but not the canopy ET (Condon et al. 2002). These authors reaffirmed the importance of scale (plot size) in such studies.

In conclusion, while the well-established trend for modern varieties to exhibit greater stomatal conductance is somewhat increasing ET, it seems unlikely that this trait is noticeably reducing canopy TE efficiency or overall crop WUE. Even so, more research is needed, but must be undertaken at a sufficient scale to properly measure effects that would be seen in canopies in farmers' fields. On the other hand, if P_{\max} can be increased by increasing internal leaf photosynthetic activity (rather than stomatal conductance)—as, for example, by converting rice from C_3 to C_4 photosynthesis (Section 9.4 on increasing RUE)—both canopy TE and WUE should unequivocally increase. This may be the case in a recent field study of genetic variation in WUE in sorghum (Narayanan et al. 2013).

Does yield progress in rainfed cropping threaten catchment water yield?

Under rainfed cropping, the same considerations apply for WUE determination as have been described above for irrigated situations. Yield improvement through better agronomy and breeding (see Section 9.6) has greatly increased WUE; for example, by reducing in-crop soil evaporation losses—which can be large relative to ET under low rainfall—and by increasing HI with no change in ET. Where better agronomy and breeding have increased crop ET—for example, through more efficient fallowing; deeper roots, especially where groundwater can be tapped (as occurs in parts of the Argentine pampas); and longer duration crops—the source of this extra crop water use needs to be identified as it could carry an opportunity cost (a value in alternative uses).

Rainfall in excess of ET_p in **high rainfall regions** contributes to stored soil water at crop maturity, deep drainage and/or run-off. In most situations, these three components of the water balance usefully contribute to groundwater and streamflow, and thus benefit the catchment landscape elsewhere. **With yield improvement, however, the increases in crop ET that reduce deep drainage and run-off are likely to be small in terms of catchment hydrology** and may be beneficial for dryland salinity reduction. Under moderate to high rainfall, where annual crops have replaced natural deep-rooted perennial vegetation (grass or trees), the annual drainage and/or run-off components are likely to be greater from cropland than from the original vegetation. Over time, problems may arise, including watertable rise and, in some places, what is known as 'dryland salinity'—gradual surface soil salinisation when the watertable is naturally saline. Conversely, the volume of water reaching aquifers and

streams can decrease when a landscape is converted from annual cropping back to perennial forage crops (such as lucerne), biofuel crops—such as *Miscanthus* spp. and switchgrass (*Panicum virgatum*)—or trees (such as *Eucalyptus* spp.).

In cropping regions of **low rainfall**, one major component of yield improvement has been increasing transpiration as a proportion of the total precipitation falling before and during the crop cycle. In such situations, water reaching aquifers and streams is generally a small component of the catchment hydrological balance, and **any increase in crop transpiration (and/or ET) will mostly occur at the expense of weed transpiration and soil evaporation before planting**—meaning greater stored soil water at time of planting. WUE in low-rainfall situations may seem very low, but it has nonetheless improved notably with yield improvement for the reasons outlined above and because of improved drought tolerance in modern crop varieties. Run-off can occur sporadically, but improved agronomy (such as conservation agriculture) can greatly reduce run-off to the benefit of crop ET. Run-off events are usually erosive, creating sediment-laden flows. Thus, reducing run-off should be considered as a benefit (rather than a cost) to the environmental water system. Overall, any concern that an increase in rainfed crop yield (and consequently water use) will incur a cost to the regional water balance remains unwarranted. Similarly, the commonly asserted criticism of grain production from rainfed cropping regions as ‘virtual water export’ is without foundation.

Conclusions for water use efficiency

Approaches to modernising agriculture (including irrigated cropping) through increased PY, PY_w and farm yield (FY; see Chapter 2) have clearly improved WUE (and WUE_c), even as water use has increased. The most positive yield effects have likely derived from agronomic improvements—for example, better managed and often more fertilisation, and improved crop timing and duration—which have enabled wasteful soil evaporation losses to be replaced with useful crop transpiration. Moreover, breeding progress has also brought genetic improvements that have raised HI and yield per day, with clear benefits for WUE because ET has been unaffected.

In irrigated settings, however, the greatest scope for efficiency gain lies in reducing water loss during delivery to the field and by better matching water supply to crop demand so as to avoid overirrigation. Also, crop WUE should increase as PY increases, more so if PY increases are not associated with increased stomatal conductance. However, the response of canopy ET to conductance increase appears to be much attenuated relative to the transpiration response of an isolated leaf.

In rainfed cropping, where annual rainfall is the only water supply, crop ET and WUE have increased through agronomic and breeding advances. However, the opportunity cost of any extra water used through these ET advances in rainfed cropping has been close to zero because it is highly likely that extra water made available to crops by improvements would have otherwise been consumed by weeds and evaporation.

11.3 Nutrient use efficiency

Modern agriculture removes large amounts of nutrients from the land (as product yield), such that nutrient loss must sooner or later be counterbalanced by the addition of chemical and/or organic (largely manure) fertiliser, given the very slow breakdown of soil minerals to give available plant nutrients. Application of fertiliser is also necessary to overcome any plant nutrient deficiency. A comparatively smaller (and variable) amount of available nitrogen (N) and sulfur (S) can also be obtained from atmospheric deposition, while legumes can fix substantial amounts of atmospheric nitrogen (see later).

Fertiliser science has been reviewed by Angus (2012), who gives an agronomist's up-to-date view across all the essential elements for plant growth and other contemporary issues. Discussion here focuses on fertiliser nutrient use efficiency for the macro-elements nitrogen and phosphorus (P) (see this section, below, for a discussion of P).⁵² Other major elements—potassium (K) and sulfur (S)—can also be deficient in intensively cropped situations and certain soils (especially with high-demand crop species), but because world supplies are generally adequate, these elements are not discussed here further. Calcium (Ca) and chlorine as chloride (Cl) are additional elements found in larger amounts in plants, but are rarely deficient.

Also important for high crop yield are the minor elements for plants—for example, zinc (Zn), iron (Fe), boron (B) and copper (Cu). However, minor elements are not discussed here because quantities involved are small (usually <1 kg of element is removed per hectare per year) and are unlikely to face limited supply. Suffice to note that constant vigilance is required to avoid micronutrient deficiency; alleviation is inexpensive and automatically boosts efficiency of use of all other inputs. Moreover, there have been notable advances in application efficiency for microelements through sprays or compound fertilisers, and in exploiting genetic tolerances to microelement deficiencies in some crops.

Nitrogen

Fertiliser nitrogen is a major cropping input. In 2007–09, FAOSTAT (2013) reported that global annual application of nitrogen was ~100 Mt nitrogen (elemental weight only, i.e. irrespective of the compound applied), of which 55% was used on cereals (Heffer 2009). Furthermore, Smil (2001) estimated that >40% of the protein nitrogen consumed by humans was derived from fertiliser nitrogen.

⁵² Elemental phosphorus (P) content is used throughout this book, although the fertiliser industry often refers to phosphorus pentoxide (P_2O_5) content, of which 43.66% is elemental phosphorus, so that 1 kg P = 2.29 kg P_2O_5 .

The global application of fertiliser nitrogen is supplemented by the 31 Mt N annually that is applied as manure (Peoples et al. 2009). In addition, the estimated contribution of atmospheric nitrogen fixed by bacteria in legume roots in agricultural ecosystems—termed ‘biological nitrogen fixation’ (BNF)—is ~46 Mt N, of which 20–22 Mt may derive from grain legumes (Peoples et al. 2009). Non-legume BNF (microbes in other plants or free-living microbes) is considered negligible in crop systems, with few exceptions.

Finally, a significant component of nitrogen input (albeit one that is difficult to estimate) is atmospheric deposition (wet plus dry, meaning in rain and in dust) of reactive nitrogen—i.e. ammonia (NH_3) and nitrogen oxides (NO_x)—on crops and croplands. US values for atmospheric deposition in 2001 ranged from <5 kg N/ha/yr in sparsely populated areas, to as high as 20 kg N/ha/yr in heavily polluted areas; an average of ~10 kg N/ha/yr was reported for the Mid West (EPA 2011). In China, Liu et al. (2013) reported wet deposition alone contributed 23 kg N/ha/yr in eastern China, with up to 80 kg N/ha/yr total deposition in the North China Plain. Sources of deposited atmospheric nitrogen are identified as industry, transport and agriculture itself (largely NH_3 from the animal industry). Emissions from these sources have abated, notably in the USA and Europe through regulation.

Fertiliser nitrogen is often the major input cost for achieving attainable yield with non-leguminous crops. It is largely manufactured from non-renewable energy sources (nowadays mostly natural gas). Priced at US\$1–2/kg N, the cost of nitrogen is better appreciated as a ratio to grain price—that is, kilograms of grain to buy one kilogram of nitrogen (at farm gate prices). This number typically ranges from 2 to 10 for cereals; low numbers occur in countries where fertiliser is subsidised.

Significant losses of reactive nitrogen to the environment occur in cropping when NH_3 and nitrogen oxide gases—especially nitrous oxide (N_2O)—are released from the soil, and where nitrate (NO_3^-) is leached from the soil. Non-reactive nitrogen gas (N_2) arising from denitrification is a further source of losses, in this case, however, with no direct environmental consequences. Losses can arise both from fertiliser nitrogen and other nitrogen sources in the soil, but NH_3 losses arise only from NH_3 -based fertilisers (and manure), while all losses clearly increase with heavier fertiliser use. Crop leaves can also lose NH_3 , especially during grain-filling and if the root zone contains high levels of ammonium (NH_4^+). However, the rate of NH_3 loss from leaves is generally low, given (in elemental nitrogen equivalent) as <3 kg N/ha/crop (Hayashi et al. 2011). Losses of N_2O , a long-lasting greenhouse gas, are discussed in more detail in Section 11.6.

Given the above considerations, it is not surprising that nitrogen use efficiency (NUE) is a major issue in modern agriculture. NUE refers to kilograms of grain yield per kilogram of nitrogen supply. NUE is complicated by the presence of two nitrogen sources: fertiliser nitrogen applied to the crop in consideration, and nitrogen from the decomposition of soil organic material, usefully referred to as ‘indigenous soil nitrogen’. Because the latter is difficult to measure, this book uses **NUE expressed as yield per kilogram of fertiliser-applied nitrogen (kg/kgN) only, abbreviated to NUE_f** —in

other words, the partial factor productivity of nitrogen fertiliser (e.g. Wortmann et al. 2011), without considering the contribution of indigenous soil nitrogen. However, there is no escaping the complications that excluding indigenous soil nitrogen from NUE_f causes. The following equations provide a useful separation of NUE_f components:

equations (13), (14) and (15) Understanding the component effects on nitrogen fertiliser use efficiency (NUE_f)

Source: Moll et al. (1982)

$$NUE_f = NUpE_f \times NUtE \quad (13)$$

$$NUtE = (DM/NUp) \times HI \quad (14)$$

$$NUtE = NHI/GNC \quad (15)$$

where

NUE_f is nitrogen fertiliser use efficiency, or kilogram of harvested grain per kilogram of nitrogen fertiliser applied (kg/kg N)

$NUpE_f$ is the uptake efficiency of fertiliser nitrogen (kg/kg N), or nitrogen uptake by the crop (NUp) measured in kg N/ha, divided by fertiliser nitrogen supply (kg N/ha)

$NUtE$ is the utilisation efficiency of grain production from nitrogen taken up by the crop (kg/kg N)

DM is the total dry matter of the crop at maturity (kg/ha)

HI is the harvest index (grain dry weight divided by total DM, a dimensionless ratio)

NHI is the nitrogen harvest index (the proportion of crop nitrogen uptake in the grain at maturity, a dimensionless ratio)

GNC is the grain nitrogen concentration (w/w, or often given as a percentage)

As equation (13) shows, nitrogen fertiliser use efficiency (NUE_f) is a function of the efficiency of both nitrogen uptake and utilisation ($NUpE_f$ and $NUtE$, respectively). $NUpE_f$ relates to capture of nitrogen by the crop root system, while $NUtE$ is determined by how efficiently the nitrogen absorbed by the crop is used in growth and ultimately in producing grain. Equations (14) and (15) are two ways of expressing the same thing ($NUtE$). They assist in understanding how $NUtE$ has been increased by breeding; greater detail is given in Box 11.1 where a specific example is discussed. The key point is that these measures of efficiency are most useful when fertiliser rates are close to the economic optimum (see Box 11.1).

Box 11.1 Nitrogen use efficiency—an example and complications

Assessing how effectively crops take up and use nitrogen needs is complex. A typical grain yield response to nitrogen fertiliser—along with the key component, nitrogen fertiliser use efficiency (NUE_f)—for irrigated wheat in south-eastern Australia is used as an example here to show some of the factors that affect such assessments. Components of NUE_f (as defined in equations (13), (14) and (15)) appear in part (b) of the figure.

In the example, a low nitrogen uptake (NU_p) of only 12 kg N/ha with zero application of fertiliser indicates that the indigenous soil nitrogen supply was very low. As the rate of applied fertiliser nitrogen increased, NU_p steadily increased from the fertiliser source. The uptake efficiency of fertiliser nitrogen (NU_pE_f)—not shown, but calculated by dividing NU_p by rate of fertiliser nitrogen—would have declined as nitrogen rate increased. Also, nitrogen utilisation efficiency ($NUtE$) in part (b) decreased as NU_p increased in association with a continuous fall in nitrogen harvest index (NHI) and, after an initial fall, the steady rise in grain nitrogen concentration (GNC).

Obviously neither NUE_f nor NU_pE_f has relevance at zero or low fertiliser rates. At this point indigenous nitrogen dominates NU_p , inflates calculated fertiliser efficiencies, and explains much of the early decline in NUE_f as nitrogen rates rise. Thus, to be relevant to best practice, **improvements in NUE_f (and its components) through better agronomy and breeding must be assessed at the economic optimum nitrogen fertiliser rate**—and the possible influence from other sources of soil nitrogen always noted. The economic optimum is given when the slope of the grain yield curve in box figure (a) equals the nitrogen-to-grain price ratio; at a typical 5 kg/kg (i.e. 5 kg of grain to buy 1 kg of fertiliser nitrogen), the optimal rate was about 250 kg N/ha in figure (a).

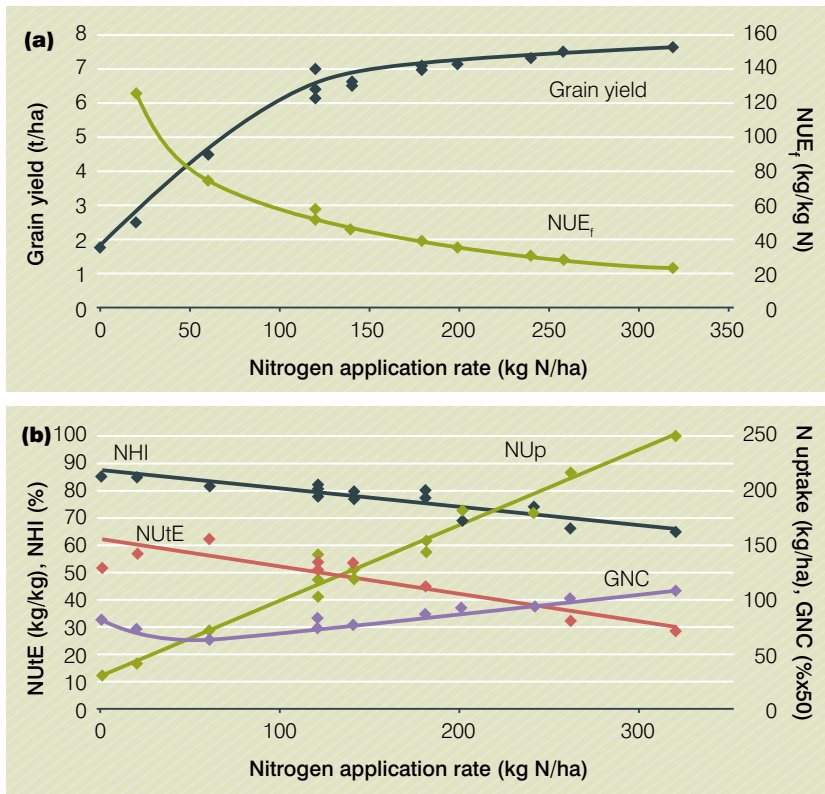
Note that a decrease in the nitrogen-to-grain price ratio will lift optimal nitrogen rates, inevitably lowering NUE_f and risking greater nitrogen losses. If the indigenous soil nitrogen supply is greater than the low level apparent in the box figure—for example, through including legumes in the system—the optimal nitrogen fertiliser rate will be lower. Also, because the definition and method of calculation of NUE_f and NU_pE_f ignore the (greater) supply of indigenous soil nitrogen, both these efficiency measures will appear to improve markedly. The reality may be different, and can be seen only if the extra yield per unit fertiliser nitrogen is measured. A proper understanding of NUE must consider all these issues.

Another more direct way of measuring NU_pE_f is the **apparent fertiliser recovery efficiency**—nitrogen uptake with fertiliser less uptake without

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fertiliser, divided by fertiliser rate. For single applications of 120 kg N/ha, this was 70%, while measuring fertiliser nitrogen recovery using fertiliser labelled with the ^{15}N isotope gave a value of 50%. Thus, fertiliser stimulated uptake of additional indigenous soil nitrogen, a not unusual observation. Finally, it can be useful to calculate 'agronomic nitrogen use efficiency' which refers to **the increase in yield per unit fertiliser nitrogen applied**. This latter measure is the true equivalent to WUE_i in irrigated cropping, and requires knowledge of yield in the absence of fertiliser nitrogen.



All variables shown on the Box Figure are defined in the text

Response of irrigated spring wheat to nitrogen fertiliser, showing (a) grain yield and fertiliser nitrogen use efficiency (NUE_f), and (b) nitrogen uptake (NUp), nitrogen utilisation efficiency (NUE_f), nitrogen harvest index (NHI) and grain nitrogen concentration (GNC). Source: All nitrogen fertiliser treatments in Fischer et al. (1993) and Fischer (1993), except late (poststem elongation) single nitrogen applications

Nitrogen use efficiency—past progress

Figure 11.2 plots US maize grain yield (i.e. FY), nitrogen fertiliser use and NUE_f against time and is illustrative of the evolution of NUE_f in modern agriculture. Application rates of nitrogen fertiliser to maize rose sharply between 1940 and 1980, after which rates steadied with less attractive grain prices, to be followed by small increases recently with the advent of bioethanol from maize. Initial NUE_f values were inflated by reliance on indigenous soil nitrogen (and perhaps manure), and fell sharply to a minimum of 42 kg/kg N as this source of soil organic carbon and nitrogen declined and was replaced by increasing amounts of fertiliser nitrogen. However, as other factors (see below) lifted FY and the efficiency of nitrogen management, **in US maize NUE_f then began to improve steadily to reach 62 kg/kg N in 2005–10**. In comparison to this temporal pattern of NUE_f evolution shown for the USA, developing countries generally operate at earlier stages (also see below).

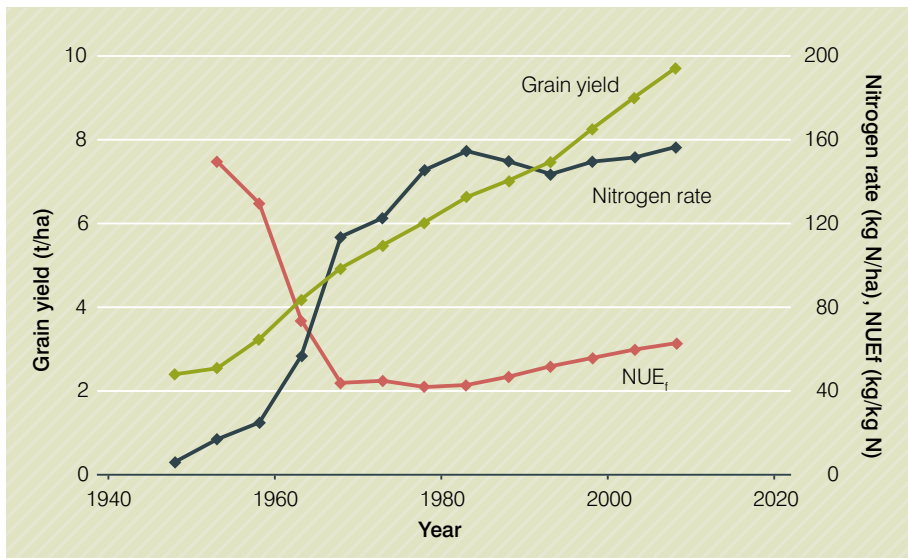


Figure 11.2 US maize grain yield, rate of nitrogen fertiliser applied on maize, and nitrogen use efficiency (NUE_f) summarised as 5-year means from 1946 to 2010. Source: USDA (2012)

The NUE_f increase seen in maize during the past 30 years has been driven by many synergistic improvements in technology. Importantly, nitrogen loss to leaching and denitrification has been reduced by agronomic techniques that better match timing and amount of nitrogen fertiliser to crop need—examples include tactical topdressing based on measured crop need and variable-rate capability incorporated into fertiliser applicators to account for field variation (often considered part of precision agriculture). However, the most important contribution to increased NUE_f has arisen through PY

progress driven by breeding gains (Ciampetti and Vyn 2013) and other agronomic improvements such as earlier planting, better soil water conservation, better seed fungicides and higher plant density. Any indirect increase in PY automatically increases NUE—a principle based on Liebscher's law (de Wit 1992) that is broadly relevant to multiple resource use efficiency. This increase means that the apparent diminishing returns with increased nitrogen initially seen in Figure 11.2 were overridden when other yield increasing factors came together.

Just as with maize in the USA, **FY for winter wheat in the United Kingdom (UK) has been rising steadily without any increase in application rates for nitrogen fertiliser since 1981**; the current rate of application is ~ 190 kg N/ha, and NUE_i has now reached ~ 42 kg/kg N. Some manure is also applied to wheat in the UK. Consideration should also be given to atmospheric nitrogen deposition (rain and dust), as the contribution was quite high in the late 1980s in the south-east of the UK—estimated at 35–40 kg N/ha (Goulding 1990)—but this may have since decreased.

Sylvester-Bradley and Kindred (2009) looked closely at NUE_i with older (1977–87, $n = 10$) and newer (1991–2007, $n = 15$) winter wheat varieties in nitrogen fertiliser experiments across the UK, as described in Section 3.8. At a given nitrogen level (e.g. 200 kg N/ha) new winter varieties out-yielded old varieties (9.47 t/ha vs. 8.34 t/ha, respectively), and delivered higher NUE_i (47.4 kg/kg NUp vs. 41.7 kg/kg NUp, respectively). The improvement in NUE_i was probably due to small gains in $NUpE_i$ and in $NUtE_i$ (i.e. NHI increased slightly and GNC was slightly lower; see equation (15)). An important result was that optimal nitrogen rates (using a nitrogen to grain price ratio of 5) differed as expected (174 kg N/ha for new varieties, vs. 146 kg N/ha for old varieties), as did grain yield (9.54 t/ha for new vs. 8.35 t/ha for old), but NUE_i no longer differed noticeably (54.8 kg/kg N vs. 57.2 kg/kg N); neither did GNC (average 2.04%).

Newer, higher yielding and generally shorter varieties of irrigated spring wheat in north-western Mexico were found to have higher NUE_i , relative to older ones; this was derived through higher $NUpE_i$ at lower nitrogen supply, and through higher $NUtE_i$ at higher nitrogen supply (Ortiz-Monasterio et al. 1997). The $NUtE_i$ increase with breeding in spring wheat was the result of increases in NHI (associated with increases in HI), and by decreases in GNC (Calderini et al. 1995; Ortiz-Monasterio et al. 1997), which possibly carry a grain quality penalty.

Spring barley released in western Europe between 1931 and 2005 **showed a 0.6% p.a. (relative to 2005 values) increase in both PY and in NUE_i** (Bingham et al. 2012). Forty per cent of NUE_i improvement was attributed to increased $NUpE_i$ (largely through greater postanthesis nitrogen uptake). The remainder was attributed to $NUtE_i$, which was clearly increased by breeding in association with increased HI. These authors saw scope for further modest genetic improvements in NUE in barley.

Nitrogen use efficiency—current status and agronomic practices

Table 11.1 summarises fertiliser nitrogen application rates across the major cereals in some important world regions. Average country NUE_i has been calculated by dividing

yield by nitrogen application rate. Sub-Saharan Africa is not shown, because the current rate of nitrogen application, at ~ 7 kg N/ha across all crops, it is too low for meaningful NUE_f calculations. Of the crops shown in Table 11.1, NUE_f tends to be greatest in maize and lowest in wheat. Very high (i.e. excessive) nitrogen rates are evident in China, as are correspondingly low NUE_f values. Rates are more moderate in India, where NUE_f is higher than for China. The relatively high NUE_f values in the USA, Argentina and Brazil may reflect the extra soil nitrogen from prior soybean crops, commonly grown in rotation with maize in these three countries. Crop and country differences, and the effect that better agronomic practices could have on NUE_f , are examined below.

Compared with genetic improvement, **agronomic management** can more strongly influence NUE_f (especially by $NUpE_f$). This approach is encapsulated in the '4 Rs' of best nitrogen management practice promulgated by the IPNI (2009): the right source, the right time, the right place and the right rate. Good and Beatty (2011) reviewed published field trials and found many examples of treatments that increased NUE_f in maize and wheat in North and South America, wheat in Europe and rice in Asia, when compared with common farmer practice. Increases in NUE_f arose especially through reduced nitrogen rates combined with improved nitrogen timing, and NUE_f gains of 20–50% (or even more) were achieved without loss of yield.

Table 11.1 Average nitrogen fertiliser application rate and nitrogen use efficiency (NUE_f)^a across world regions and countries in 2007–09

Country	Variable	Wheat	Rice	Maize
China	Fertiliser rate (kg N/ha)	202	211	182
	NUE_f (kg/kg N)	23.2	30.8	29.2
India	Fertiliser rate (kg N/ha)	113	70	46
	NUE_f (kg/kg N)	24.9	47.3	49.3
USA	Fertiliser rate (kg N/ha)	71	177	163
	NUE_f (kg/kg N)	41.2	46.7	60.2
European Union	Fertiliser rate (kg N/ha)	105	na	123
	NUE_f (kg/kg N)	50.6	na	54.6
Argentina	Fertiliser rate (kg N/ha)	61	na	76
	NUE_f (kg/kg N)	40.9	na	87.2
Brazil	Fertiliser rate (kg N/ha)	35	57	57
	NUE_f (kg/kg N)	65.4	73.1	67.8

a Given as kilogram grain yield per kilogram nitrogen applied as fertiliser (kg/kg N)
na = not available

Source: FAOSTAT (2013) for crop yield to calculate NUE_f and overall fertiliser use; Heffer (2009) for fertiliser use distribution among crops at country level

However, best practice agronomic management of nitrogen fertiliser is not easy. Dobermann et al. (2011) conducted detailed nitrogen rate trials in 32 irrigated maize fields (2002–04) in the central part of southern Nebraska, USA. They illustrated this point by calculating the economically optimal nitrogen rate (N to grain price ratio of 7:1), and the yield and NUE_g value at that nitrogen rate. For maize-following-maize rotations, the average values were 171 kg N/ha optimal application, 14.9 t/ha grain yield and 83 kg/kg N for NUE_g at the optimal nitrogen rate. For maize-following-soybean rotations, the corresponding figures were 122 kg N/ha, 14.5 t/ha and 117 kg/kg N, respectively.

Unfortunately, the measured economically optimal nitrogen rates varied considerably among fields in each of the Dobermann et al. (2011) groups (standard deviation ~ 40 kg N/ha), and were overestimated by existing predictive functions used by crop advisers. It was also evident that there was greater potential for economic return to be reduced by using insufficient nitrogen fertiliser, compared to the potential for reduced returns by using excess fertiliser—a common worldwide observation that favours excess nitrogen application ‘as an insurance’, especially at low nitrogen to grain price ratios (with detrimental environmental consequences; see Section 11.5 on sustainability). The southern Nebraskan soils are currently maintained at a high level of fertility, because in the absence of nitrogen fertiliser, average yield was 10 t/ha (range 6–14 t/ha) and indigenous nitrogen uptake was ~ 160 kg N/ha. At the economically optimal nitrogen rate for these crops (given above), apparent recovery of fertiliser nitrogen was 64%, and $NUtE$ averaged 57 kg/kg NU_p , associated with a NHI value of 65% and GNC of 1.3% (Wortmann et al. 2011).

In the same Nebraskan region, Grassini et al. (2011a) examined 777 irrigated maize crops in 2005–07, and reported an average FY of 13.0 t/ha for an average nitrogen fertiliser rate of 183 kg N/ha;⁵³ the average NUE_g was therefore 71 kg/kg N, which is well above the Nebraskan state average of 64 kg/kg N. The nitrogen rate used by farmers ranged widely from 100 to 250 kg N/ha across the 777 crops; this range occurred without apparent explanation and without any observable relationship to yield, except for the higher rate (+21 kg N/ha) used for maize-following-maize (representing 38% of maize crops), compared with maize-following-soybean. All of these Nebraskan studies point to scope for better temporal matching of fertiliser nitrogen applications to crop demand in order to further lift NUE .

There are no reports on NUE progress in rice on a broad scale, but rice $NUtE$ should be higher than other cereals because of the intrinsically low GNC of $\sim 1.2\%$ (see equation (15)). **Rice is, however, also well known for its low $NUtE$,** values that are commonly $<50\%$ and sometimes as low as 30% (e.g. Spiertz 2010; Angus 2012) because of high losses from NH_3 volatilisation and denitrification associated with flooding. The NUE situation in China is extreme with rice—and other crops (see Table 11.1)—because nitrogen fertiliser prices are subsidised, nitrogen application

53 Additional nitrogen input in irrigation water for maize in Nebraska, USA, amounts to ~ 30 kg/ha/yr but atmospheric deposition is less than 10 kg/ha (P. Grassini, pers. comm. 2012).

rates are very high, and the forms of nitrogen fertiliser primarily used (i.e. urea and ammonium bicarbonate) favour NH_3 losses (L. Ma et al. 2010).

Rice agronomists have developed several techniques to improve NUE_i (and hence NUE) that once again involve better matching of supply and timing to crop need and which can be measured at panicle initiation by tissue analysis or leaf colour. Horie et al. (2005a) describe the steady improvement in rice NUE in Japan, such that overall NUE_i improved from 25% to 80%, by moving successively through the following steps:

1. single application of nitrogen fertiliser at sowing
2. split application of nitrogen fertiliser (partial application at sowing)
3. localised application of nitrogen fertiliser
4. nitrogen fertiliser rates adjusted according to leaf colour
5. introduction of controlled-release urea.

Among farmers of smallholdings growing rice in Asia, the Japanese experience has evolved into **site-specific nutrient management** based on crop nitrogen fertilisation according to leaf colour (Dobermann et al. 2002). With site-specific nutrient management, yield can be improved even as nitrogen rates are reduced—such that NUE_i can be improved by 20–30%, particularly because in-season nitrogen management lifts NUE_i . Another technique is the use of deep placement of urea super-granules, which lessen nitrogen losses by concentrating the urea several centimetres below the soil surface (IFDC 2012).

The low NUE_i at farm level in Asia partly reflects the majority production by smallholder farmers who are yet to adopt the more complex techniques for efficient nitrogen management. Recent developments using mobile phones to relay leaf colour pictures and then deliver recommendations for in-crop nitrogen addition may help the techniques to be adopted, because there remains large scope for improved NUE_i in rice (particularly in China) by improving management of nitrogen fertiliser.

While experiments show opportunities to increase NUE_i , **surveys of observed practice** tend to reveal another picture. For example, the USDA's Agricultural Resource Management Survey (ARMS; Ribaud et al. 2011) of nitrogen use on all field crops (excluding rice) across the USA in 2006 found that relative to best practices for application rate, timing and method:

- 21% of the area exceeded best practice rate for nitrogen application by > 10%
- 25% missed best timing for nitrogen application
- 38% missed best method of nitrogen application.

For maize, the dominant crop in the sample, the figures were not greatly different from the average of all crops. But 14% of maize crops received manure as a source of applied nitrogen, while 2% received manure as the only source, and (for maize) those crops receiving manure scored lower on best management practices than

those receiving only nitrogen fertiliser. A later (2010) ARMS report found only slight improvements in the adoption of best practice (Ribaudo et al. 2012).

Overall the ARMS data indicate considerable scope for NUE improvement through better agronomy, even in the USA. It is notable that regulations regarding best nitrogen practices in various European Union countries are beginning to affect nitrogen fertiliser rates, which now tend to be static or decreasing (Good and Beatty 2011; Mikkelsen et al. 2011). At the other extreme, the scope for improvement in China is clearly large, and marked progress in NUE_i has been demonstrated in on-farm experiments and demonstrations with smarter management—often achieving higher wheat, rice and maize yields with less nitrogen fertiliser use—but the challenge is to reach the millions of tiny farms there (Zhang et al. 2013). In most other developing countries NUE_i is deceptively high because nitrogen fertiliser rates are usually suboptimal and indigenous soil nitrogen is a larger component (see Box 11.1).

Nitrogen use efficiency—novel approaches and limits

What is not clear from the above discussion of NUE and FY progress is whether further PY increases through breeding will continue to improve (or at least maintain) NUE under modern farming at optimal nitrogen rates, and whether improved nitrogen management has more to offer. Breeding specifically targeted at NUE (i.e. more yield with low nitrogen supply) has attracted attention in maize from CIMMYT, and there appear to be large gains reflected across all nitrogen supply levels (see Section 5.4 on maize in Sub-Saharan Africa). The International Rice Research Institute (IRRI) has targeted incorporation of nitrogen fixation capacity into rice roots for several years with limited progress, although sugarcane (another grass crop) can fix appreciable nitrogen through bacteria in its stems (see Section 7.6).

Some predict that $NUpE$ can be further increased, for example, by breeding for root systems that will vigorously grow to capture early mineral nitrogen—when it is most vulnerable to leaching and denitrification losses (Palta and Watt 2009)—or that will penetrate deeper in the soil to retrieve NO_3 that has leached. Other gains could come from root exudates that suppress nitrification. This process, termed 'biological nitrification inhibition', has been found in the tropical perennial grass *Brachiaria* spp. (Subbarao et al. 2013), with promising effects on NUE_i for maize following *Brachiaria*. Gains could also come from engineering of ion transporter proteins to increase the rate of NO_3 uptake at the root surface (Good and Beatty 2010).

When breeding to increase $NUtE$ —the second component of NUE—then the two simple relationships (equations (14) and (15)) must be satisfied. Equation (14) indicates that increased DM production or increased HI is required without extra NUp if $NUtE$ is to be raised. Unless genetic engineering (GE) can deliver a complete switch in C_3 crops to more nitrogen-efficient C_4 photosynthesis—which seems very unlikely (see Section 9.4 on increasing RUE)—it is difficult to envisage greater photosynthetic activity and DM production without a heavy nitrogen demand and a corresponding increase in NUp . In addition, as has already been noted in Section 9.2, HI may be reaching its limits.

Similarly, conditions in equation (15) must also be satisfied to raise NUtE. NHI, which is related to, but always greater than, HI, could be independently increased if less nitrogen than the typical proportion of ~30% of crop NUp in a modern variety is left behind in non-grain crop parts at maturity. This is a difficult trade-off for the plant, since nitrogen is needed in leaves to continue photosynthesis during grain-filling at the same time that it is needed in the grain to build NHI. If NHI is held constant, NUE can only increase only if GNC continues to fall, but this brings quality penalties in wheat and possibly nutritional penalties in rice. Barraclough et al. (2010) pointed to the influence of grain classification of recent UK winter wheat varieties: both yield and NUtE were inevitably lower in bread-making varieties because selection has sought higher GNC than for biscuit and feed varieties.

On the agronomic front, there is undoubtedly scope to lift NUE through adopting existing best practices. Newer technologies such as controlled-release urea have been mentioned in the context of rice in Japan. In addition, Yang et al. (2011) used controlled-release urea in irrigated winter wheat in the province of Shandong, China, and reached the economically optimal nitrogen rate with at least 33% less urea nitrogen than for straight urea. Adding nitrification inhibitors with fertiliser granules is another strategy. For example, in Iowa, USA, Parkin and Hatfield (2010) significantly lifted NUE of maize by 7% with the nitrification-inhibitor nitrapyrin applied with the autumn anhydrous NH₃, but currently such inhibitors are relatively expensive and not used.

Upper limits to NUE_i at the economically optimal fertiliser rate can be determined by using equation (15). Assuming that GNC remains (for grain quality reasons) at typical minimal acceptable values of 1.5% for wheat, 1.2% for paddy rice and 1.3% for maize, and that NHI is fixed at 0.7 for all three crops, then NUtE will be limited to 47 kg/kg N for wheat, 58 kg/kg N for rice and 54 kg/kg N for maize. If NUpE_i were to reach 100%, then these NUtE_i values would equate to NUE_e. But this is not the whole picture, because apart from current applications of fertiliser, NUE_i is also influenced by changes in the indigenous supply of soil nitrogen. These nitrogen sources are:

- accessions from atmospheric deposition, irrigation water and applied manure (see also Section 11.5 on sustainability)
- biological nitrogen fixation
- net change in soil inorganic nitrogen fraction involving soil organic matter mineralisation, NO₃ leaching and denitrification
- residual nitrogen from previous fertilisation and from crop residue.

The fact that NUE_i in Table 11.1 exceeds the above estimated limits for wheat in the European Union (50.6 kg/kg N) and maize in the USA (60.2 kg/kg N) must reflect that such sources of nitrogen have been excluded from the above estimation. This nitrogen supply could be sustainable if the sources are carryover fertiliser nitrogen, manure, accessions or legume nitrogen. Otherwise, if they arise from net loss of soil organic matter through mineralisation, such high NUE_i results will be unsustainable.

Furthermore, for any cropping system there will be an upper limit to NUE_f when nitrogen removal by grain yield equals nitrogen replacement by fertilisation. In this book this is called the 'balancing limit' and suggests another way of looking at the NUE_f limit. Grain yield divided by GNC gives this limit if it can be assumed that: (1) accessions in water and dust, manure and nitrogen fixation balance any nitrogen losses due to gaseous nitrogen losses and NO_3 leaching; (2) all crop residue nitrogen is returned to soil; and (3) soil organic matter (and thus total soil nitrogen content) is stable. Using the GNC values specified above, the **balancing limit NUE_f is 67 kg/kg N for wheat, 85 kg/kg N for rice and 77 kg/kg N for maize**. These values are higher than would be calculated assuming 100% fertiliser uptake above, because the latter approach ignores return of nitrogen to soil in crop residue.

NUE_f values for maize in the USA shown in Table 11.1 (60.2 kg/kg N) and in the Nebraskan maize examples above (71 kg/kg N) are close to the balancing limit NUE_f ,—a surprising outcome given how difficult it is to avoid nitrogen leaching from occasional heavy rainfall events in the US Corn Belt. Of course, much US maize is now planted in a rotation that follows soybean, in part to exploit the small net positive effect that soybean contributes to the soil nitrogen balance. Soybean receives little nitrogen fertiliser under normal practice and 10% of maize crops receive some nitrogen from manure applications. Moreover, atmospheric deposition and nitrogen in irrigation water are not insignificant. Nitrogen input in irrigation water in Nebraska amounts to ~ 30 kg/ha/yr (P. Grassini, pers. comm. 2012). EPA (2011) maps suggest that total nitrogen deposition in the US Corn Belt is ~ 10 kg/ha/yr. On the other hand, for economic reasons much fertiliser nitrogen for maize is applied in the autumn ahead of planting and is at greater risk of loss by leaching with spring rains. So the conclusion could be that although the system may be close to the balancing limit for NUE_f , there are still moderate non-fertiliser nitrogen inputs balanced by moderate amounts of nitrogen escaping into the environment.

For wheat in Table 11.1, the NUE_f result for the European Union (50.6 kg/kg N) is closest to the balancing limit, possibly reflecting the best example of nitrogen management. For rice, ignoring the figure of 73 kg/kg N from Brazil, which may reflect soils with a short history of cropping and high organic matter, the best NUE_f occurred in India and the USA (each close to 47 kg/kg N). But these figures are still well below the balancing limit (85 kg/kg N), probably reflecting high losses of fertiliser nitrogen in irrigated rice.

Stability of soil organic matter is the biggest uncertainty in these calculations. Carbon sequesters nitrogen at a ratio of about 12:1 in soil organic matter—that is, one tonne of extra carbon sequesters 100 kg of nitrogen. If soil organic matter were to increase (say, if the cropping system switches to conservation tillage), more soil nitrogen would be sequestered and NUE_f would decline. On the other hand (and other things equal), as climates warm, soil organic matter may decline (Sentilkumar et al. 2009), which will initially boost nitrogen supply to crops and raise NUE_f . As difficult as it may be to increase NUE_f , and NUE_t , none of these important nitrogen balance complications and uncertainties lessen the urgency for seeking new techniques to achieve this goal, in particular, easier and less-expensive ways for farmers to meet the '4 R's' of best management practice.

Nitrogen—role of legumes

If managed to maximise nitrogen fixation, legume grain crops generally receive little or no fertiliser nitrogen; therefore NUE_i is irrelevant for these crops. Further, depending on crop type, grain legume crops can make small net contributions of around 10–50 kg N/ha to soil nitrogen. As a rule of thumb, legumes may fix 20 kg of atmospheric nitrogen per tonne of total DM produced (Peoples et al. 2009). This production is generally more than the amount of nitrogen removed when the grain is harvested.⁵⁴

Nitrogen in remaining underground DM (roots, nodules, rhizosphere exudates) adds to the legume contribution of nitrogen to the soil. Peoples et al. (2009) estimated that 190 Mha of legume grain crops globally contribute ~5–7 Mt N to soil after allowing for removal of about 6 Mt through grain harvest; this is a contribution of about 30 kg N/ha. For this and other reasons, legume crops are almost always followed by non-legumes, as shown, for example, by the soybean–maize rotation in the USA and Brazil, and pulse–wheat or pulse–canola rotations in Europe, Canada and Australia. In such systems, proper nitrogen fertiliser recommendations acknowledge the nitrogen contribution from the legume, so that less nitrogen fertiliser is applied to post-legume crops, and NUE_i correspondingly increases as discussed previously for maize-following-soybean.

Soil organic matter and nitrogen accumulate much faster under legumes sown as green manure crops or pasture (rather than legume grain crops), with rates of 50–300 kg N/ha/yr depending on legume DM production. However, these practices have declined in popularity everywhere because of negative economic return in the green manure year, or reduced returns from grazed pastures (relative to crops), and the widespread availability of cheap nitrogen fertiliser (except generally in Sub-Saharan Africa). For example, the rainfed wheat cropping system in Australia did not use fertiliser nitrogen until the 1980s, but relied on nitrogen from preceding years of leguminous pasture, with the ratio of leguminous pasture to wheat area approximately 1:1. Since then, economics favoured cropping, and rotational pastures and livestock numbers on wheat farms have declined, so that by 2000 wheat was receiving fertiliser nitrogen at an average rate of 30 kg N/ha (Angus 2001). However, the very high national average NUE_i of ~63 kg/kg N suggests that legumes still contribute an important amount of nitrogen to wheat production in Australia. When the ratio of livestock to crop prices changes, so does the attractiveness of including legume forage years in a cereal crop rotation, both in Australia's wheat–sheep system (e.g. Thomas et al. 2009) and in the maize–leguminous forage system in Iowa, USA (e.g. Davis et al. 2012). However, what discourages retaining traditional mixed farming or switching to it are the capital costs and the much greater management complexity of such systems.

⁵⁴ Kilograms of grain nitrogen removed can be calculated per tonne of total DM (above-ground only) by multiplying HI by GNC by 1,000. GNC is lower for pulses (3–4%) than soybean (6.0–6.5%). A crop with HI = 0.4 and GNC = 4% removes as grain 16 kg N/t DM, leaving a net gain of only 4 kg N/t.

Legume research has been neglected relative to cereal research so there is considerable scope to redress this imbalance, with benefits for cropping system NUE. The success of soybean as a new crop confirms the responsiveness of legume yield to investment in research and development. Furthermore, recent work suggests that while nitrogen fixation in legume root nodules consumes photosynthate, it appears that rate of photosynthesis is stimulated more by the nodule sink resulting in no net cost (in terms of DM) from nitrogen fixation (Kaschuk et al. 2009). It is, however, wishful thinking to expect legume-fixed nitrogen to supply all the nitrogen demands of the global non-legume grain crop. Green manures probably account for <1% of current world crop area, and would need to expand to perhaps equal the non-legume crop area (i.e. 1,200 Mha) to supply all nitrogen demands for these crops (Connor 2008; see also Box 11.2). Even so, grazed legumes (ley farming) could produce high-protein animal products during the legume phase of rotation with little reduction in the accumulation of soil nitrogen relative to green manure legumes.

Nitrogen—some conclusions

Cereals and other non-legume crops need large amounts of nitrogen for current economically optimal or attainable yields. The amounts of nitrogen are proportional to target yield (~20 kg N/t for wheat and rice, and ~15 kg N/t for maize), but inevitably increase the risk of some losses of nitrogen from the cropping system. If soil nitrogen is not to be depleted, nitrogen demand must be met by nitrogen fertiliser. In a stable system, the amount of applied nitrogen should be more or less equal to nitrogen removed in grain, provided losses from leaching and denitrification can be balanced by the small accessions from dust, rain, irrigation water, legume and non-symbiotic nitrogen fixation.

Although the need for nitrogen fertiliser can be reduced in a cereal cropping system by increasing the frequency of legumes in rotations, the nitrogen contribution from legumes is limited if the grain is harvested, and legumes do not reduce the risk of nitrogen losses to the environment. Improved agronomic techniques have improved NUE_c (largely through greater NUPE_c) and genetic improvement has lifted NUE (largely through greater NUTE). However, modern cropping operates at higher optimal soil nitrogen levels, which somewhat counters these gains.

Further progress in NUTE through breeding seems difficult, because it will require further increase in NHI, or reduction in GNC, which could threaten grain quality. However, scope exists for raising NUPE—perhaps through genetics, but especially through improved agronomy. Such improved practice would ensure that nitrogen is supplied only to meet crop needs at each stage of the crop cycle while avoiding excess supply. Besides research, more expensive nitrogen and regulation are probably necessary to achieve more efficient nitrogen fertiliser use.

Phosphorus

The current global amount of phosphorus applied annually as fertiliser is ~17 Mt (average for 2007–09; FAOSTAT 2013), of which ~46% is applied to cereals (Heffer 2009).⁵⁵

The global supply of non-renewable rock phosphate—the source of all fertiliser phosphorus—is adequate for many years to come, although grades are falling and costs are rising (Van Kauwenbergh 2010). The alarming price spike of 2007–08 should not be attributed to long-term supply shortages but rather to a temporary shortage in the face of heightened demand, along with profit-seeking behaviour of suppliers (Cornish 2010). On a weight basis, phosphorus costs about three times as much as nitrogen, and although grain phosphorus concentration is usually only one-fifth of that of GNC, phosphorus can be an expensive input to cropping in deficient or phosphorus-fixing soils. Thus an important productivity objective is to increase phosphorus use efficiency (PUE) or more specifically, PUE_i (defined similarly to NUE_i).

Table 11.2 shows average elemental phosphorus rates and PUE_i for the key cereals in several world countries or regions. Sub-Saharan Africa is again not shown because rates, at ~1.5 kg P/ha across all crops, are too low. Compared with the USA and the European Union, phosphorus rates in China, India, Argentina and Brazil are higher and PUE_i is clearly lower for both wheat and rice, suggesting inefficiencies in those countries. For maize, rates are higher in the USA, the European Union and Brazil, but efficiencies are similar across all countries except for the low value in Brazil. The low PUE_i values may be caused by excessive application rates, especially in China, but the uniquely low PUE_i in Brazil may reflect the highly P-fixing soils in Brazil in general and the new maize area of the Cerrado in particular.

PUE can usefully be dissected in the same way as NUE (Box 11.1)—thus PUE increases as all other factors contributing to PY are optimised—yet there are notable differences between phosphorus and nitrogen. Phosphorus is relatively immobile in soil and, apart from topsoil erosion, or leaching risks in very sandy soils, it is not subject to losses. However, depending on soil chemistry, fertiliser phosphorus is fairly readily fixed into inorganic forms (with iron, aluminium and calcium) and/or organic forms, and thus plant-available phosphorus will gradually decrease over time (McLaughlin et al. 2011)—this represents another type of loss, at least to the plant, if not to the environment. Because of this, soil testing for levels of available phosphorus can provide a useful guide to optimal fertiliser rates; the practice is especially appropriate because phosphorus must be applied before crop planting.

Highly phosphorus-fixing soils require phosphorus to be applied for many years at rates well in excess of crop demand until available soil phosphorus is high enough to

⁵⁵ Elemental phosphorus (P) content is used throughout this book, although the fertiliser industry often refers to phosphorus pentoxide (P_2O_5) content, of which 43.7% is elemental phosphorus, so that 1 kg P = 2.29 kg P_2O_5 .

permit only replacement (or maintenance) rates of phosphorus fertiliser to balance phosphorus removal as grain. In theory, crops with a lower critical requirement for available phosphorus should reduce the phosphorus investment needed before ‘balancing’ phosphorus applications are reached, but this approach is more complex in practice (Simpson et al. 2011).

Table 11.2 Average phosphorus fertiliser application rates^a and phosphorus use efficiency (PUE_f)^b across world regions and countries in 2007–09

Country	Variable	Wheat	Rice	Maize
China	Fertiliser rate (kg P/ha)	35.0	28.3	11.9
	PUE _f (kg/kg P)	134	230	447
India	Fertiliser rate (kg P/ha)	20.1	16.3	5.1
	PUE _f (kg/kg P)	140	202	438
USA	Fertiliser rate (kg P/ha)	10.0	11.7	22.7
	PUE _f (kg/kg P)	291	709	433
European Union	Fertiliser rate (kg P/ha)	8.6	na	17.7
	PUE _f (kg/kg P)	618	na	379
Argentina	Fertiliser rate (kg P/ha)	12.5	na	13.1
	PUE _f (kg/kg P)	200	na	505
Brazil	Fertiliser rate (kg P/ha)	14.3	22.2	21.8
	PUE _f (kg/kg P)	161	187	177

a Elemental phosphorus weights are used, not phosphorus pentoxide (P₂O₅) weight

b Given as kilogram of grain yield per kilogram of phosphorus applied as fertiliser (kg/kg P)

Source: FAOSTAT (2013) for total fertiliser used and for yields to calculate PUE_f; fertiliser use distribution among crops at country level based on Heffer (2009)

PUpE_f increases as phosphorus-fixing sinks in soils become saturated with continuing application in excess of removal. Separately, improvements to PUpE_f have arisen through manufacturing techniques that have improved availability of fertiliser phosphorus—for example, superphosphate compared with rock phosphate, and liquid instead of granular forms (at least on calcareous soils)—or which place fertiliser phosphorus below (or otherwise close to) the crop seeding row. Soil phosphorus tends to be concentrated in the upper soil levels, especially with modern zero-till systems; thus deeper location of fertiliser phosphorus to where soil water is more consistently available (even into the subsoil) may be advantageous in rainfed situations, and may be made possible without deep tillage if new formulations are used (McLaughlin et al. 2011).

Applying NH₃ forms of nitrogen fertiliser along with the phosphorus fertiliser can increase early growth in phosphorus-deficient calcareous soils (Jing et al. 2012),

possibly because acidification of the rhizosphere in the fertiliser band aids phosphorus solubilisation. Intercropping cereal and certain legumes in phosphorus-deficient situations can markedly improve the cereal yield, leading to overyielding⁵⁶ of the intercrop. For example, this effect occurred with an intercrop of maize and faba bean because of the intermingling of the rhizospheres of each crop, and probably because of acidification arising from the faba bean rhizosphere (Li et al. 2007). Note that the overyielding effect in this example was present with high nitrogen fertiliser, but not with high phosphorus fertiliser, when the maize presumably had less need for the solubilising effect of the faba beans. Thus the general but poorly understood phenomenon of legumes complementing or aiding phosphorus supply to intercropped cereals (Hinsinger et al. 2011) may operate only in phosphorus-deficient situations, thus reducing its usefulness.

PUE_i has also increased as breeding has lifted PY, probably largely because phosphorus-utilisation efficiency (PUE) by the plant has increased for the same reasons as has NUE. Certainly, modern short wheat varieties show higher values for phosphorus HI (and lower values for grain phosphorus concentration) than older, taller varieties (Batten 1993; Calderini et al. 1995), without difference in total phosphorus uptake. In contrast to grain nitrogen, much grain phosphorus is in the form of inositol or phytate phosphorus—forms that do not benefit (and can actually reduce) grain food and feed quality because phytate reduces calcium uptake by animals. Thus PUE gains made through lower grain phosphorus concentration may carry no hidden cost, and such changes have arisen as the indirect consequence of genetic yield progress, at least in wheat. Researchers now directly pursue reduced wheat grain phytate content (and hence lower grain phosphorus concentration) to further increase PUE. However, to date, at least with wheat, low grain phytate lines do not necessarily show lower grain phosphorus concentration, and hence improved PUE_i ; neither do they show improved nutritional quality.

Most efforts for the future focus on increasing phosphorus uptake efficiency (PUE) through increasing the availability of soil-fixed phosphorus. Several mechanisms for achieving this exist in plants naturally adapted to soils with low available phosphorus, so there is considerable variation in PUE among crop species. For example, crops like lupins (*Lupinus* spp.) or buckwheat (*Fragopyrum esculentum*) can extract several times more indigenous soil phosphorus than wheat (McLachlan 1976). Mechanisms showing intraspecific variation have been extensively reviewed (Richardson et al. 2011). They include root foraging and root mining characteristics such as:

- more and finer roots (especially close to the soil surface, where phosphorus is concentrated)
- longer root hairs

⁵⁶ 'Overyielding' is best expressed as a 'land equivalent' ratio of >1.0 —the ratio of the land area of the two crops as sole crops needed to produce the same amount as unit area of intercrop; in the maize–faba bean example used above, the land equivalent ratio was 1.35 under phosphorus deficiency.

- propensity to harbour root associations with fungal arbuscular mycorrhiza
- root exudates such as malic, citric or piscidic acid as well as phosphatase enzymes, often associated with cluster root formation.

Some progress has been made in identifying varieties with roots that are more efficient phosphorus foragers; this has been achieved in beans (*Phaseolus vulgaris*) by Liao et al. (2001) and in wheat by Manske et al. (2000). Rice is known to contain a natural gene (*Pup1*) that increases phosphorus uptake and confers tolerance to phosphorus deficiency. Known for some time, *Pup1* has been mapped and studied, and appears to operate by increased early root growth and hence greater phosphorus acquisition (Gamuyao et al. 2012). Other research groups are now pursuing GE approaches such as improved phytase exudation to release soil phytate phosphorus, a major component of the unavailable soil organic phosphorus. So far success in the field has been very limited (Richardson et al. 2011). These mechanisms will not be useful if they are facultative—that is, if they operate only when the plant is seriously phosphorus deficient. By comparison, microbial inoculants have been available for some time, and are promoted as increasing phosphorus solubility in the rhizosphere. On occasions these inoculants appear to stimulate root growth rather than increase phosphorus solubility, but either way, their performance in the field is still very unreliable (Richardson et al. 2011).

Note that improved PUpE can only reduce the need for fertiliser phosphorus until soil phosphorus levels build to a point sufficient to supply PY, when phosphorus applications can then fall to levels balancing phosphorus removal by grain. As applies for nitrogen—although free from complicated gains and losses from the system, except for possibly slow decrease in the availability of fixed forms of soil phosphorus—the upper balancing limit to PUE is reached in a stable cropping system, and is given by grain yield divided by grain phosphorus concentration. Based on typical grain phosphorus concentrations of 0.35%, 0.27% and 0.40% **for wheat, paddy rice and maize, the upper balancing PUE_i limits are determined to be 290 kg/kg P, 370 kg/kg P and 250 kg/kg P, respectively.**

Observed farm values from Table 11.2 that are lower than these upper limits (e.g. rice and wheat in China and India, maize in Brazil) suggest either overfertilisation or ongoing fixation of phosphorus, undoubtedly the latter in Brazil. Table 11.2 values that are higher (rice in the USA, wheat in the European Union and maize in all regions except Brazil) indicate that soil phosphorus is being mined—possibly from excess phosphorus applied to the systems at earlier times. However, considerable uncertainty surrounds observed values of PUE_i and the lower limits of grain phosphorus content.

In conclusion, just as has occurred for NUE, PUE has benefited from the multiple ways in which PY (and PY_w) have been improved, but the existence of soil phosphorus fixation brings unique considerations, including very low soil phosphorus losses if erosion is controlled. In the phosphorus build-up phase, best practice management of phosphorus fertiliser can increase uptake efficiency and reduce application rates, so that less investment in soil phosphorus accumulation is needed before a stage of

balance is reached. While large differences appear to exist between plant species in uptake efficiency, it has proved very difficult to exploit such traits in crop plants and much more research is needed. At the same time, direct selection for lower grain phosphorus concentration could bring further small gains in PUE (and PUE_g), both benefits which would be seen in the build-up phase as well as afterwards, when phosphorus application should only need to balance product removal.

11.4 Energy use efficiency

Setting the scene

While food scientists are wedded to the use of calories, energy use efficiency here is reported using the international system of units (SI units)—megajoules (MJ) and gigajoules (GJ).⁵⁷ The definition of energy use efficiency is the weight of grain, corrected if necessary for differing grain energy densities—15 MJ/kg for cereals and 24 MJ/kg for soybean (Rathke et al. 2007)—per unit of energy used both directly and indirectly in producing the grain. Here this is expressed as kilograms of yield per gigajoule (kg/GJ). The reciprocal of this is sometimes called ‘energy intensity’ (Schneider and Smith 2009).

While systems with low fossil fuel inputs may maximise efficiency with respect to fossil fuel energy, these systems come at the cost of much higher and often-overlooked labour (and animal) energy inputs, and generally lower outputs per hectare (Connor et al. 2011), which brings other inefficiencies (see Box 11.2 ‘Organic agriculture’). The question is therefore how modernisation of agriculture can change energy use efficiency in major crops where yield progress is accompanied by growth in the number, complexity and quantities of inputs. Many authors comment (without evidence) that energy use efficiency is deteriorating and that cropping systems are becoming more sensitive to energy price shocks. In fact, this is generally not correct.

Table 11.3 shows approximate energy costs (including indirect costs) for some key agricultural inputs that can be used for full life cycle analysis. Direct sources of energy (e.g. diesel) have relatively stable energy costs, but embodied energy in other inputs varies considerably depending on efficiencies. For example, substantial improvements in NH₃ manufacture have notably reduced energy costs for NH₃ and urea nitrogen (see also Section 10.5 on greenhouse gases), but these process improvements have recently approached the thermodynamic limit of the Haber–Bosch process (Smil 2008). Energy costs for biocides are quite high per kilogram of active ingredient (a.i.), but application rates have steadily decreased over time with the arrival of more efficient and effective chemicals.

⁵⁷ 1 joule = 0.239 cal; 1 MJ = 239 kcal; 1 cal = 4.18 joules

Table 11.3 Energy costs of key agricultural inputs (on-farm)

Source of energy cost	Units	Value	Comments and reference
Labour, fuel, machinery and irrigation			
Labour	MJ/d	600	Estimated energy (mainly electricity, fuel and food) needed to support one farm worker at a modern standard of living in a developed country. Source: Connor et al. (2011)
Diesel	MJ/L	37	Estimates vary from 42 MJ/kg to 47 MJ/kg, with diesel weighing 0.85 kg/L; some add ~15% to cover full life cycle machinery costs. Source: Smil (2008)
Petrol	MJ/L	33	Estimates vary from 42 MJ/kg to 48 MJ/kg with petrol weighing 0.74 kg/L. Source: Smil (2008)
Machinery manufacture	MJ/kg	80	Kilogram refers to weight of the unit, which can be amortised or depreciated over time Source: Connor et al. (2011); note that Rathke et al. (2007) used 108 MJ/kg in Nebraska
Irrigation	MJ/mm/ha	44	For diesel pump at 80% efficiency, 50 m lift and 250 kPa (35 psi) delivery to centre pivot system. ^a Source: Martin et al. (2010)
Artificial grain drying	MJ/kg water removed	4.65	Equivalent to 0.0465 GJ/t to lower grain moisture by 1%, but ranges from 2.5 to 7 MJ/kg water. Source: Hellevang (1994)
Transport			
Truck	MJ/t/km	2.4	Dependent on road surface; rail is only ~8% of the road figure. Source: IEA (2008)
Fertiliser			
Nitrogen	MJ/kg N	57	Source: Keystone Center (2009). Smil (2008) gives 55–58 MJ/kg N as urea at the average factory, and 40 MJ/kg N for NH ₃ , but newest factories now achieve NH ₃ with only 34 MJ/kg N
Phosphorus	MJ/kg P	22	Source: Zentner et al. (2004). Smil (2008) gives 19 MJ/kg P (superphosphate) and 25 MJ/kg P (triple super) at the factory; while Connor et al. (2011) give 16 kg/kg P
Protectants			
Herbicides	MJ/kg a.i.	267	Source: Keystone Centre (2009), general figure. Zentner et al. (2004) use 511 MJ/kg a.i. for glyphosate
Fungicides	MJ/kg a.i.	356	Source: Connor et al. (2011). Keystone Center (2009) uses 285 MJ/kg for the USA
Insecticides	MJ/kg a.i.	358	Source: Connor et al. (2011). Keystone Center (2009) uses 289 MJ/kg for the USA

a Typical for Nebraska (USA) irrigated maize. If lift is doubled, energy will rise by 65%. If pressure is reduced to zero (e.g. pumping direct to a channel, as occurs in the Indo-Gangetic Plain, India and Pakistan), energy will fall by 35% to become proportional to lift.

a.i. = active ingredient

Not shown in Table 11.3 is the variation among tillage and machinery operations that arises because of differences in soil, scale and efficiency. For example, Rathke et al. (2007) used the following fuel consumptions:

- direct seeding = 10 L/ha of diesel (1.25 GJ/ha)
- mouldboard plowing to 25 cm depth = 34 L/ha of diesel
- pesticide application = 2 L/ha of diesel
- tandem discing = 7.5 L/ha of diesel.

Furthermore, according to Zentner et al. (2004), ~15% should be added to each of these consumption figures to cover machinery overheads (such as manufacture and maintenance) if it has not been included elsewhere in the calculation (as in Table 11.3).

Overall, in most energy budgets for cropping (at least for non-legumes), nitrogen fertiliser represents the major energy cost, often amounting to 50% of the total. Therefore, energy budgeting must accommodate situations where nitrogen fertiliser is saved by running down soil nitrogen, as this will only falsely and temporarily boost energy use efficiency. The second highest cost is usually tractor fuel, but where moist atmospheric conditions prevail, such as at high latitudes or where there is frequent rain at harvest, artificial grain drying replaces natural solar drying and the energy costs can be higher than that for tractor fuel (Connor et al. 2011).

Energy use efficiency increases with cropping intensification

Aggregate energy use has steadily increased in world agriculture. For maize in the USA, the energy input per hectare has increased about fourfold between 1945 and 1985 (Evans 1993). Since then energy input may have levelled off or even declined (Swanton et al. 1996; Keystone Center 2009). At the same time at the global level, efficiency has risen in developed countries, while in contrast, it has declined slightly in developing countries as energy use in agriculture increases (Schneider and Smith 2009).

Some inputs in Table 11.2 are independent of yield, while others are linked. It is therefore not surprising that energy use efficiency—in terms of kilograms of grain harvested per gigajoule of energy input (kg/GJ)—can increase even as energy input per hectare has increased under intensification. For example, the Keystone Center (2009) looked at maize in the USA and reported that between 1987 and 2007, yield rose more rapidly than energy input per hectare—average yield increase of 37% vs. average energy increase of 9%—the latter settling at ~18 GJ/ha by 2007. As a result, energy use efficiency increased steadily by 25% over the period, to reach 450 kg/GJ by 2007. Since NUE_f for maize in the USA is 62 kg/kg N (Section 11.3), and assuming the energy cost of nitrogen used is 57 MJ/kg (Table 11.3), then the fertiliser energy fraction of total energy for producing maize in 2007 was 0.41—calculated from $(57 \times (450/62)/1000)$.

The improving NUE reported in Section 11.3 is clearly one reason why energy use efficiency is increasing in maize in the USA. Swanton et al. (1996) reported that energy use efficiency for maize in Ontario, Canada, increased by 50% from 1975 to 1991 to reach 593 kg/GJ, and part of this substantial improvement arose from more efficient production of nitrogen fertiliser.

A comprehensive study across fields of irrigated maize in the central part of southern Nebraska, USA, (see also Grassini et al. 2011a in Section 8.2) calculated 440 kg/GJ average energy use efficiency for maize production (Grassini and Cassman 2012). The total energy input averaged 30 GJ/ha, of which irrigation pumping accounted for 42% (for an average 272 mm per crop, pumped from an average depth of 36 m); nitrogen fertiliser for 32% (applied at a rate of 183 kg N/ha); and field operations and grain drying each for 9%. The average grain yield was 13.2 t/ha and the energy output-to-input ratio was 6.6—a fairly typical average value for high-yielding maize in the USA, according to these authors. Energy use efficiency, however, varied greatly between fields, suggesting scope for further improvement. For example, centre pivot irrigation was more efficient than surface irrigation (less water pumped), reduced tillage was more efficient than cultivation and excess nitrogen rates were (obviously) inefficient. Efficiency gains from zero-till were also evident from a long-term small plot experiment in Nebraska (rainfed soybean–maize rotation) where energy use efficiency for maize was 788 kg/GJ under the plough treatment and 898 kg/GJ for zero-till (Rathke et al. 2007).

For soybean over the 1987–2007 period, Keystone Center (2009) reported that energy use per hectare fell by 50% while yield rose by 33%. This outcome produced a staggering 166% increase in energy use efficiency. Energy use in 2007 was only 3.1 GJ/ha, and efficiency reached 840 kg/GJ, reflecting the legume advantage over maize in that study. Earlier, Swanton et al. (1996) calculated that energy use efficiency in soybean production in Ontario, Canada, increased by 50% from 1975 to 1991, to reach 677 kg/GJ.

The Keystone Center (2009) also analysed wheat in the USA, and found that between 1987 and 2007, yield increased somewhat faster than energy input per hectare (17% vs. 8%) so that energy use efficiency rose only 8% to reach 312 kg/GJ. In Saskatchewan, Canada, Zentner et al. (2004) reported 360 kg/GJ for both conventional and zero-till wheat. Wheat's lower energy use efficiency than maize probably explains the lower yields.

Using Keystone Center (2009) values for energy use efficiency in 2007 and the energy content of grains (recall 15 MJ/kg for cereal and 24 MJ/kg for soybean) allows energy output-to-input ratios to be calculated for the USA, in general, as 7 for maize, 20 for soybean and 5 for wheat. However, processing costs for bioethanol production from maize will notably reduce the net energy yield in ethanol (Connor et al. 2011), but processing does also deliver an energy-rich feed by-product.

Future PY increases are likely to further increase energy use efficiency, especially where NUE_i can continue to increase. But it is becoming increasingly difficult to further progress NUE_i in modern agriculture, given the high NUE_i levels already achieved, as

seen, for example, in the USA and Europe (Table 11.1). However, much scope remains in developing countries for improved energy use efficiency by this route.

The other area for improved energy use efficiency is fuel saving through reduced or zero-till and controlled traffic, although the quoted examples of reduced tillage reveal that fuel saving is often largely counterbalanced by high energy costs of herbicides. This is particularly the case with glyphosate, the current mainstay of most reduced-till systems—1 kg of glyphosate a.i. carries the energy cost equivalent to that of 14 L of diesel. By avoiding overlap, precision guidance for biocide (and fertiliser) applicators can reduce chemical use by up to 10% without yield loss. Although not yet widely practised because of the capital costs involved in machinery, controlled traffic (whereby wheels are confined to fixed lanes across the field) also offers modest fuel energy savings on most soils, in addition to benefits of the precision guidance and reduced soil compaction.

In conclusion, there is little doubt that modern technology has improved the energy use efficiency of crop production in terms of kilograms of grain per unit energy input, with some prospects for further increase. In the context of energy debates, also note that in modern food systems, less than 20% of the total energy cost of putting food on the table accrues on-farm (Connor et al. 2011; FAO 2011a). In the USA, transportation energy is only between 4% (Canning et al. 2010) and 12% (FAO 2011a) of the total. Thus most scope for energy saving exists outside the farm and outside the transport system, notwithstanding the popular notion that sourcing food locally saves substantial energy. Movement of goods by heavy truck requires ~10 times more energy per tonne per kilometre than container shipping and ~3 times more than by rail, while movement by lighter vehicle would be even more energetically expensive than by truck.

11.5 Sustainability in modern intensive agriculture

While there are many definitions for **'sustainability' in cropping** (e.g. Keystone Center 2009; Spiertz 2010), this book considers the term to mean those situations where the resource base (soil, water and agricultural biodiversity) is not degraded, but is maintained or, if necessary for greater productivity, improved over time. Also, any definition must include the minimisation of negative off-site environmental impacts, such as agricultural chemicals and greenhouse gases and, conversely, the maximisation of environmental services to the extent possible in a cropped landscape. Climate and clean air (e.g. absence of toxic levels of ozone) are also part of the agricultural resource base; these factors have been covered in Chapter 10. The vast and controversial subject of sustainability (and the following discussion on environmental impact) can only be briefly examined here; more depth can be found in appropriate chapters in Nösberger et al. (2001) and Connor et al. (2011).

Perceived constraints on future water, nutrient and energy supplies often form part of the popular view that modern high-yielding agriculture is unsustainable, but as already shown, modernisation has generally increased the productivity of these inputs in cropping. The global supply of these resources is important, but at least for nutrients and energy, is generally external to the cropping sustainability debate. These resources may become scarcer and/or more expensive, but this will drive the search for new sources, and in the case of nutrients, recycling. However, because of the approaching limits to water for irrigation in some regions, and the very high cost of desalination, water is included here as part of the cropping sustainability debate.

Many other sustainability-related aspects of modern agriculture appear also to concern some of the general public. This is reflected in (and encouraged by) a vocal and influential minority in society who challenge modern farming methods and support alternative farming strategies. Despite initial plans for a balanced scientific debate on these issues, a report by McIntyre et al. (2009) for the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) presented unbalanced criticism of modern agriculture, having been unfortunately dominated by non-government advocates of alternative farming models based on ill-defined 'agroecology' (Wood and Lenné 2011b). The criticism of modern cropping is wide-ranging and some arises elsewhere in this book—for example, see Section 8.4 on the need for new agricultural extension models, Section 13.2 on the ownership of plant breeding and Section 13.6 on the fate of small farms. Other issues relate to sustainability, such as the reliance of modern agriculture on 'artificial' chemicals (i.e. fertilisers and biocides), or the loss of biodiversity associated with the simplification of cropping systems and the dominance of monocultures. The issues pertaining to sustainability are discussed in this and the following sections, including the notion of organic agriculture as a more sustainable approach to feeding the world (see Box 11.2).

Soil resource

Soil sustainability is threatened by **soil degradation due to poor cropping practices**, which result in long-term decline in productive capacity of the soil; degradation of cropland due to other causes (e.g. industrial pollution) is likely minor and not considered here. Soil sustainability is a poorly understood and emotive concept, subject to misunderstanding and exaggeration. The scientific literature refers to much degradation of currently cropped land, with a presumably yield-lowering effect. However, the yield effects of soil degradation remain susceptible to opinion, and the key matter is the extent of cropland being lost due to degradation that is too expensive for farmers to reverse.

Oldeman et al. (1991), using expert opinion, concluded that >1,300 Mha of agricultural land (including 550 Mha of cropland) was degraded by human-induced activities, implying reductions in productivity; 16% of this land could only be recovered, if at all, with major capital investment beyond the resources of the

farmers. Much later, Bai et al. (2008) attempted another global estimate, this time using satellite images to detect degraded and currently degrading areas as those in which plant primary productivity showed a negative trend between 1981 and 2003. The result was about 666 Mha of degraded and currently degrading cropland, much of which the authors claimed did not overlap with the Oldeman et al. (1991) estimate (which could have been dominated by historic degradation). Neither of these two approaches estimated current annual rates of cropland loss due to severe degradation, and neither were such statistics provided in the latest pronouncements of the Food and Agriculture Organization of the United Nations (FAO 2011b).

However, using various sources, Scherr and Yadav (1996) estimated the rate of cropland soil degradation, suggesting that 5–10 Mha were annually lost in developing countries, due to severe degradation, while yield losses were accumulating on the remaining degrading cropland at an alarming rate of ~0.4% p.a. of observed yield. However, in Section 1.4, the numbers of Lambin and Meyfroidt (2011) were accepted as more realistic, amounting to 1–3 Mha of cropland per year completely lost to severe degradation. It is also likely that FY progress may be depressed to some degree by ongoing degradation in some situations, particularly in Sub-Saharan Africa. Thus, there is clear reason for the current level of confusion and alarm regarding the magnitude of soil degradation, but the key question for discussion here is whether sustainable intensification of cropping exaggerates the problem. This seems very unlikely.

Soil degradation that can arise from cropping activities includes:

- accumulation of toxins associated with some inputs (e.g. cadmium and/or arsenic)
- acidification
- compaction
- erosion (physical loss especially of topsoil but also terrain deformation)
- fertility decline and nutrient imbalance
- loss of beneficial soil biota and build-up of soil-borne diseases
- salinisation
- structural decline.

The native (or original) soil state is generally taken as the base, but this base is not necessarily something that should be maintained. Prior to conversion to agricultural production, some soils were inherently poor (e.g. naturally sodic, saline or nutrient deficient), meaning that these soils have been (or can be) improved by modern cropping. For example, lime and phosphorus are applied to overcome native acidity and severe phosphorus fixation in the Brazilian Cerrado, and phosphorus and microelements are added to overcome native phosphorus and microelement nutrient deficiency in many parts of southern Australia. Moreover, although most originally fertile soils have lost organic matter during cropping, with adequate fertiliser applications productivity will not necessarily suffer, at least until soil organic carbon is reduced to very low levels.

Sustainability from the point of view of **soil fertility** refers to maintenance of soil organic carbon levels (and total nitrogen levels, because these are closely linked to organic carbon in an approximate ratio of 1:12) such that the breakdown of organic matter, when combined with regular nutrient additions, is sufficient to meet the demands of PY (or PY_w). By decomposing, soil organic matter fulfils its most fundamental role in cropping, as wisely noted by Janzen (2006). The regular additions of nutrient must be equivalent to net removal, which is dominated by harvested products but also includes nutrients volatilised, leached or eroded from the system and nutrients in unavailable forms (e.g. phosphorus fixed into unavailable compounds). Nutrient addition is achieved through fertiliser, animal and/or human manures, legumes (for nitrogen), atmospheric deposition (for nitrogen and sulfur only) and irrigation water.

Where there has been a long history of cultivation with inadequate nutrient application, such as in Sub-Saharan Africa (e.g. Craswell and Vlek 2013), some soils have reached very low soil organic carbon levels (<0.5%). These soils have become chemically and physically impoverished to a point where recovery—although still possible—will depend on substantial organic amendments in addition to fertiliser (Tittonell and Giller 2013). Such soils are probably classified by some as severely degraded. However, the key point is that action to reverse degradation through increased inputs is generally more profitable than inaction (Nkonya et al. 2011). Increased yields inevitably mean higher soil organic carbon and greater nutrient fluxes, and larger risks of unproductive nutrient losses. However, as discussed above, better matching of nutrient inputs to crop demand can reduce losses, and pricing nutrients (and pollution) at real cost can drive more efficient use.

There is no inherent threat to soil fertility from modern cropping, but a great deal of scientifically based soil management is needed to maintain nutrient balance at high enough fertility levels for PY while minimising losses. Nitrogen is the most important element to manage. Connor et al. (2011) reported nitrogen budgets for the high-productivity wheat–legume pasture rotation in southern Australia and the maize–soybean rotation in Iowa, USA. In the former, soil nitrogen fluctuates between a maximum at the end of the pasture phase (~0.14% topsoil nitrogen) and a minimum at the end of the crop phase (~0.12% topsoil nitrogen)—in other words, these values are equivalent, respectively, to ~1.7% and 1.4% of soil organic carbon. In Iowa and much of the Mid West of the USA where maize–soybean cropping is practised, levels of soil nitrogen (and soil organic carbon) are now apparently high and stable, fluctuating slightly as nitrogen is transferred from the soybean to the maize phase. Connor et al. (2011) suggested that a typical topsoil nitrogen level in this very productive system is 0.18% (or 2.25% soil organic carbon), well below its level under the original prairie.

Nutrient application through **manures and sewerage sludge** can contribute to sustaining soil fertility (and soil organic matter and structure) and is a positive

environmental service that can be provided by croplands. Huge amounts of manure are produced by the intensive livestock industry and must be disposed of as safely as possible, something increasingly regulated in developed countries. In the USA, 6.0 Mt of animal manure nitrogen was produced in 2002. Much was deposited by grazing animals on pastures and rangelands and the remainder accumulated in intensive animal operations, of which ~1.3 Mt was returned to cropland; about 1.6 Mt of manure nitrogen is lost as NH_3 volatilisation, and unknown amounts are lost in leaching and run-off (EPA 2011). The USDA (2009) reported that in 2006 only 6.4 Mha (or 5% of total cropland) was manured, and maize received the bulk (58%) of this manure, which amounted to approximately 10% of nitrogen applied to this crop.

Transport costs severely limit the distance that manure—especially wet product from pig and dairy farms—can be moved, emphasising the importance of co-locating where feed is grown and manure is produced. Proximity is currently widely neglected, but through no fault of modern cropping. Where cropping lands are distant from intensive animal husbandry (as is unfortunately common), manure may have more value as bioenergy, especially since some of the nutrients (particularly phosphorus and potassium) are retained, dried and concentrated in the process, to become more attractive as fertilisers (USDA 2009). If toxins such as heavy metals are present, the application of manures and especially sewerage sludge can lead to gradual soil degradation, so toxin levels require regular monitoring.

All cropped soils gradually acidify when cations are leached and removed in products. To counter **acidification**, lime (or an alternative alkaline source) is eventually needed in amounts that depend on the soil buffering capacity. Using acid-tolerant crops and breeding for better acidity tolerance in crops have benefits, but it would be dangerous to expect breeding to eliminate the eventual need for agronomic measures to counter acidification.

The physical processes of **soil erosion** in rainfed cropping are well understood. The attributes of modern cropping—reduced till, maximum groundcover of crop residue (and growing crops), and adequate soil organic matter and fertility—work together to greatly reduce both water erosion in all but the steepest fields (provided that fields are not subject to off-site water overflow), and wind erosion. The Keystone Center (2009) report on US cropping suggests soil loss (tonnes per hectare) fell by >30% between 1987 and early 2000. Soil loss per tonne of product was reduced by ~50% on maize and soybean lands (where water erosion is dominant), and similarly by ~50% on wheat lands (where wind erosion is dominant). However, in humid situations around the world, without conservation agriculture or its soil-protective practices, water erosion remains a problem in the period between first ploughing and restoration of adequate crop groundcover. This period is usually late autumn to early spring in intermediate latitudes, or at the early part of the wet season at lower latitudes. The larger scale of fields resulting from the advantages of modern mechanisation can amplify the volume of water flows and the problem of water erosion, and may call for special landscape measures (e.g. cover crops, contour banks, grassed waterways and riparian borders).

Reduced soil erosion has also been one of the great successes with the widespread uptake of **conservation agriculture** in the high rainfall zone of Brazil and Argentina (see Box 5.5 and Section 8.5 on success stories) and in rainfed cropping in Australia, Canada and the USA. Crop residue retention practised under conservation agriculture protects the soil from water erosion and (as an additional incentive) improves infiltration to supply more water to the crop. Nevertheless, adoption of conservation agriculture has been slow elsewhere in the developing world (Friedrich et al. 2011; Giller et al. 2011). Slow adoption is particularly attributed to competing uses for crop residue (such as forage) but conservation agriculture is looking very promising in farmers' fields of Sub-Saharan Africa in places where competing demands are fewer (e.g. Malawi; Ngwira et al. 2013). In much of Europe and the US Mid West, adoption of conservation agriculture is hampered by heavy residue loads from high-yielding crops and by the cooler spring soil temperatures resulting from the heavy residue; thus residues are often buried by ploughing.

Conservation agriculture, and to a lesser extent residue burial, also helps to maintain or improve **soil organic carbon**, to which **soil structure** is closely linked. However, Kirkby et al. (2011) provide a reminder that improved nitrogen and phosphorus nutrition is also needed to significantly build soil organic carbon, which is largely composed of humus with a fixed carbon-to-nitrogen-to-phosphorus-to-sulfur ratio (see Section 10.5 on greenhouse gas emissions). Again, these agronomic developments for physically maintaining and improving soil are generally compatible with, if not essential for, increasing yield. Often these soil improving developments benefit from research outside of agronomy, such as breeding for adaptation to conservation agriculture systems, in particular resistance to new pests and diseases that have been favoured by the switch to conservation farming, or engineering to adapt machinery to the high residue loads.

Soil compaction sometimes arises naturally, but it can also occur from the use of heavy modern machinery and especially if operated under high soil moisture (as is sometimes necessary, such as during wet harvests). Deep tillage (chiselling) is currently the only way to recover soil from compaction below the surface, but this practice is energetically expensive⁵⁸ and the solution is temporary. Thus compaction must be avoided as much as possible, and zero-till systems combined with controlled traffic are probably the best way to ensure this outcome (Rainbow and Derpsch 2011).

Soil salinisation is another form of soil degradation. 'Irrigation salinity' occurs when saline groundwater rises as a result of excessive irrigation; it is discussed under the 'Water' subheading below. 'Dryland salinity' occurs in rainfed areas where deep-rooted perennial vegetation has been replaced by shallow-rooted annual cropping, as mentioned in Section 11.2. Dryland salinity can be managed by strategic restoration of perennials, better crop agronomy, and crops and varieties more tolerant of salinity. None of the measures to manage salinity clash with efforts to push for higher crop yield.

58 Rathke et al. (2007) reported 15 L of diesel per hectare (0.7 GJ/ha) for subsoiling to 36 cm.

Box 11.2 Organic agriculture

In 2010, certified organic agriculture occupied 13 Mha of cropland (Organic World 2012), equivalent to 0.9% of global crop area. Some claim organic agriculture could feed the world (Badgley et al. 2007; Seufert et al. 2012), a notion that does not stand up to scientific scrutiny. Organic and animal manure is the staple input for organic systems, and the positive response of many soil properties—such as structure, biodiversity and/or water infiltration—to their additions is not surprising (Gomiero et al. 2013), but it does not necessarily equate to higher crop yield. A recent meta analysis of published results suggests that, in reality, yields for staples grown under commercial organic production are generally lower by ~25% (Seufert et al. 2012). Opportunity costs are attributed to lower yield (Connor 2013). For a given amount of food production, comparatively more cropland is needed under an organic system than under a modern system, although Seufert et al. (2012) did not consider this type of opportunity cost in their analysis.

A much bigger problem for organic farming is the source of the nutrients in manure, principally coming from the feed crop inputs for animal production that deliver the manure. These feed crops will have inevitably received chemical fertiliser. Unfortunately, this feed source is often overlooked by the proponents of a major role for organic farming (e.g. Gomiero et al. 2013), even if the authors are ecologists who claim to understand system issues. Organic farmers recognise that they must replace nutrients removed in produce, and this goal poses their most serious challenge (Connor 2008; 2013; Dobermann 2012). Put simply, organic nutrient sources—such as manure, legumes or composted vegetation collected from outside the field—are insufficient to replace even a fraction of the 100 Mt of nitrogen applied globally as chemical fertiliser. The situation cannot be solved by higher nitrogen use efficiency (NUE) because organic farming generally faces the same nitrogen losses as conventional agriculture (Angus 2012). Legumes have been proposed as a means of meeting crop nitrogen demand (e.g. Badgley et al. 2007), but even if legumes were to deliver a generous 200 kg N/ha/yr, an additional 500 Mha of cropland (i.e. 36% of the current global total) would be needed to be planted to legumes (used for either green manure or grazing) in order to generate 100 Mt of nitrogen (see also Section 11.3). Thus, legumes are no panacea and it should be noted that legumes without an immediate economic return are unattractive to farmers large and small.

The second most important nutrient is the 17 Mt of phosphorus applied annually to world crops. Organic farmers can use rock phosphate, but even the reactive forms are very slow to release phosphorus to plants, meaning the quantities required for proper crop nutrition are large. The other sources of phosphorus are manure and compost, but these sources encounter the same problems as

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nitrogen, and supply remains insufficient for even a fraction of the world's crops. Shortages of other elements are not a serious problem for organic farming because potassium sulfate, lime, dolomite, gypsum and magnesium sulfate are mined and hence 'natural', and trace elements are permitted on a needs basis. In addition, deep-rooted crops or rotational perennial plants can retrieve trace nutrients from below the rooting zone of staple annual crops.

A large proportion of the nutrients leaving the field in food products end up in human waste streams (whether eaten or discarded), but retrieving waste to apply back to the source land is a huge challenge, and sewerage sludge is currently not permitted in organic systems. The animal manure situation is more complicated. Ideally the nutrient cycle could be partly closed, with animals feeding near feed production—so as to minimise expensive transport of manure (and thus nutrient) back to the field—but in reality, the site of feed consumption may be thousands of kilometres from that of production. Local use of the manure carries little transport cost, but it does not close the nutrient cycle because the system demands that nutrients in manure and compost be sourced from the soil somewhere, and the source is most likely to be chemical fertilisers applied to feed crops in any system that is not running down the soil fertility with its feed crops or forage production. Also, in the case of nitrogen (and to a lesser extent sulfur), there can be considerable nutrient loss in manure and/or compost systems through leaching and bacterial conversion to gaseous forms.

By avoiding artificial biocides, organic agriculture tends to require more labour and additional mechanical interventions (including more tillage). These additional activities carry costs, particularly energy, especially where energy in labour has been properly accounted (see Table 11.3). For example, for a given amount of crop production, Tuomisto et al. (2012) reported a low net energy output from a low-input organic cropping system, meaning that the energy contained in the output was less than the energy required for the inputs. In comparison, a more intensive conventional cropping system produced a much higher yield and, because higher intensity required less land for the given amount of food production, the conventional system was able to use 'saved' land to grow a biofuel crop. Hence, in general, organic agriculture is no more energy efficient than conventional agriculture per kilogram of grain produced (Dobermann 2012), especially when the energy cost of imported mineral nutrients is accounted for.

Finally, numerous studies have shown that organically produced food is no more nutritious and only marginally safer for human consumption than conventionally produced foods (e.g. Rosen 2010; Smith-Spangler et al. 2012). Furthermore, despite the potential for genetically engineered (GE) traits to control certain pests without resorting to pesticides, and despite their amply proven safety, such traits are excluded from certified organic food.

Chemical pollution of agricultural land from all sources was considered a very minor component of all human-induced degradation (22 Mha or 1.1%) in the Oldeman et al. (1991) study, and was mostly confined to Europe. Nevertheless, the gradual net accumulation of cadmium, a toxic element, has been measured with continued use of phosphorus fertiliser on cropland—especially fertiliser manufactured from rock phosphate with higher than normal trace levels of cadmium. Levels appear to be far from dangerous, and plant uptake depends on soil acidity (pH) and crop species (Grant et al. 1999). A more serious concern is the accumulation of arsenic in soils. In Bangladesh, for example, crops are receiving water from relatively recently installed tube wells that tap aquifers naturally high in arsenic (Heikens 2006). Some water sources may need to be avoided for this reason. It is therefore essential that public regulators monitor potential sources of cadmium and arsenic pollution, and other trace industrial toxins (e.g. chromium), on a continuing basis.

Of more concern lately in the popular media has been the possible accumulation of the common herbicide, glyphosate, in cropping soils. However, Duke et al. (2012) thoroughly reviewed the subject and reported that glyphosate is very strongly bound in soils, and is otherwise rapidly broken down by microbes, especially under warm soil conditions. Furthermore, these authors concluded that most scientific literature reported that neither glyphosate residues nor the glyphosate resistance trait affected mineral nutrition or increased disease in glyphosate-resistant crops. However, depending on soil and temperature, highly sensitive glyphosate-susceptible crops and varieties may show some sensitivity if planted soon after glyphosate use (Duke et al. 2012). Such issues also require regular monitoring where biocides are used.

Soil-borne diseases (and pests), and soil microbiology in general, are areas of agriculture that still offer rich opportunities for scientific discovery to soil scientists and others. The subject is complex—often lumped under the catch-all of ‘soil health’—and is only gradually yielding to research, including the new molecular tools for characterising life in the soil.⁵⁹ The fact that soil solarisation or fumigation—and often crop and even variety rotation—can give large increases in yield of the following crop only serves to increase the interest. Apart from the nitrogen benefits from legumes, rotational benefits can usually be explained by changes in soil pathogens, or in available soil water left by some crops, although at other times the origin of benefits or synergism between succeeding crops is unclear (e.g. Anderson 2011). Soil pests and pathogens are probably the most common explanation for why continuous cropping with the same crop species usually leads to yield decline—although build-up of foliar pests and diseases can add to the problem and sometimes yield decline ceases after some years and may even reverse. Many modern systems avoid continuous cropping, but continuous paddy rice is common in Asia, as is continuous maize in the USA and continuous wheat in some rainfed areas such as the Great Plains of the USA or the Anatolian Plateau. Many regions of the world, however, appear to continuously grow two crops in a binary sequence (e.g. rice–wheat or maize–soybean) apparently without much penalty relative to greater rotational diversity (but see also below).

⁵⁹ This area of discussion could equally be considered under the ‘Biodiversity’ sub-heading.

High soil organic carbon, and associated high levels of microbiological activity, have been claimed to sometimes lessen the soil pathogen problem, but evidence is not strong. Host-plant resistance is a more important control measure, while fungicide at planting (usually applied to the seed or fertiliser) is increasingly being used in modern systems. Biocides used on crops (including glyphosate used on herbicide-resistant transgenic varieties) and the *Bacillus thuringiensis* (*Bt*) toxin for transgenic insect resistance have been accused of changing and damaging the soil biota. However, there is little evidence for damage; most biocides and toxins bind to the clay or break down quickly in the soil. The whole field of soil biology, however, definitely warrants more research because many cropping systems lack diversity, which possibly limits yield. Even so, from a soil biology viewpoint, it is difficult to argue that striving for higher yield with modern agriculture is unsustainable.

Water

Although precipitation is likely to be influenced by climate change in an as-yet unpredictable way, it is taken as a given and exogenous driver of cropping sustainability. Sustainable rainfed cropping must plan for the inevitable annual fluctuations in water supply, but this is nothing new. Preparedness for events like floods and droughts brings into play the notion of resilience, which is commonly linked with sustainability and inevitably with profitability; crop insurance schemes are also a useful tool in this regard. Currently, however, the biggest water sustainability issues arise with irrigated cropping and involve management of salinity, drawdown of aquifers (through extraction at rates exceeding inflow), and from competition with non-agricultural uses for water.

To varying degrees, the crop root zones in all irrigation systems face **accumulation of salt** from incoming irrigation water and often also from rising of shallow saline watertables. Generally, agronomic measures—such as avoiding over-irrigation and better matching water supply to crop demand—can help control salinity. Beyond the farmers' control there can be accessions to the watertable from supply canals, poor management of flows in the system, or periods of heavy rain. To maintain acceptable salinity levels for irrigated crops, from time to time extra water of high quality is needed to leach salt from the root zone, and this activity needs to be combined with drainage to safe salt disposal areas. Unfortunately this type of landscape management is expensive and is often overlooked in the original system design.

It has been estimated that 20% of global irrigated lands were salt-affected by the late 1980s (Ghassemi et al. 1995), and the slow net growth in irrigated land area (as shown in Figure 1.4) probably partly reflects loss of land to salt. Rehabilitation is possible, but neither statistics nor the current exact rates of land loss appear to be available. Studies have shown that the cost of inaction far exceeds the cost of rehabilitation of saline areas to permit higher yield cropping (Nkonya et al. 2011). Saline-tolerant crops can increase management options, but breeding of saline-tolerant varieties offers only a partial solution because genetic variation is small relative to the soil salinity levels encountered.

Thus, tolerant varieties can bring only temporary relief from irrigation-induced salinity, and proper drainage is the only long-term solution. Drainage requires input resources, and the cost will be attractive only if it results in higher yields (and profit). Clearly availability of input resources and the potential for yield gain will tend to be greatest on those irrigated farms that are already highly productive. Hence it is these resource-rich farms that are most likely to sustainably manage salt (Nkonya et al. 2011). Salinity tends to be worse in arid areas (and crop WUE is less), so if the option exists, it makes sense for new irrigation to be located in more humid environments.

Irrigation uses what hydrologists call 'blue' water—the water in rivers, lakes and aquifers. Global predictions by the International Water Management Institute (IWMI) suggest blue water demand from all uses in a business-as-usual scenario will rise from 2,400 km³ to 5,250 km³ between 2010 and 2050, but water for irrigation, due to its lower priority than for other uses, will fall from 72% of this total to 37% (Chartres and Sood 2013). Thus the IWMI modelling implies that water for irrigation will increase to 2050 by only 12% of the 2010 value. Of course some river basins have already reached maximum irrigation water use (see below), and their water for irrigation is likely to shrink. Adding uncertainty are possible shifts in rainfall patterns due to climate change, and warming will increase vpd and potential evapotranspiration (ET_p), although rising carbon dioxide (CO₂) could counter this effect for C₃ crops

The projected changes in water demand and supply emphasise the imperative of raising WUE_p, which is clearly helped by the modernisation and intensification of cropping (see Section 11.2 on WUE). Egypt provides a clear example of a country facing this challenge today. By intensifying cropping, this populous region can reduce the extent to which it will need to depend on imported food in the future.

Water scarcity in irrigated cropping is already occurring with overcommitment of water in canal systems and overpumping of aquifers, and at the same time, there is increased extraction for non-agricultural uses. Overpumping increases the pumping depth and cost, and will ultimately exhaust the system. This effect is particularly evident with shallow aquifers that are replenished during the wet season, but not sufficiently to balance withdrawals. Key examples include the upper Indo-Gangetic Plain (IGP) in Pakistan and India, the North China Plain and the Great Plains of the USA. The groundwater level in the rice–wheat region of the north-western parts of the Indian IGP is annually declining by ~0.2 m on average (Humphreys et al. 2010); the rate has recently been confirmed by gravity satellite measurements to be 40 mm of water per year (Rodell et al. 2009).⁶⁰ More alarming are the reports of Moiwo et al. (2011) that the watertable of the Huai River valley in the North China Plain is annually falling 1.5–2.0 m. This problem is exacerbated in Asia where energy for pumping is often subsidised.

⁶⁰ The specific yield (water supplying capacity) of an unconfined aquifer will vary depending on the geology from 0.05 to 0.35 (thus 50–350 mm of water is available per metre of aquifer thickness).

As aquifer levels fall, physics increases pumping costs (Table 11.3) so that costs eventually become prohibitive even if the deeper aquifers are not totally exhausted. Technologies described in Section 11.2 can increase WUE_i —especially in pumped systems where the farmer can control supply—but ultimately, where aquifer replenishment is less than current ET_p , cropping will have to substantially change. One approach is to switch to crops with lower ET_p and/or to higher value crops, such as replacing rice in the summer in the north-western parts of the IGP with crops such as maize, soybean, pulses or vegetables. Another option is to switch from double cropping to single cropping, such as dropping wheat from the wheat–maize system in the North China Plain.

The magnitude of the overuse of aquifer and canal water and the timing of an eventual move to sustainable use are unclear, but the effects on crop area and production are likely to be substantial by 2050. The timing is a question of economics, regulation and policy, as much as one for crop science. As mentioned, there is considerable scope to reduce off-field water losses. Related to this, in the policy area several options to ease the water crisis include:

- establishing water rights and enforced measurement and charging for water usage
- setting up and supporting schemes to give water users a bigger role in management (participatory irrigation management)
- investing in water storage
- processing and re-using wastewater.

However, governments in developing countries have been singularly reluctant to embrace good water policy (Chartres and Sood 2013), probably because the short-term political costs are high.

In contrast to Asia and the Middle East – northern Africa region, Sub-Saharan Africa and Latin America have only small areas of irrigation and considerable untapped surface water reserves. In addition, large groundwater resources have been recently inventoried for Africa (MacDonald et al. 2012)—these can exceed 100 times annual precipitation, and in places aquifers are shallow and commercial irrigated cropping would be quite feasible.

Modern cropping and agricultural biodiversity

Two types of biodiversity can be considered in cropping: the first is an integral part of the cropping system, and second is the largely native non-agricultural remnant biodiversity that is generally displaced or impoverished by cropping. The former is considered directly below, while the latter is discussed under the heading ‘Cropping intensification and non-agricultural biodiversity’ in Section 11.6.

A lot has been written about modern varieties displacing rich ancient **crop biodiversity**. Lenné and Wood (2011) have edited a comprehensive book on the subject, which they refer to as 'agrobiodiversity'. The following discussion focuses on this type of biodiversity, which is represented by:

- diverse crops (and varieties, landraces, and related germplasm therein)
- soil biodiversity (with both beneficial and noxious organisms—many of which are unstudied)
- suites of beneficial and noxious plants and animals found in agricultural landscapes.

Efforts to collect and conserve the **genetic resources of crops and wild relatives**—largely as a result of timely warnings some 50 years ago—have ensured secure ex situ conservation of much of the crop biodiversity in gene banks. This effort has been largely publicly funded, because genetic resource conservation for cropping has so far proven to be a non-viable market (Swanson 1996). Similar arguments support in situ conservation, the adequacy of which is uncertain. Focus has now turned to efficient use of conserved genetic diversity, and to the governing international treaties that currently do not necessarily support this objective well (Wood and Lenné 2011a).

Most obviously, genetic diversity contributes to the wide array of **host-plant resistance genes deployed in modern varieties** of many crops (especially rice and wheat), helping to give generally adequate (if not yet durable) resistance to pests and pathogens. The genetic diversity within a species and its relatives could also contribute to PY progress and abiotic stress resistance (Section 9.10 on genetic resources). One estimate based on a survey of the plant breeding industry in the early 1990s suggested that development of new varieties across cereals relied on a 4% annual inflow of genetic material from wild species and landraces (Swanson 1996). It is not an easy task to locate and then incorporate such new diversity into elite varieties that farmers will want to grow, although the advent of molecular markers should make the process more efficient. As this ongoing task is very important for cropping sustainability and for yield advance, it is an obvious area for greater public investment.

Modern agriculture is characterised by large areas growing identical or closely related crop varieties, to which common management practices (particularly biocides) are applied. This is especially the case in the New World, and to some extent the former Union of Soviet Socialist Republics (USSR) and its eastern European neighbours who also collectivised farming. Compared especially with western Europe 40 years ago and even now, **landscape heterogeneity** (or diversity in space) has decreased—an effect exaggerated by the growing scale of crop fields; similarly, diversity in time has also decreased with simplification of crop rotations and specialisation of farms (Baudry and Papy 2001). Field consolidation has been driven by large-scale mechanisation in the face of rising labour costs, and the advent of satellite mapping, global positioning systems (GPS) and variable rate technology now permit farmers to manage the large soil variability that can be encountered in such fields.

The apparent lack of biodiversity in **large-scale monoculture and lack of crop rotation** is often seen as a threat to sustainability (e.g. Heinemann et al. 2013). An often-cited example is the widespread outbreak of southern corn leaf blight in 1970 in USA, which occurred due to weather and genetic uniformity of US maize hybrids at the time; national maize yield was reduced by ~17% and production by ~25 Mt. There is no problem with monoculture per se but, on a large scale in space and time, it creates greater selection pressure for (and consequences from) the continuing **evolution of avoidance and resistance strategies among the biotic stress organisms (pests, pathogens and weeds) that target these crops**. Globalisation adds to the risk by spreading the uniformity around the world. Globalisation increases the likelihood of introducing virulent pests from distant growing regions—such as the arrival of soybean rust in South America only a few years ago. It increases the appearance of totally new pest organisms, which can happen when crops push into new continents for the particular crop species (e.g. guava rust adapting to plantations of eucalypt trees in Brazil, and before long, appearing for the first time in Australia to which eucalyptus is endemic).

Probably the greatest threat to the sustainability of modern cropping **is the evolution of virulence against host-plant resistance genes and against biocides in target organisms**. Currently, various strategies (which can be further strengthened) are used to minimise this risk. It is notable that since 1970, there has been no comparable disease outbreak to the aforementioned southern corn leaf blight case. The visual impression of crop uniformity says nothing about the strength or diversity of the host-plant resistance genes used; neither does the genetic diversity as commonly calculated from pedigree information on which Heinemann et al. (2013) appear to rely. The solution lies with continued breeding for host-plant resistance, including the deployment of greater resistance-gene diversity (both within and between varieties), and of so-called minor, more durable resistance-genes. This approach to breeding has steadily moved crops like wheat and rice towards greater stability of resistance.

Transgenes for resistance to pests (e.g. *Bt* genes) and viruses (e.g. bean golden mosaic virus resistance) offer a totally new genetic approach, which thus far has been extremely successful. But just as with natural major resistance genes, transgenes need to be managed carefully so as to avoid breakdown. Transgenes are also beginning to offer opportunities for novel resistance to fungal diseases. Global cooperation and vigilance fostered by international agricultural research centres and relevant international professional associations, and the pre-emptive research usually found in the public sector, constitute the front-line of defence. Its effectiveness was seen in the world response to the evolution of a new highly virulent race of wheat stem rust in Uganda in 1999 (R.P. Singh et al. 2011). Conserved germplasm is an important contingency against such eventualities but should not be left unexplored until the need arrives. More investment is clearly needed in these areas to better guarantee sustainability of disease resistance.

Often, evolution of biocide resistance arises from **misuse of biocides**, more so because of strong commercial pressure for unnecessary use. This situation is exemplified by recent widespread glyphosate resistance in weeds in cropping—especially in the USA and Australia, but also in South America (Heap 2013)—that has arisen because of excessive reliance on this one herbicide and complacency generated by assurances from (among others) the herbicide manufacturer (Waltz 2010). It is unlikely that agricultural chemistry can ever solve the problem of evolution of biocide resistance, but this possibility must not be ignored. Meanwhile a new but more **complex integrated management strategy** will restore a reasonable balance, and this applies to pests and diseases as well as weeds. Herbicide resistance in weeds is a particular concern for developing countries because the added complexity of integrated management increases the challenges for smallholder farmers. However, the issue is being tackled, for example, in the rice–wheat system of India as it inevitably moves towards direct seeding (Kumar et al. 2013). Resolution of the glyphosate problem in developed countries will be a critical milestone in this march towards greater sustainability in modern cropping.

There is an unfortunate trade-off in this for the ‘life science’ companies involved in breeding and biocide manufacture, because better disease or pest resistant varieties reduce the demand for biocides. Increased public sector investment in all control strategies is essential. Add to this integrated or smarter pest, disease and weed management, and modern agriculture can stay ahead of biotic stress agents, despite the inevitability and magnitude of the challenge. As with a similar problem in public health, the solution to resistance evolution in modern cropping will come only from continuous vigilance that has been backed by research on multiple control strategies.

Part of the solution to the threat created by the current lack of diversity in cropping lies in developing more complex crop rotations. The size of the problem is seen in the domination of simple binary **crop rotations (or sequences)**⁶¹—or even continuous cropping—as frequently noted earlier in this book. Lack of diverse crop rotation is commonly associated with the intensification of cropping almost everywhere, often encouraged by government policies that support particular crops. Australia is one exception—perhaps because government intervention once favoured wool production—and for the past 30 years government policy has not supported any commodities. Hence, even with 60% of harvested cropland under wheat, the cropping rotation in Australia includes canola, barley, oat, triticale and pulses (and summer crops in the north-east). Frequently crops are found within a pasture ley system with leguminous pastures grazed by sheep and cattle. Bell and Moore (2012) reported that in 2008–10 Australia’s ‘wheat–sheep’ zone harvested a crop area of 20 Mha—well below the total farm area of ~47 Mha—while the zone carried ~60 million dry sheep equivalents (DSE).⁶² Western Europe and the southern parts of the province of

61 ‘Cropping sequence’ is becoming a more common term than ‘rotation’, as cropping sequence implies more flexibility in the succession of crops being grown.

62 Dry sheep equivalents: wethers (1.0), ewes (2.0), cows (12.0), heifers (8.0) and steers (10.0). Other surveys estimated that ~85% of farm area was arable (Fischer 2009), meaning the pasture area rotated with crop was ~20 Mha.

Manitoba, Canada, provide other examples of modern cropping diversity, but there is now little integration of grazing in these systems.

This domination of binary or continuous cropping is partly explained by the desire to simplify and standardise decision-making, particularly in light of the special and expensive machinery demands of many crops. The system is further favoured by government policy that limits subsidies and/or research to only a few crops. The unfortunate result is that the potential benefits of rotation for crop performance remain poorly explored. Undoubtedly the success of the major crops crowds out research efforts on more complex rotations, pastures and potentially useful minor crops (such as pulses), and this is an obvious area for more public research. The development of totally new crops may be too difficult a task, as the lack of precedents attests, but investigation of neglected and underused minor crops presents a worthwhile target for such research (Janick 2001).

While monoculture is the norm in most modern cropping systems, **'intercropping'** (two or more crops intimately mixed) is another form of agricultural biodiversity; it is common among traditional smallholder farmers and has been retained by some as they modernise. One widely cited example is planting of one row of high-value disease (blast) susceptible glutinous rice between four rows of lower value disease-resistant hybrid rice in the province of Yunnan, China (Zhu et al. 2000). The intercropped glutinous variety was much less affected by disease and yielded about double the yield per row in monoculture, delivering a significant total profit increase over monoculture. Also, as previously mentioned, intercropping legumes and cereals can lead to additional total yield in phosphorus-deficient soils (see Section 11.3 'Nutrient-use efficiency'). In these intercropping examples the advantage derives directly from interactions among the diverse components of the mixture.

Another intercropping strategy is 'relay cropping' when, in order to gain time, a second crop is planted before harvest of the first. Common examples include the relay planting of maize or cotton into wheat in the North China Plain; sugarcane into wheat in the irrigated north-west of India; or pigeon pea into sorghum in rainfed central India and eastern Africa. Component yields suffer relative to monoculture but the practice is justified by the increase in total yield.

All the above intercropping examples depend on hand planting and harvesting; this has limited long-term viability. Mechanisation of such systems is difficult but precision guidance permits the mechanical relaying of soybean into sunflower in Argentina to facilitate double cropping where the warm season is too short for a sunflower–soybean sequence (Calviño and Monzon 2009). However, multiple cropping is rarely found in developed countries because it creates mechanical harvesting problems, although grazing–grain cropping as practised in Australia and the southern Great Plains of the USA could also be considered intercropping on a large modern scale. In these systems, cereals (and canola in Australia) are grazed early and then left for harvest; such dual-purpose crops help to diversify income sources.

Box 11.3 Role of agroforestry in crop yield increase

Agroforestry may be considered as 'trees serving agriculture', and for the purposes of discussion here, refers to the spatial integration of trees (and shrubs) with annual cropping. Agroforestry delivers some useful tree products and many claimed environmental advantages (Garrity et al. 2010; Glover et al. 2012), but the effect on crop (or total food) yield is the key question.

The developing world (especially Sub-Saharan Africa) shows a strong tradition and interest in agroforestry. In the western African Sahel region, up to 5 Mha of 're-greening' has taken place since ~1985 through farmer-managed natural regeneration of a variety of tree species; this has partly been the response to policy changes giving farmers ownership of their trees. In parts of southern Niger (latitude 14 °N and 400–500 mm annual rainfall) the apparently traditional agroforestry system is reported to have doubled the yields of annual crops like sorghum, cowpea, peanut and cassava (Pretty et al. 2011; Sendzimir et al. 2011). Extremely low yields of ~0.2 t/ha were otherwise common, since soils were (and still are) exhausted and lack of input suppliers and reasonable credit continues to minimise fertiliser use. Crop yields are apparently more limited by lack of soil fertility than lack of water (see Section 5.4 on maize), and trees can improve soil fertility by nitrogen fixation, recycled nutrients, and manure from cattle attracted to the treed landscape. Trees can also protect crop seedlings from sandblast damage and (probably) hot spells, and in this degraded landscape may improve water infiltration (which may or may not compensate for tree transpiration).

One example from around Zinder, Niger, involves the leguminous tree *Faidherbia albida*, a wet-season deciduous tree that grows in the non-cropping dry season by tapping groundwater with very deep roots. When sorghum and millet were grown without substantial tillage in traditional system between the *Faidherbia* spp. trees (density of 10–50 trees per hectare), crop yield approximately doubled compared with cropping without trees, and this amounted to a yield increase of 400–500 kg/ha (Garrity et al. 2010). Yield improvement has been even more impressive with *F. albida* intercropping in Zambia, where annual rainfall of >750 mm is higher than Niger. Introduced to complement early conservation farming efforts, yields of maize in the absence of fertiliser have increased from 1.3 t/ha without trees to 4.1 t/ha under *Faidherbia* (Garrity et al. 2010). The recommended density of planting is 100 trees per hectare, later thinned to 25–30/ha, and coverage of 300,000 ha is now claimed for Zambia. Planting in straight lines has also enabled mechanised cropping to be adopted, where this is favoured by economics.

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Another form of agroforestry that is practised in Sub-Saharan Africa is cropping between relatively narrow alleys of shrubs or trees (rows 1–2 m apart) that are pruned or coppiced closer to the ground during the crop-growing season to lessen competition. This has been a traditional practice in the millet–peanut region in northern Senegal (450 mm annual rainfall, one crop per year), where these annual crops are planted among the coppiced, non-leguminous, indigenous shrub, *Guiera senegalensis*. Dossa et al. (2012) reported that a density of ~1,660 shrubs per hectare on a very sandy soil raised average yield across peanut–millet crops from 78 kg/ha to 247 kg/ha with no fertiliser. The shrubs were pruned annually and prunings, which contained substantial amounts of nitrogen and phosphorus, were returned to the soil.

An example of non-traditional shrub intercropping is observed in Malawi and Zambia where maize has been planted between alleys of the leguminous species *Gliricidia sepium* (Sileshi et al. 2012). Over 12–13 years of a continuous cropping experiment on typically poor soils in relatively wet locations (~1,000 mm annual rainfall), average maize yield without fertiliser doubled from 1.6 t/ha without *Gliricidia* shrubs to 3.2 t/ha with planting between coppiced *Gliricidia* alleys. When fertiliser was used (nitrogen at a rate of ~100 kg N/ha plus phosphorus and potassium) in the absence of *Gliricidia* alleys, the average yield was 4.2 t/ha. The coppiced parts that were returned to the soil between the alleys amounted to ~200 kg nitrogen and 15 kg phosphorus per hectare per year. One impediment to adopting alley cropping is the labour requirement for frequent coppicing.

Considerable optimism surrounds the agroforestry or ‘evergreen agriculture’ movement in Sub-Saharan Africa (Garrity et al. 2010). However, the region is unique in terms of very low soil fertility and unavailable or very expensive fertiliser. This same situation is not generally found with smallholder farmers in Asia or Latin America, and is unlikely to become the case. More research is needed to determine the general applicability of such agroforestry systems if and when fertiliser supply improves.

Another more widespread type of intercropping about which there is much enthusiasm in Sub-Saharan Africa is **agroforestry**. The trees provide some products (i.e. wood, fodder and edible fruits) and often benefit the annual crops. However, as discussed in Box 11.3, the role of such agroforestry systems may be limited to regions where fertilisers are unavailable. Similarly, native or introduced perennial vegetation as a part of the landscape can perform useful functions for the surrounding agriculture, for example, to stabilise sloping land, regulate watertables, reduce wind and shelter farm animals. In humid climates, field border vegetation (especially riparian vegetation) can play a more important role in trapping eroded soil and abating the transfer of

agrochemicals from cropped zones (see below). Whether borders can play a role in biodiversity is another question.

It would also seem appropriate to consider **border vegetation—which often occupies the edges of fields and rural and farm roadways**—as part of the agricultural biodiversity. Although the vegetation sometimes belongs to the original landscape, it is always disturbed vegetation. The sustainability role for border vegetation has been debated by Lenné (2011)—in particular, the roles of **pest abatement and provision of pollinators** as claimed in western Europe where hedgerows continue to be protected. Similarly the raised bunds around rice paddies in Asia are a recognised source of predators and parasites of rice pests, but also a home for rats. Lenné (2011) concludes this subject by emphasising the need for much more research on the complex interactions involved before practical and reliable border systems can be promoted. In any case, until now, large fields in the New World (and the former USSR) continue to be cropped without special pest issues, and with the considerable advantage of suitability for large-scale mechanisation. However, in humid climates, field border vegetation (especially riparian vegetation) can play a more important role in trapping eroded soil and abating the transfer of agrochemicals from cropped zones (see below).

Finally, agrobiodiversity must consider **soil biodiversity**. With the advent of new molecular tools interest in the subject, as well as a search for evidence of its expected importance, have seen a resurgence. Apart from the presence of soil pathogens (and their suppression by certain other microbes) and the importance of symbiotic organisms—including microbes like *Rhizobium*, mycorrhiza in certain situations, and burrowing animals like earthworms—there is as yet little evidence in cropland soils of a relationship between microbial diversity (which can be vast) and soil function or productivity (Kuyper and Giller 2011). There is no evidence that modern cropping threatens soil biodiversity—indeed conservation agriculture will likely encourage it, as has been widely reported for soil macrofaunal populations.

11.6 Off-site effects of cropping intensification

The substantial release of greenhouse gases from cropping (CO_2 , N_2O and methane) has been fully discussed in Section 10.5. Other off-site effects have been mentioned in this chapter, particularly those cases where there has been notable improvement. For example, in many developed countries, under best land management, sediment and dust erosion from farmland has decreased to almost acceptable levels—remembering that erosion is a natural process (for example, most dust in eastern Australia now comes from non-agricultural rangelands). With the reduction in topsoil erosion, contamination of streams with phosphorus-rich sediment from croplands has also been equally reduced.

Agriculture accounts for 70% of water extraction. Crop irrigation from rivers (and aquifers that feed rivers) can be detrimental to the downstream river and riparian environments, and can become a serious off-site effect of cropping when extraction exceeds a critical fraction of annual streamflow. Unfortunately, in the past, when irrigation systems were built or expanded this effect hardly rated a mention, sometimes with serious downstream environmental consequences—as occurred, for example, with rivers feeding into the Aral Sea in central Asia—but it is unlikely to be ignored in future irrigation developments. Overextraction is not, however, a direct consequence of per-hectare cropping intensification.

Other off-site effects of modern cropping deserve more attention, and these are considered in more detail below.

Reactive nitrogen pollution

The largest off-site polluting effect of cropping intensification is the **nitrate anion (NO_3^-) leaching** into aquifers, rivers, lakes and oceans that accompanies intensive cropping in humid regions. It has been a major problem in many countries—in North America and Europe it is now subject to major research efforts and regulation as described in Section 11.3 ('Nutrient use efficiency'). The largest negative consequence of NO_3^- leaching is eutrophication and algal growth, a process limited by nitrogen if the nitrogen-to-phosphorus ratio is less than 16:1, as is common in oceans, but less common in inland waters where phosphorus is often more limiting. The Baltic Sea, the Gulf of Mexico and the Yellow Sea have all been especially affected. NO_3^- in drinking water is another but lesser problem; it tends to be higher in wells under humid cropping areas (EPA 2011). However, controversy surrounds the maximum safe level of NO_3^- for drinking water (currently set at ~ 10 mg N/L by European and US authorities), with evidence that this is an unnecessarily low limit (Addiscott 2005).

David and Gentry (2000) cite general studies around the world suggesting that 20–25% of net anthropogenic reactive nitrogen⁶³ inputs to river basins—that is, fertiliser, plus agricultural nitrogen fixation, plus atmospheric deposition, less product removal—is exported in rivers to the ocean as dissolved nitrogen, of which consistently $\sim 70\%$ is NO_3^- . However, the precise sources of nitrogen in water are not easy to track down.

This challenge is exemplified by the detailed calculation of David and Gentry (2000) for nitrogen (and phosphorus) export between 1980 and 1997 from the whole of Illinois, USA. This state is humid (mean run-off ~ 300 mm/yr), $\sim 64\%$ in area is under maize and soybean, and much of the cropland contains underground tile drainage. Nitrogen

63 Reactive nitrogen is either reduced or oxidised. Almost all nitrogen in organic materials is reduced; ammonia (NH_3) and ammonium (NH_4^+) are the dominant reduced forms in the soil, atmosphere and fertiliser. Oxidised forms include NO_3^- in the soil and fertiliser, and nitrous oxide (N_2O), nitric oxide (NO) and nitrogen dioxide (NO_2) in the atmosphere, along with NO_3^- , which is formed in reactions with ozone (O_3). Nitrogen gas (N_2) is the only non-reactive form of nitrogen.

efflux in the river system was a high 51% of the net anthropogenic nitrogen input (as defined above), and if all this nitrogen carried in the river system was accrued from maize–soybean cropland, the loss equated to 26 kg N/ha/yr. However, some of the river nitrogen may not have originated in cropland—this nitrogen would have included fixed nitrogen from non-cropland (e.g. permanent alfalfa), nitrogen from manure not recycled to cropland and nitrogen from human sewage. Also, some of the cropland nitrogen (and other reactive nitrogen) would have been denitrified in the water bodies before reaching measuring points in the rivers. These authors thus estimate that ~40 kg N/ha/yr left the maize–soybean fields of Illinois. This estimate is not far from direct loss measurements that they report in drainage water coming directly from small maize–soybean watersheds (25–64 kg N/ha/yr). In the Illinois study, denitrification accounted for the portion of net anthropogenic nitrogen input not found in the river system (i.e. 49%), of which an estimated 40% occurred in the soil and 60% in water bodies and streams before reaching the river measuring points.

Data from the US Environmental Protection Agency (EPA 2011) permit a more recent approximation of cropland dissolved nitrogen losses. The EPA estimated that in 2002, 34.9 Mt of reactive nitrogen was introduced into the USA, comprising:

- 9.9 Mt of fossil fuel and industrial sources largely emitted into the atmosphere during combustion
- 10.9 Mt of fertiliser nitrogen for cropland, recreational areas and explosives
- 14.1 Mt of biological nitrogen fixation.

Nitrogen fixation was divided into soybean and other grain legumes (3.4 Mt), alfalfa and clovers (4.4 Mt), and non-cultivated vegetation (6.4 Mt). Cropland received 9.7 Mt of fertiliser nitrogen and probably ~4 Mt of nitrogen fixation, for a total of 13.7 Mt across 130 Mha, or 105 kg N/ha.

Regarding the fate of almost 14 Mt of reactive nitrogen loaded onto US cropland in 2002, EPA (2011) reported that nitrogen harvested as crop product was 9.3 Mt, but ~1.3 Mt was returned to cropland as manure. Thus net solid removal of nitrogen was 8 Mt, and net reactive nitrogen input 6 Mt. Reactive nitrogen gaseous emissions from cropland were ~1.5 Mt and probably balanced by deposition of other such emissions (and their by-products) from agriculture and industry. Overall, from all sources in the USA, about one-half of the 10 Mt total of reactive nitrogen emitted to the atmosphere—including all of the N₂O, because of its great longevity—is blown beyond the US landmass to end up in the ocean or world atmosphere. About 1 Mt of nitrogen was estimated by EPA (2011) to be stored in the cropland system (vegetation, soil and/or water) leaving ~5 Mt of the net reactive nitrogen input to be distributed between denitrification and drainage, the latter linked ultimately to river discharge.

For 2002, EPA (2011) reported that ~5 Mt of reactive nitrogen left the USA as dissolved nitrogen in rivers, and of this, 1.8 Mt exited via the Mississippi River alone (accompanied by 0.16 Mt of phosphorus). As significant denitrification was likely, cropping could have accounted for only part of the nitrogen reaching the ocean. Much of the remainder presumably derived from deposition of reactive atmospheric

nitrogen on, and nitrogen fixation in, the humid, uncropped parts of ~85% of contiguous landmass in the USA. If one-half of the river-discharged nitrogen derived from cropping in 2002, denitrification losses would equal to drainage ones (as reported in the above David and Gentry 2000 study); each loss would therefore have been ~2.5 Mt, or 20 kg N/ha of cropland. Finally, EPA (2011) pointed out that considerable uncertainty surrounds estimates of atmospheric emission and deposition, especially for denitrification losses.

NO₃ can also be a serious contaminant in developing countries where nitrogen fertiliser is subsidised and/or used in excess. One well-documented example is contamination of the Gulf of California, Mexico, at certain times by NO₃ pollution from excessive nitrogen fertiliser use on irrigated wheat in the Yaqui Valley adjacent to the Gulf (see Section 3.2 and Beman et al. 2005). Nitrogen fertiliser use in Chinese agriculture is also clearly excessive (Table 11.1), leading to serious NO₃ pollution of groundwater and waterways, and contributing to very high reactive nitrogen levels in the atmosphere (see Section 11.3). Keating et al. (2010) calculated that excess nitrogen fertiliser used in China would go a long way to correcting Sub-Saharan Africa's nitrogen fertiliser deficit. Fortunately, further modernisation of Chinese agriculture provides great scope to reduce NO₃ pollution (see Section 11.3). In other parts of the developing world where nitrogen fertiliser rates are not excessive, point sources of NO₃ pollution—such as unsewered villages, corrals and intensive animal industries—may be as significant as cropland sources.

The approach to managing nitrogen fertiliser to minimise NO₃ pollution will be the same as management designed to maximise NUE (see Section 11.3), and also to mitigate N₂O losses from cropland as discussed in Section 10.5 and illustrated by recent progress in Denmark (Mikkelsen et al. 2011). In the case of NO₃ (and sometimes other agricultural chemical pollutants from croplands), there are also other lines of defence. One such practice is the use of catch crops in the winter to extract surplus NO₃ and reduce drainage relative to fallow. Vos and van der Putten (2004) reported an average 50% reduction in NO₃ losses with winter catch crops on sandy soils in the Netherlands. Another control measure comprises vegetated riparian buffer zones; unfertilised wet zones rich in organic matter can remove considerable amounts of dissolved NO₃ largely through denitrification, but this process unfortunately also risks emission of N₂O (e.g. Hefting et al. 2003).

After NO₃ pollution, the second major nitrogen-based pollution from agriculture (including cropping) is the **emission to the atmosphere of reactive nitrogen forms**. N₂O is long lived and has been discussed in the context of greenhouse gas emissions (see Section 10.5). The other reactive forms—ammonia (NH₃) and nitrogen oxides (NO_x)—are fairly rapidly deposited and can gradually alter (e.g. through slow acidification) natural downwind environments. The EPA (2011) report for the USA also highlighted the relevance of these reactive nitrogen emissions for human health, arising especially because of the role of these emissions in forming fine particulate aerosols and ground-level ozone. This problem is very evident in eastern China (Liu et al. 2013), but in this case, it is difficult to separate cropping sources from those linked to industry and animal agriculture.

Other off-site pollutants

Phosphorus is another element that commonly leaves croplands and plays an important role in eutrophication of water bodies. It is mostly carried in soil particles resulting from soil and stream bank erosion, meaning that as erosion has been reduced, phosphorus loads in rivers have fallen. The above Illinois study of David and Gentry (2000) found that by 1990—following years of phosphorus fertiliser application that exceeded removal in exported produce—these two components were more or less in balance. Increase in soil phosphorus apparently picked up any early surplus of application over removal because between 1980 and 1997 the phosphorus export in rivers, after allowing for 47% derived from sewage, amounted to only 0.8 kg P/ha/yr of cropland if it was assumed that the remaining 53% was derived from cropland. These results also point to a ratio of 47:1 for nitrogen-to-phosphorus leaving fields, but stream denitrification would alter that to ~30:1 at the state border. In this study one-half of the phosphorus apparently left the fields in dissolved form and one-half in fine particulate form.

Irrigated agriculture and land clearing for rainfed cropping can mobilise salt in shallow saline aquifers, not only causing cropland salinisation (referred to in Section 11.5), but also contributing to **salinisation of local streams and adjacent non-agricultural land**. Dryland salinity arising from clearing of native perennial vegetation is a particular issue—for example, cyclic salt has accumulated over eons in the landscape in Western Australia, where damage has extended to infrastructure (such as roads) and even urban structures like building foundations. Dryland salinity can be a serious off-site consequence of cropping in such landscapes, but can be alleviated by strategic revegetation with perennials and drainage. Remediation means that land must be retired from cropping, but this should not affect intensification of cropping where the underlying hydrology permits. Management of dryland salinity is not unlike the difficult community decisions that need to be made to protect landscapes from erosive overland water flow that can be exaggerated by cropping practices (Baudry and Papy 2001).

Another undesirable off-site effect of modern cropping results from **biocides carried off-farm by air or water**. This biocide transport is preventable with correct management, but the use of some highly persistent biocides (e.g. triazines) requires special attention. A related and more serious concern for human health in the developing world is misuse of biocides on the farm. Research, training and regulation can generally satisfactorily minimise all these problems, but there is a lack of monitoring and publication of biocides levels in cropping environments. The Keystone Center (2009) began to rectify this situation for the USA, but the task remains to be completed. In this context host-plant resistance and especially genetic engineering (GE) for pest resistance (and to some extent herbicide resistance) has markedly benefited the general cropping environment through reduced reliance on chemical biocides (James 2012). Much scope exists for GE resistance to be extended to other crops (particularly vegetables) that receive heavy insecticide applications.

Health problems can also be caused by **smoke from the burning of crop residues** (a proscribed activity in some countries), as with the burning of rice straw ahead of wheat planting in the state of Punjab in India and the state of Punjab in Pakistan. Planting directly into crop residue with the appropriate drilling machinery—a practice of conservation agriculture—is a promoted solution that usually brings other benefits. Using rice residue as biofuel is also being researched. In California, USA, burning of rice straw is no longer permitted; it is retained for the benefit of wildlife (ducks), and later incorporated into the soil as organic matter.

While the pests, diseases and weeds of croplands have little off-farm impact,⁶⁴ **GE crops** for the control of such biotic stresses have been criticised because of the possibility of outcrossing with wild or weedy relatives that may be found nearby off-farm. Thorough scrutiny in the registration process minimises these possibilities; in any case, ‘super-resistant weeds’ are very unlikely to survive outside croplands, and transgenic mechanisms for preventing outcrossing are already envisaged (Gressel 2011b). More common is the accidental spread of GE crop pollen and seeds to crop fields whose owners pursue a GE-free status. Sensible separation distances and realistic tolerance levels for contamination will minimise this problem.

Cropping intensification and non-agricultural biodiversity

Section 11.5 discusses the part of biodiversity that is an integral part of the cropping system. The second type of biodiversity found in many cropping landscapes relates to the **original natural landscape** that has been displaced and/or destroyed, or threatened by further cropping expansion. This subject is uppermost in debates about agriculture and the environment, particularly regarding loss of tropical forest to agriculture.

In the face of growing global demand for agricultural products, a powerful argument for cropping intensification is that increased crop yield reduces the requirement for further clearing for farmland; this is known as the **land sparing argument**. Highlighting this point, global arable area has remained almost unchanged in the past 40 years (increasing by only 5%), while world population has doubled. Nobel Laureate Norman Borlaug often made this point and suggested that yield increase in cereals alone saved over 600 Mha of pasture, woodland and forest from clearing (Borlaug 2007). Forests have even returned through ‘forest transition’ in some situations where agriculture has declined as a result of industrialisation, urbanisation or the economic inefficiency of farming, allowing trees to re-establish the landscape. This has occurred, for example, in the eastern and southern USA, and some parts of Europe and Puerto Rico.

Economists such as Stevenson et al. (2013) have attempted to estimate the **land sparing effect of yield increase** with equilibrium modelling. Suffice to say that

64 Exceptions include mouse plagues, which originate in grain fields under certain conditions.

because of crop substitution and the elasticity of supply and demand, the effect in cereals alone may have been much less than claimed by Borlaug, and closer to 70 Mha.⁶⁵ Moreover, Angelson and Kaimowitz (2001) reported that more recent technology for increasing agricultural productivity can increase pressure for clearing of tropical forests, especially if demand for the crop is elastic, such as occurs with strong export markets. This is probably the case with the technologies that are increasing soybean yield in the northern Brazilian Cerrado region where improved soybean and maize yields increase pressure for crop area increase into adjacent woodlands.

Thus yield increase clearly does not always result in land sparing and/or forest transition (Perfecto and Vandermeer 2010). Sound policy formulation and execution regarding land use obviously play essential roles if forests are to be protected in such situations. But it needs also to be recognised that increased soybean production in Brazil, or anywhere, reduces the need to produce feed protein in the importing nations like China and the European Union, probably aiding the forest expansion these countries have lately recorded. A more perverse policy was promotion of biodiesel by the European Union, which helped stimulate oil palm expansion into tropical forest land; this policy has now been revised.

Although the above discussion describes the land-sparing potential of cropping, often agriculture (especially in the tropics) is embedded in a non-agricultural matrix of **land sharing** with nature (Phalan et al. 2011). The contribution of the matrix of **native perennial vegetation within agricultural landscapes** to conservation of native plants and animals is supported by some. Rather than pursue the land-sparing model, Perfecto and Vandermeer (2010) argue that native biodiversity can be better supported by an interconnected matrix of native vegetation combined with smallholder farmers using few external inputs—a notion supported in the IAASTD report mentioned in Section 11.5. However, landscape food productivity suffers with this model, agricultural interaction with the non-agricultural lands is boosted with the maximisation of field borders, and importantly, the effect in terms of species conservation is not assured, as Phalan et al. (2011) found in Ghana and India. Where native vegetation and cropland meet, the former must be protected from farm animals and chemicals while the cropland needs also to be protected from wild animals, whose feeding activities can be damaging and can gradually transfer fertility from fields to the native vegetation. In a more disturbed European cropping landscape, Edwards and Hilbeck (2001) argued that it is futile to attempt to conserve past land-use systems in agricultural landscapes, but that targeted stewardship payments to farmers could conserve some useful non-crop biodiversity (some native and some introduced) in the form of hedgerows, woodland and riparian borders, and/or wildflower strips.

65 Stevenson et al. (2013) modelled the land-saving effect of CGIAR-mediated yield improvement in cereals, taken as 33% of the total yield increase; their final best-bet number was 23 Mha, which has been multiplied here by three to estimate the effect of total yield increase. There are many uncertainties in this modelling.

Moving from a largely interconnected matrix of native vegetation—as is typical of the cropping frontier in the subtropics and tropics—to **small patches of remnant (or introduced) perennial vegetation**, or simply scattered **remnant trees** in crop fields, the benefits of remnant vegetation for conserving native biodiversity becomes limited. Yet this is the situation in much of the New World wherever cropping has expanded into woodland and forest (as distinct from native grassland, where remnant native vegetation tends to be rare). It is also the case for the fields of millions of Asian smallholder farmers in irrigated river basins, representing by area and production the world's most important cropping landscape—here the main function of remnant vegetation is to provide shade, firewood and some fruit harvesting.

Modernisation will inevitably drive expansion of field size, prevent native vegetation regeneration, and gradually eliminate the remnant vegetation. Preservation of remaining uncropped tracts of land in appropriately large reserves—and possible establishment of some new, strategically located reserves—appears to be the only way that native biodiversity will survive in these situations. Again strong regulation and enforcement are needed, but this is difficult even in the developed world. There is no automatic incentive for agriculture (or cropping in particular) to be involved in this task; native biodiversity, and in-crop weeds, are not an important part of the natural resource base of agriculture.

11.7 Conclusions on efficient resource use and sustainable cropping

Chapter 11 argues the case for the **sustainable intensification of cropping**, something which is underway and must continue. Others have used the term the 'ecological intensification' to emphasise the goals of acceptable standards of environmental quality; the term 'eco-efficient' has also arisen in this context. However, the word 'ecology' seems even more misused than 'sustainability' with its clear sense of endurance without threat of collapse. Note that intensification here refers to both greater management skills and often more inputs.

It is clear that well-managed intensified cropping and its associated technologies have increased the efficiency with which resources of water, nutrients and energy are used to produce grain. Some of the component efficiencies may be reaching limits (e.g. energy efficiency in nitrogen fertiliser manufacture), but overall efficiencies should not decline with further intensification, and could be considerably improved with better agronomic management in situations of input overuse. Supply of these three resources is not a major issue except that of irrigation water, which is threatened by use in excess of annual replenishment in some key basins, and by competition from non-agricultural uses. There is scope for improving the efficiency of irrigation systems, especially by eliminating non-productive water losses.

Sustaining the soil base of cropping is vital for maximum productivity. This can be achieved in cropping by management that:

1. operates so as to maintain at least moderate levels of soil organic carbon (>1%)
2. balances nutrient removal with nutrient addition (from fertilisers, legumes, manure, compost and/or atmospheric deposition) and on non-calcareous soils, counters inevitable acidification with regular liming
3. engages in reduced till (or zero-till) while maintaining soil surface protection with crops and crop residue
4. avoids continuous monoculture by using binary or even more complex crop (and pasture) sequences.

The first three objectives reinforce one another to maintain the physical and chemical soil quality; there is nothing to suggest that this will threaten the soil biotic composition, which should benefit also from the fourth strategy. However, better managing the influences of the soil biota on crop yield is poorly understood and may bring modest yield gains with more research.

Biodiversity in cropping refers to crops, and soil and pest biota. Modern cropping has weakened crop biodiversity, but appearances can be deceptive: host-plant resistance genes are the main line of defence, and diversity at this level is increasing in staple crops. However, there is little doubt that rapidly evolving resistance of weeds, pests and diseases to biocides remains a major (and perhaps increasing) threat to modern agriculture—resistance to glyphosate is a special challenge. It is therefore vital to maintain not only research into integrated systems of control but also unrelenting monitoring and vigilance, as well as boosting farmer training in these techniques. Ongoing host-plant resistance breeding, including genetic engineering, should ultimately help deliver a more sustainable situation.

Intensive cropping can produce substantial greenhouse gas emissions (see Chapter 10 on climate change) and threaten the non-farm environment; reactive nitrogen pollution is a particular problem, with the largest contribution deriving from NO_3 draining from fertile high-yielding cropped fields in humid environments. Research on (and adoption of) techniques for matching nitrogen supply to crop need will provide scope to reduce reactive nitrogen pollution—at the same time as fertiliser costs are reduced—but much greater effort is required. Other off-site effects arise from misuse of biocides, but again, better host-plant resistance and skilled integrated management will reduce (but never completely eliminate) biocide use and minimise off-site effects.

Nurturing native biodiversity within modern cropping landscapes is difficult, even with stewardship payments. It is probably more important to target the enforced legal protection of environmentally valuable undeveloped land suitable for cropping, especially such land adjacent to cropland where yield-increasing technology can increase pressure for gradual cropland expansion. However, on the whole, crop yield increase will undoubtedly continue to reduce pressure on the biodiversity of the world's reserves of (as yet) undeveloped potential cropland.

Trends in total factor productivity

12



Key points

- Agricultural output growth is the sum of area expansion, input intensification and total factor productivity (TFP) growth.
- TFP measures the efficiency of production of agricultural goods relative to all inputs. Growth in TFP drives lower real prices.
- TFP has been steadily rising since the 1960s. This has especially been the case in the last two decades when world TFP increased at a rate of 1.75% p.a. with no sign of slowdown. However, TFP rise has been weaker in South Asia and Sub-Saharan Africa.
- Country cases discussed in this chapter reveal the importance of research and development (R&D) in TFP rise; good examples are reported for the United States of America (USA), Brazil, Uruguay and China. R&D lifts TFP by pushing out the technical frontier.
- However, there is little evidence of TFP growth resulting from improved technical efficiency of farmers; that is, their ability to close the gap between their current practice and the technical frontier.

Trends in total factor productivity

12.1 Introduction

The primary theme of this book is crop yield considered as production per unit of land area (i.e. 'land productivity'). This concept is expanded in Chapter 11 with the notion of production per unit of other consumable resources (e.g. 'water productivity'). These measures are partial factor productivities. On the other hand, **'total factor productivity' (TFP) expresses production in relation to all measured inputs combined and aggregated according to their value share in production costs.**

TFP is usually measured for agricultural production as a whole by aggregating individual outputs (also according to their value share). Thus, TFP is the ratio of an index of outputs and inputs, and hence is dimensionless. However, TFP is still valid for broad efficiency comparisons among industries, countries and years. Crop-specific estimates of TFP growth are sometimes available, but should be interpreted cautiously given that it is difficult to allocate fixed costs across crops and to account for interactions between enterprises in farming systems.

This chapter presents analysis of TFP change as a complement to previous analyses of yield increase of individual crops. Compared with yield increase, TFP increase is a better indicator of overall technical progress because **unit production costs are the fundamental driver of food prices**; yield increase driven solely by increased input is not necessarily technical progress or improved efficiency. For example, Linehan et al. (2013) demonstrated with partial global equilibrium modelling that a 10% increase in rate of TFP growth delivered three times the agricultural price decrease to 2050 (relative to the baseline price simulation for 2050) when compared to a 10% increase in yield .

Food prices are a critical indicator of success in feeding the world, and are especially important for people of lower socioeconomic status who spend a high proportion (sometimes >60%) of their income on food. As the largest food exporter, the USA strongly influences world grain price, which explains why the long decline in real grain prices to 2006 (see Figure 1.2) has closely tracked TFP growth in US agriculture (Alston et al. 2010a).

12.2 Explaining total factor productivity

In exploring TFP, this section explores the conceptual framework for components of agricultural output and TFP increase, and discusses measuring total factor productivity.

Conceptual framework

Components and measures of agricultural growth are represented diagrammatically in Figure 12.1. 'Agricultural growth' in real value is made up by changes in 'real output growth' and changes in real prices or 'price effects'. The latter reflect differences in the rate of change in agricultural prices relative to overall price change in the economy. Not shown in Figure 12.1—but frequently used to measure agricultural growth—is 'agricultural gross domestic product (GDP)' or agricultural value-added, which is calculated as agricultural value minus all the costs of intermediate inputs such as fertiliser and fuel, but not the primary factors of land, labour and capital.

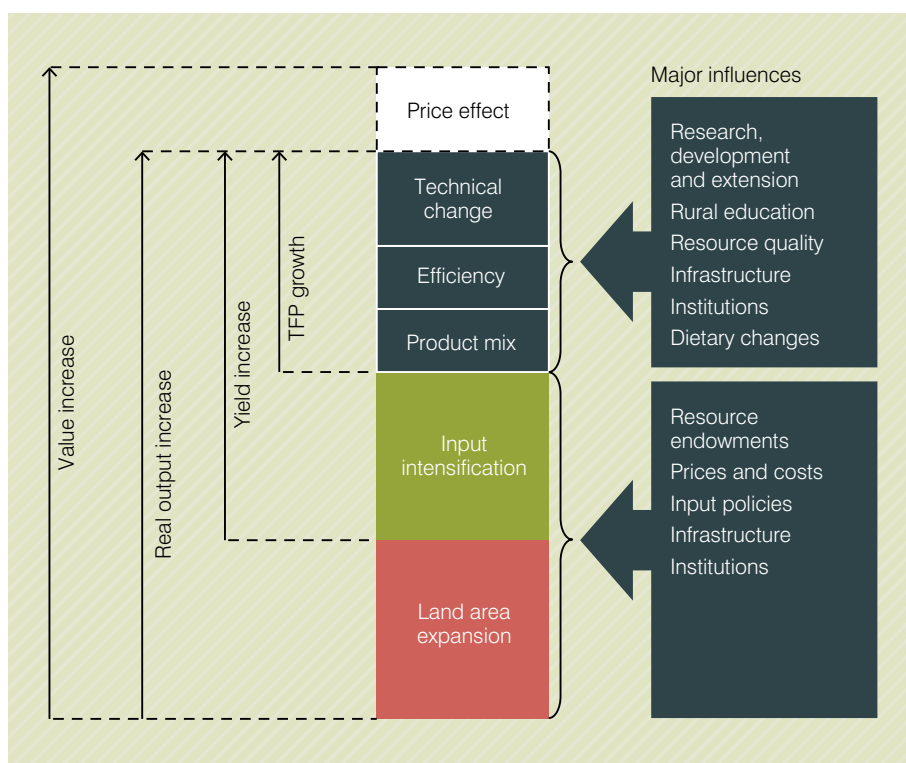


Figure 12.1 Components of agricultural growth and their major influences. TFP = total factor productivity. Source: adapted from Fuglie and Rada (2012)

As agricultural output is a physical measure of production, an index based on weighted price is needed in order to be able to aggregate across product outputs. In other words, a high-value product, in terms of dollars per kilogram (\$/kg), will carry more weight in the index for a given quantity of output than a low-value one, and the output index is more than the sum of the mass of products.

Real agricultural output growth is driven in part by area expansion (which is easy to measure by summing across all crops), and in part through increased yield, where yield is simply the output index divided by crop area—in this context, a value-weighted aggregate farm yield (FY; see Chapter 2). Yield increase is in turn made up of two elements: (1) increases in the use of non-land inputs such as capital, labour, water and fertiliser per hectare—also known as **input intensification**, and (2) **TFP growth** which is driven by technical change, improved efficiency or changes in the product mix (Figure 12.1).

Technical change results from pushing out the production frontier by developing and adopting new technologies. It is closely related to gains in potential yields discussed in previous chapters (see also Box 2.2 on efficiencies, profit maximisation and TFP under technical change).

Efficiency gains are measured with respect to the way inputs are used or combined in the most cost-effective way when using existing technology; efficiency gain is a measure of the gap between the farm operation and the technical frontier. These gains can be further distinguished as those due to technical efficiency, allocative efficiency and scale efficiency. **Technical efficiency gains** can arise when better management of the same level and combination of inputs (for example, through better timing or placement of fertiliser) achieves a higher output, or when the same output is achieved using fewer inputs. **Allocative efficiency gains** occur when expenditure among input categories (between, for example, labour and fertiliser) is better allocated to achieve the same level of output at lower cost. **Scale efficiency (inefficiency)** may occur if total production cost per unit of output is negatively (positively) related to the scale of operation.

Changes in product mix occur as result of a move to a higher quality output of a given product (e.g. varieties that are preferred by consumers), or when higher value products become more important than others over time. Since consumers with rising incomes demand higher value products, changes in product mix generally contribute to TFP growth.

It is also important to note that **yield increases can take place through input intensification without corresponding gains in TFP**, so yield gains may not be closely related to TFP growth. As alluded to in Box 2.2, yield increase without TFP increase is more likely to occur in the early stages of input intensification. In agricultural regions where input use is already high, yield gains are likely to closely track TFP growth.

Policy and institutional factors shown in Figure 12.1 affect real output growth, although specific factors exert differing effects on area increase, input intensification and TFP growth. For TFP growth, a large general literature suggests that the primary driver

for technical change is investment in research and development (R&D).⁶⁶ Crop genetic improvements can increase potential yield (PY; see Chapter 2) and this will directly translate into TFP growth through technical change if costs associated with using improved seed are low (as has been the case until recently).⁶⁷ In low-income countries with scarce land resources, land-saving technologies such as crop genetic improvement and improved management practices that raise yields per unit of land are generally the primary source of TFP growth. In land-abundant countries, and countries with rapidly rising wages, increased labour productivity (output per unit of labour input, a technical change) through substitution of machinery for manual labour is often the major source of TFP growth.

Because improving efficiency is a major component in closing the yield gap—as discussed extensively in Chapter 8 ‘Yield gap closing’—extension, education, roads, communication, risk mitigation and (sometimes) farm size play important roles in TFP growth. In addition, institutional changes can also contribute—for example, China’s agricultural take-off from 1979 was largely caused by dismantling of collective farms and introducing the household responsibility reforms that provided large efficiency gains and initiated a period of rapid TFP growth (Fan 1991).

Measuring total factor productivity

There is a large general literature on how best to measure TFP in practice. Measurement problems (Alston et al. 2010b) arise from issues of the:

- method of indexing—i.e. weighting and adding of inputs and (separately) outputs—which in turn depends on assumptions about the shape of the underlying production function (relating outputs to inputs)
- method of accounting for changes in the quality of inputs and outputs
- coverage and level of disaggregation of inputs and outputs
- degree of spatial disaggregation of the input, output and price data.

A comprehensive discussion of methods and pitfalls in estimating TFP growth is provided by Alston et al. (1995). In general the more disaggregated the analysis (in terms of inputs and outputs), the better TFP growth can account for changes in quality of inputs and outputs—for example, rainfed vs. irrigated land as input, and rice of different qualities as output. Even then estimates will inevitably be incomplete for input

66 Agricultural R&D generally does not include expenditure on agricultural extension, although it is not easy to separate some R&D from extension, especially in the private sector. Where extension is included, it is commonly abbreviated RD&E.

67 However, proprietary hybrids and genetically engineered (GE) seed can carry significant costs. One example of recent price increase has been observed in Iowa, USA, where seed costs for maize now amount to US\$250/ha, more than the market price of 1 tonne of maize grain, vs. only US\$64/ha in 2000.

coverage, so TFP can be thought of as residual growth that is not explained by the basket of inputs included. For these reasons, economists increasingly refer to the measure as 'multifactor productivity', although for the purposes of discussion here, the conventional TFP nomenclature has been retained.

TFP estimates based on international statistics will be particularly prone to errors arising from aggregation and omission of variables, relative to estimates based on more disaggregated national statistics where such errors can be seen and dealt with by experienced national economists. In a few cases, primary data from farm surveys conducted over years are used to construct TFP estimates (e.g. Hughes et al. 2011, see below). This method is potentially more accurate if the same population of farms is sampled each time.

Because of different methods for measuring TFP and different sources of data, estimates of TFP growth may vary considerably from one author to another. Thus the TFP figures have been selected for discussion in Chapter 12 based on subjective assessment of the quality of underlying studies; in some cases, several sources are reported for the same country. According to the convention in the economics literature, TFP growth rate is expressed as exponential growth throughout this chapter.

12.3 Global and regional trends in total factor productivity

In recent years, there has been an upsurge in tracking long-run growth in TFP (Alston et al. 2010a; Fuglie et al. 2012b). At a global level, Fuglie (2012b) provided an up-to-date and comprehensive overview of TFP growth. Although this included important corrections to standardise for land quality and estimated factor shares specific to regions at different levels of development, Fuglie (2012b) recognised the inherent limitations of a global analysis.

Figure 12.2 provides an overview by time of the sources of agricultural growth for 1960–2009, following the framework of Figure 12.1 (Fuglie 2012b). Note that because of its importance, irrigation has been separated from other input intensification in Figures 12.2 and 12.3. Over the past 50 years, TFP has clearly become the dominant source of real agricultural output increase globally, accounting for 74% of growth in the past decade (2001–09) compared with <10% in the first decade (1961–70). At the same time, land area expansion and input intensification have fallen as sources of output increase (Figure 12.2). This is good news for real food prices and input use efficiencies, as was seen in Chapter 11.

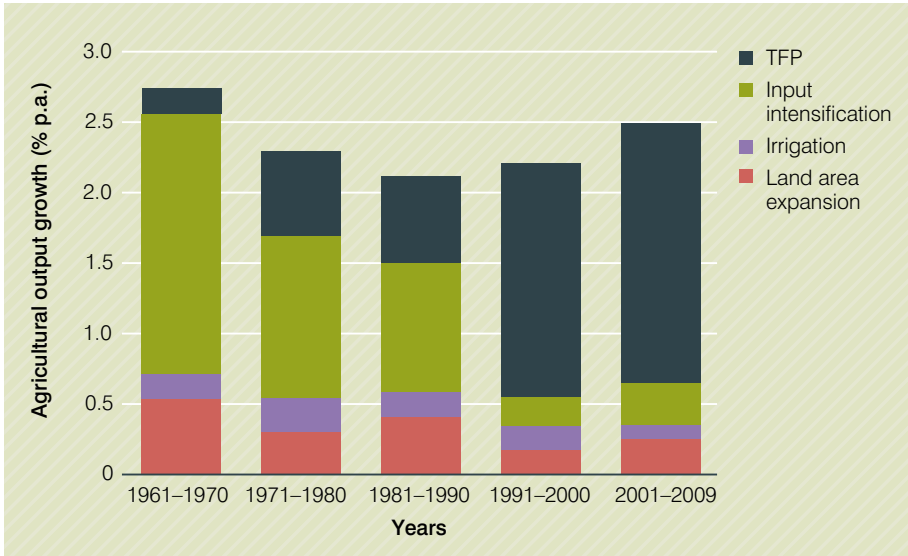


Figure 12.2 Sources of increase in global real agricultural output by decade from 1961 to 2009. TFP = total factor productivity. Source: Fuglie (2012b)



Figure 12.3 Sources of growth in real agricultural output by region from 1960 to 2009. TFP = total factor productivity. Transitional = Eastern Europe and former Union of Soviet Socialist Republics (USSR). Source: K. Fuglie, pers. comm. (2012), based on Fuglie (2012b)

As might be expected, there are major differences in sources of growth by region (Figure 12.3). Land expansion has been important in the relatively land-abundant regions of South-East Asia, South America and Sub-Saharan Africa, but cultivated area has fallen in developed and transitional regions. In Asia, irrigation and input intensification have made important contributions to output growth. TFP growth has been important in all regions except in Sub-Saharan Africa, and in the transitional region where overall real agricultural output growth was much slower than in other regions.

Similarly, marked regional differences are seen in trends in land and labour productivity growth, depending on relative endowments of land and labour, and stage of economic development (see Box 12.1).

The primary question for food security is, of course, whether the growth observed in TFP over the past 50 years is now slowing. Fortunately, at the global level, there is little evidence for this. Rather, **global TFP growth rate has increased steadily from 0.2% p.a. in the 1960s to 1.8% p.a. in the most recent decade** (Figure 12.2 and Figure 12.4a). TFP increase has notably accelerated in Asia (because of growth in East Asia and South-East Asia) and Latin America, while an observed acceleration of TFP growth in Africa (Figure 12.4b) and the transitional countries (Figure 12.4a) reflects mainly negative performance in earlier decades. Although TFP growth in East Asia (mainly China) has declined since 2000 (Figure 12.4c), growth remains high by almost any standard.

Box 12.1 Trends in land and labour productivity

The figure below, from Fuglie and Wang (2012), is an excellent depiction of trends in land and labour productivity in agriculture across key world regions and/or countries. In high-income countries, such as Europe, North America and the developed countries of East Asia, the rate of growth of labour productivity from 1961 to 2010 was much faster than the rate of growth of land productivity—hence the flatter trajectories shown in the figure (note the log scale). As expected due to a large endowment of moderate-quality farmland and to high wages, North America and Australia showed lower land productivity, but higher labour productivity than Europe and developed East Asia. In all these developed regions, rapidly rising labour productivity reflects efforts to save labour through mechanisation and increasing farm size.

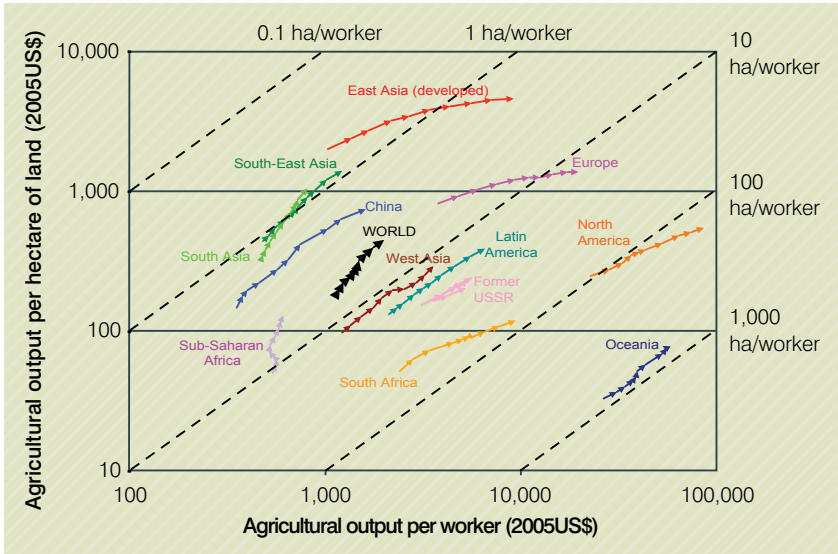
Latin America, West Asia, northern Africa and the former USSR are relatively land-abundant regions, but these regions are intermediate on both land and labour productivity (see centre of figure). The short length of the line for the former USSR indicates overall low productivity increase there. South Asia,

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Continued

South-East Asia and China are land-scarce regions with relatively high land productivity but low labour productivity—although China is clearly making strong gains in labour productivity. Sub-Saharan Africa is low on both measures, and labour productivity has hardly changed in nearly half a century—hence the near vertical trajectory in the figure.

The variations in the trajectories among regions reflect efforts by countries to save on their most scarce resource (land or labour), as well as overall success in increasing productivity. While this figure provides an interesting view of the relationship between land and labour productivity, caution is needed when translating these productivity measures into changes in TFP, since the simple two-way graphic shown does not take account of changes in other inputs that may have contributed to output growth.



Trajectory of agricultural land and labour productivity by region in 5-year averages between 1961–65 and 2006–10. Source: Fuglie and Wang (2012)

In the box figure, agricultural output is reported as FAO Agricultural Output in constant 2005 purchasing power parity (PPP) US dollars, and agricultural land (total cropland and permanent pasture) and labour (number of economically active adults employed in agriculture) are also from FAO. Each arrow represents a 5-year average value, starting with 1961–65, then 1966–70 and so on, ending with 2005–10. East Asia (developed) includes Japan, South Korea and Taiwan.

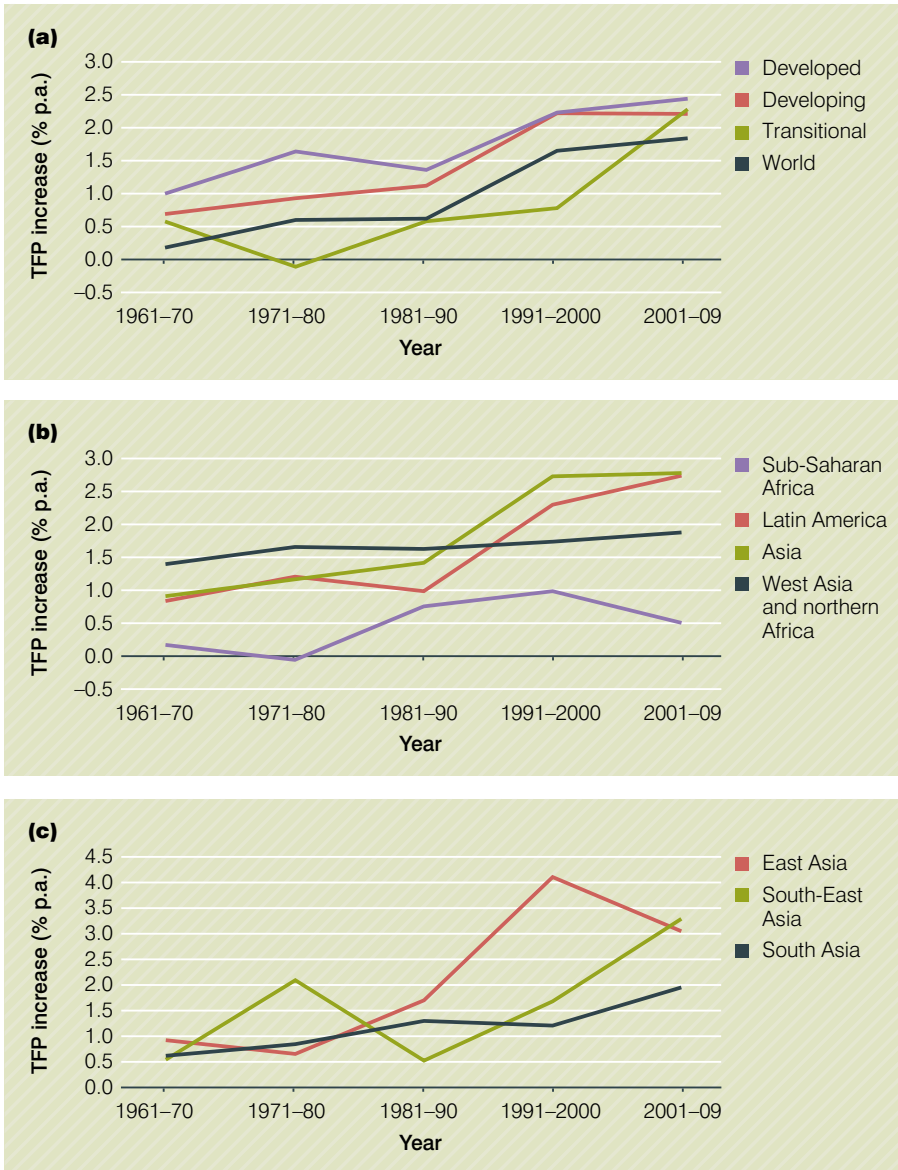


Figure 12.4 Trends in total factor productivity (TFP) growth from 1961 to 2009 by (a) type of country, (b) world regions, and further breakdown to (c) regions of Asia. Source: Fuglie (2012b)

12.4 Brief case studies of total factor productivity trends by country

The global estimates of TFP growth presented above necessarily depend on statistics produced by the Food and Agriculture Organization of the United Nations (FAO), the only comprehensive global database on agricultural outputs and inputs. FAO statistics limit TFP inputs to highly aggregated and often heterogeneous categories, and frequently lack the country-level price data that are required to compute shares of production factors such as land, labour and capital. By comparison, country-level estimates of TFP growth generally use much more disaggregated statistics on input and output categories and local prices (often at the subnational level) and hence provide more precise pictures of TFP trends. In many cases, country-level estimates allow econometric analysis of the determinants of TFP growth. Some country cases are presented below.

United States of America

There has been a long and rich tradition of estimating and analysing determinants of TFP growth in the USA (Alston et al. 2010b). Based on nearly 40 studies, and regardless of measures used, since World War II the long-term annual TFP growth rate in the USA has clustered within a range of 1.5–2.0% p.a. A comprehensive analysis by Alston et al. (2010b) is based on 58 categories of inputs and 74 outputs, all at the state level. Note that the major crops considered in this book—maize, soybean and wheat—make up only about one-quarter of the total value of agricultural production in the USA, so their weight in TFP trends is not high alongside animal products, fruit and vegetables.

Overall, Alston et al. (2010b) claimed a slowdown in TFP growth in the decade to 2002—the last year of the data series explored, with growth of 0.97% p.a. relative to rates over 2% p.a. in the previous 20 years. Consistent with yield progress data in Section 5.2 on maize and Section 6.2 on soybean, Iowa—a state in which maize and soybean predominate—was the best state performer in 1993–2002 (2.37% p.a.). By contrast, the major wheat producing state of Kansas (see Section 3.9) showed a sharp fall in TFP growth to 0.67% p.a. More recent estimates by the US Department of Agriculture (USDA) (using a slightly different methodology) have suggested only a modest slowdown (if any) in national TFP growth, which averaged 1.2% p.a. in 2000–09 (USDA 2013).

Many authors have also estimated the major determinants of TFP growth in the USA by econometric methods. Most recently, Wang et al. (2012) related 1980–2004 patterns of TFP growth trends across the 48 contiguous states to:

- expenditure on research, development and extension (RD&E)

- density of transportation networks
- labour quality.

From this analysis, the estimated annual internal rate of return⁶⁸ to investment in RD&E was 17–69%. This range reflects varying assumptions about technological spill-ins—that is, technology coming from research done outside the region of interest (in this case, other states)—and interactions of research with other variables such as factors influencing technology adoption. These findings supported those of Alston et al. (2011) who also reported (albeit with lower figures) that expenditure on R&D was the major determinant of TFP growth. Using longer research lags (benefits peaking at 24 years after the original R&D) and accounting for spill-ins from other states, Alston et al. (2011) **estimated an internal rate of return of 24%.**

The slowdown in TFP growth in the USA, to the extent that it exists, can largely be attributed to a **slowdown in public investment in agricultural R&D.** Annual public expenditure in agricultural R&D in the USA increased at a rate of 3.8% p.a. between 1950 and 1969, after which rates began to fall, and since 1990 expenditure has increased by only 1.1% p.a. In addition, a relatively smaller share of public expenditure on agricultural R&D has been allocated to productivity improvement—vs. other objectives such as human nutrition, food safety and environmental sustainability—to such a point that spending on field crops (including staple grains) has stagnated in real terms since 1990. By contrast, private expenditure on crop breeding and biotechnology has sharply accelerated. Private investment doubled between 1993 and 2005, and then almost doubled again to reach US\$2.17 billion in 2010 (Fuglie et al. 2011)—a level similar to US public investment. Thus adding public and private investments, evidence suggests that US investment in R&D for crop improvement has improved overall since 2005.

Australia

It is challenging to assess trends in Australian agriculture, given the high variability in climatic events since the 1990s. Based on annual farm surveys of crop producers, Hughes et al. (2011) estimated climate-adjusted average annual TFP growth of 2.31% p.a. from 1977 to 2000, followed by a sharp decrease to an average of 0.54% p.a. from 2000 to 2007, a period of extreme drought. It is suggested here that the climate adjustment corrected for only some of the adverse effects of the drought. As was the case for much of the world (Figure 12.3), TFP growth in Australia accounted for an increasing share of growth in agricultural output (Hughes et al. 2011).

⁶⁸ 'Annual internal rate of return' is a discount rate that equates the discounted value of future output with the discounted cost of the investment. Discounting takes into account that \$1 spent on R&D early in the research cycle is worth more than \$1 received from the extra output, say, 20 years from now.

The component contribution to TFP growth from technical change vs. gains in technical efficiency (see Section 12.2) was also determined by Hughes et al. (2011). Over the whole period 1997–2007, technical change rose strongly at a rate of 1.5% p.a., but technical efficiency fell at 0.3% p.a., suggesting an increasing divide in management skills within the farming population. Technical change also slowed in the most recent period (2000–07) to reach 0.4% p.a. The trend was partly attributed to a sharp slowdown in public expenditure on R&D without a corresponding boost in private expenditure.

Between 1953 and 1980, increase in public expenditure on R&D averaged 6.5% p.a. By comparison, since 1980, growth in expenditure has averaged only 0.6% p.a.⁶⁹ As described for the USA, public expenditure in Australia has also shifted from productivity-orientated research toward research on food safety, the environment and climate change (Nossal and Sheng 2010).

Confounding the slowdown in R&D are concerns that adoption of available technologies is also slowing. This has been attributed to:

- ageing farmers
- insufficient skills for the more complex modern technologies
- risk aversion and financing constraints in the face of frequent droughts since 2000
- the demise of public extension and information services.

Accordingly, cross-sectional analysis of grain farmers in Victoria for 2006–07 and 2007–08 found that TFP tracked innovation adoption, which in turn was related to farmer characteristics, especially education, farm size, labour availability, use of contract services and land-use intensity (Nossal and Lim 2011).

Brazil

Since the 1990s, Brazil has been one of the world's agricultural success stories. Overall, between 1970 and 2006, TFP grew by 2.2% p.a., and accounted for one-half of total real agricultural output growth (Gasques et al. 2010). Since other inputs (especially labour) have declined, the remaining share of output growth is explained by area expansion, which increased by two-thirds during this period.

Despite general success, there has been wide diversity in performance in Brazil (Gasques et al. 2010). In the state of São Paulo, where sugarcane dominates, TFP growth has been steady but slow. In Paraná, where wheat, maize, soybean and poultry are major products, TFP increase has been higher. Meanwhile in Mato Grosso, now the major soybean producing state, TFP increase rate has skyrocketed

⁶⁹ Since 2005 there has been a lift in private expenditure on plant breeding in Australia, coincident with the privatisation of wheat breeding (Fischer 2012).

to nearly 6% p.a., the highest recorded rate in the studies reviewed in this chapter. Factors in the transformation of Mato Grosso in Brazil's Cerrado region (see Box 5.5 and Section 6.3) have included widespread adoption of genetically engineered (GE) soybean adapted to low latitudes, conservation farming, soil amendments and replacement of low-quality pasture with crops.

A major factor underlying such success has been Brazil's consistent investment in R&D, especially through the Brazilian Agricultural Research Corporation—also known as *Empresa Brasileira de Pesquisa Agropecuária* (Embrapa). With a budget of over \$US1 billion, Embrapa is the largest and most effective tropical and subtropical research institute in the world. The private sector has also played an important role. Seed companies and producer organisations have released GE soybean and maize varieties, and producer organisations have developed conservation farming technologies; there has also been significant technology spill-in from Argentina.

Uruguay

Agricultural GDP growth has accelerated in neighbouring Uruguay since 2000 to reach 4.4% p.a. This rate of growth is led by crop sector growth of >8% p.a. (Bervejillo et al. 2012) so that Uruguay is now a large exporter of soybean, wheat and rice, and achieves one of the highest rice yields in the world (7.7 t/ha over 160,000 ha, average 2008–10; FAOSTAT 2013).

TFP growth rate over the 30-year period from 1980 to 2010 has been estimated at 2.1% p.a. (Bervejillo et al. 2012). In the most recent decade (2001–10) the rate was even greater at 3.9% p.a. Bervejillo et al. (2012) showed that TFP increase is strongly related to public and producer expenditure on R&D, but only weakly related to private agribusiness R&D. Spill-ins of technology from Argentina and Brazil have undoubtedly made an important contribution to TFP growth in Uruguay, especially for maize and soybean.

The results for Uruguay are significant in that they indicate the success of a small country in organising a productive research system. Modelled on the Australian system of matching agricultural production levies with public funds, Uruguay has succeeded in organising a responsive and effective public R&D system. With a research intensity of 2.0%—that is, spending as a percentage of agricultural GDP—Uruguay has the highest expenditure in Latin America. Spending has accelerated in the past decade (Byerlee 2011).

India

There is no conclusive evidence of current agricultural TFP trends in India, and this case study would greatly benefit from more recent analysis. For all agricultural production, Kumar et al. (2008) summarised various estimates from the 1960s to the late 1990s and showed TFP growth within the range of 1–2% p.a., but also indicated

a trend toward a slower rate of growth. Low labour productivity (in part due to lack of non-farm opportunities) has likely been one factor in the poor performance of TFP growth in India relative to China, discussed below. Further factors include repeated failure to reform input subsidy programs, and possible soil degradation.

Chand et al. (2012) used farm survey data to compute crop-specific TFP for India (Table 12.1). A crop-specific approach enables more precise estimates of inputs (especially labour) but suffers from the assumption that crops are produced independently of one another. Chand et al. (2012) showed that crop-specific TFP increase rates were highest for cereals (especially wheat), modest for oilseeds and some pulses and negative for other pulses and sugarcane. Gains in TFP provided less than one-half of output growth, except in the case of wheat.

Table 12.1 Total factor productivity (TFP) performance, TFP share of output increase, and returns to research and development (R&D) in India from 1975 to 2005

Crop	TFP increase rate (% p.a.)	TFP share of output increase (%)	Internal rate of return on R&D (% p.a.)
Wheat	1.92	59	38
Cotton	1.41	32	39
Maize	1.39	17	28
Millet	1.04	28	31
Rapeseed	0.79	10	20
Peanut	0.77	27	18
Soybean	0.71	6	na
Rice	0.67	25	29
Sorghum	0.63	24	39
Mungbean	0.53	10	57
Chickpea	0.16	26	34
Sugarcane	-0.41	negative	negative
Pigeon pea	-0.69	negative	negative

na = not available

Source: Chand et al. (2012)

The Chand et al. (2012) results showed little discernible trend in TFP growth over time, but consistent differences in growth rates across crops and states. The best performance was shown in the north-west of India, which was first to benefit from the green revolution (see Chapter 1 'Introduction'), and some parts of the south. Annual

internal rates of return to research were relatively high in all cases, except, of course, for sugarcane and pigeon pea where TFP decreased (Table 12.1). Since 1991, Indian expenditure in R&D has generally trended upward in real terms at a respectable rate of >6% p.a., but research intensity is still only <0.4% of agricultural GDP, among the lowest rates in the world (see also Section 13.2 on R&D investment).

More detailed studies for India are available at the subnational level. For example, based on state-level statistics of 20 categories of crop and livestock products and 12 categories of quality-adjusted inputs, Murgai (2001) estimated the TFP increase rate for agriculture in the state of Punjab to be 1.9% p.a. for 1961–94, with little discernible trend. However, when TFP estimates were corrected for factor-biased technical change—that is, a sharp increase in share of capital relative to labour—the estimates range from 2.9 to 4.8% p.a. (Murgai 2001). More importantly, the corrected TFP trends showed a marked slowdown since the green revolution. Murgai's (2001) more detailed and careful study is probably a better representation of overall trends—as discussed in Sections 3.3 and 4.4—in the important rice–wheat system in northern India (including Punjab).

China

Since the household responsibility reforms that were introduced in 1979, estimated TFP increase rates for China have been strongly positive, and this has reversed the previous poor performance of TFP increase (<1% p.a.). Since 1979, the rate of TFP increase has been 3.4% p.a., accelerating to 3.9% p.a. for the period between 1991 and 2006.

As in India, farm surveys have been used to compute crop-specific TFP values. S. Jin et al. (2010) estimated generally lower TFP growth rates for specific crops than for agriculture as a whole (Figure 12.5), probably because crop-specific studies did not account for increasing cropping intensity and diversification to higher value crops as is included in aggregate measures of TFP. In 1985–94 the only crops with strong TFP increase were Indica rice and maize; this is very likely the effect of the first hybrid varieties. For all crops, TFP increase accelerated in the most recent period, 1995–2004, probably as investment in R&D picked up (Figure 12.5). Unlike India, there has been a general convergence in TFP growth across crops in China to a range of 1.5–3% p.a. Performance has been lowest for maize, a result consistent with the yield analysis discussed in Section 5.3.

The very positive TFP trends in China are likely explained by continuing reforms (such as liberalisation of prices), rural education and heavy investment in R&D, although less in extension. Spending on agricultural R&D accelerated between 1995 and 2008 to pass 0.5% of agricultural GDP (Beintema et al. 2012). China now spends more than \$US4 billion annually (2005 purchasing power parity (PPP) dollars) on agricultural R&D. Without these research and policy-induced productivity gains, food prices in China (and the world) would undoubtedly be much higher.

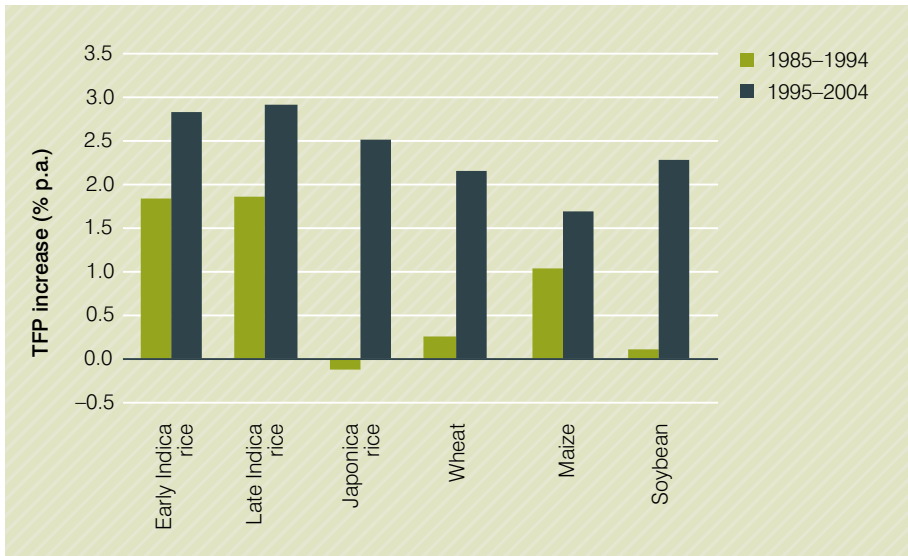


Figure 12.5 Rates of total factor productivity (TFP) increase in China by crop, for the period 1984–94 compared with 1994–2005. Source: S. Jin et al. (2010)

Sub-Saharan Africa

All estimates—averaging only ~0.5–1.0% p.a. since 1990—indicate that TFP increase in African agriculture lags the rest of the world. However, TFP increase since 1990 represents an improvement over the negative TFP rates seen in the 1970s (Figure 12.4b). The improved performance has been attributed to complex factors (Nin-Pratt 2011; Fuglie and Rada 2012) including:

- pay-offs to investments in CGIAR from 1977 to 2005⁷⁰
- more favourable price policies
- reduction in conflict
- investment in national agricultural research systems.

Even so, TFP increase has again fallen, from 1.15% p.a. in 1991–2000 to 0.43% p.a. in 2001–09. Real agricultural output growth has been maintained at 3.16% and 2.61% p.a., respectively, largely due to continuing land area growth of 1.88% and 1.77% p.a., respectively (Fuglie 2012b).

⁷⁰ There was little CGIAR activity in Africa before 1975.

As expected in a large and diverse continent, TFP performance has been heterogeneous. This reflects a wide variety of factors, including underlying resource endowments, policy environments and conflicts. Data quality has, however, generally been inadequate to explain patterns of TFP growth across countries and regions. In eastern Africa, Kenya has been a consistently better performer. In western Africa, coastal countries have performed better than inland countries (Fuglie 2012b), no doubt due to better access to inputs.

Differences in TFP growth across countries and over time have been explained by expenditure in agricultural R&D (both national and international), road infrastructure, conflict resolution and control of human diseases (Fuglie and Rada 2012). These same authors found strong evidence of economies of size in R&D spending in Africa, with highest returns resulting from investment by CGIAR and investment in large countries. In many countries, volatility of expenditure on R&D is especially problematic, in no small part due to heavy reliance on international donor support (Stads 2011).

12.5 Synthesis of trends in total factor productivity

The results of this TFP review generally support those from the yield analyses presented in earlier chapters of this book. The key finding is that a slowdown in TFP increase is not apparent at the global level (Figure 12.4), which is good news for food prices. There is no significant slowdown in any region, but TFP increase appears to be low in India and was never really high in Sub-Saharan Africa. Certainly, TFP growth in China appears to have slowed somewhat during 2000–09 relative to previous periods, but it remains high at 3.0% p.a.

The surge in food prices from 2008 to 2012 may relate as much to a surge in demand (especially for biofuels) and higher input prices, as to any slowdown in TFP growth. As expected, a higher share of real agricultural output increase almost everywhere outside of Sub-Saharan Africa is coming from TFP increase rather than input intensification and area expansion. In developed countries, the share of output increase from TFP increase is now >100%, as input use is declining.

The laggards for TFP growth are India (pending an update of national TFP estimates) and Sub-Saharan Africa. The major constraints for India appear to relate to distorted incentives from input subsidy and product price support policies, which have impeded diversification and fostered the mining of natural resources such as groundwater. Performance in Sub-Saharan Africa generally continues to lag behind other regions due to poor infrastructure, low investment in R&D and conflict (Fuglie and Rada 2012).

Finally, the results presented above demonstrate the key role that investment in agricultural R&D can play in driving TFP increase. This is evident when agricultural TFP rates and R&D investment are compared between countries, and is amply supported by bottom-up studies of individual technologies, as well as econometric analyses where the data are available (e.g. for the USA). Another econometric analysis (Fuglie 2012b) demonstrated that agricultural TFP growth across 87 developing countries over the past 20 years—ranging from zero to >3% p.a.—was significantly and positively related to a surrogate measure of R&D investment termed ‘invention and innovation’, and also showed a positive, albeit weaker, relationship to investment in agricultural extension and education.

Notwithstanding these positive results, R&D is not a sufficient condition for rapid TFP growth. Chapter 13 ‘Policies and people’ provides more evidence on the need for investments in agricultural R&D, but adds consideration of the other areas of policy that play an essential role in productivity growth.

Policies and people

13



Key points

- Growth in public sector agricultural investment in research and development (R&D) has slowed in developed countries, so that the amount of investment relative to gross domestic product (GDP), or research intensity, has fallen to 3% of agricultural GDP.
- In developing countries, there has been a faster rate of growth in public sector R&D investment, so that rate of growth there now equals that in developed countries. However, the research intensity (0.5%) in developing countries remains too low to achieve adequate productivity growth for food security.
- Private sector R&D is predominantly located in developed countries and is concentrated in a few multinational companies. Investment in private sector R&D in developed countries has grown to match that of the public sector there.
- Substantially increased investment and institutional improvements in agricultural R&D—especially in developing countries—are now needed to boost growth in total factor productivity (TFP). Other essential elements in these countries for greater TFP growth include greater increases in public sector investments in rural policies, infrastructure and institutions, and large private on-farm investments.
- Trade will play a growing role in world food security as production shifts to regions of comparative advantage and as the world continues to urbanise. It will also be essential to lift productivity in regions where trade is naturally constrained, including situations of subsistence farming (which thereby directly targets the world's most disadvantaged people).
- Operational consolidation of cropping is inevitable, but smallholding family farms will remain the mainstay of world food production, followed by larger family farms in developed countries. Corporate farming has been playing a role in food production in parts of South America and the former Union of Soviet Socialist Republics (USSR), but its long-term viability is not assured.

Policies and people

13.1 Introduction

Chapter 12 introduced the concept of total factor productivity (TFP) in agriculture and presented trends in this important measure of progress. To build on these concepts, this chapter briefly reviews the requirements for investment and public policy, and the structure of farming, that will be needed to boost TFP growth and achieve greater global food security through increased yields with limited price increases.

Section 13.2 discusses sensitivity of yield increase and TFP growth to investment in research and development (R&D) and considers future needs for this type of investment. The sections that follow examine the ways in which R&D investment may be supported through public policies and regulations and through private investment in R&D. Also, the vital importance for agriculture of several other targets for public and private investment and the associated enabling policies are considered. The final discussion (Section 13.6) reviews world food producers, both regionally and by type of farmer, and considers topics that have become controversial—the relative roles of large commercial farming and smallholder farmers, and international food trade.

13.2 Investment in research and development to accelerate productivity growth

Investment in R&D is subject to trends in both public and private sector contributions, as well as to effective partnerships among R&D institutions. This section first discusses how to estimate the investment needed for agricultural R&D.

Estimations of investment needed in agricultural research and development

Section 1.5 gave the estimation that, in order to meet future food needs, progress in the farm yield (FY) of staple crops must, at the minimum, reach 1.1% per annum (p.a.) (relative to 2010 FY) and must maintain this linear rate of increase to 2050. Furthermore, to ensure affordable prices for the world's economically disadvantaged people, it is essential that FY progress be accompanied by improvements in TFP and, to guard against unanticipated risks, progress needs to be greater than 1.1% p.a.

Thus it is appropriate to question the level of R&D that will be required to achieve these gains in yield and productivity. Although different methods have been used to determine required spending, the results depend essentially on assumptions regarding the responsiveness of yield and TFP. Given the inevitable lag in response, **the broad consensus is that R&D spending must sharply increase over the next 10 years in developing countries.** But estimations of the increase are recognised by all authors as being approximate, especially because values for the elasticity of research impact as a function of R&D are very uncertain.⁷¹

For example, Nin-Pratt and Fan (2010) estimated that if linear-extrapolated investment in R&D in developing countries doubled between 2008 and 2025, then overall annual TFP growth in those countries would increase by 0.5% (e.g. from 1.5% p.a. to 2.0% p.a.) and the effect would be sufficient to remove 260 million people from poverty. Further to this, these authors reviewed estimates of the elasticity of agricultural output to investments in R&D and provided a mean elasticity ranging from 0.17 for China and 0.093 for Africa, reflecting the benefits of a greater critical mass and experience in Chinese R&D. Similarly, Piesse and Thirtle (2010) used exponential rates and the assumption that the current global rate of 1% p.a. yield increase for all crops would need to lift to 1.34% p.a. during the whole period of 2010 to 2050 in order to feed the world. These authors estimated that global investment in R&D would need to increase by 6.8% p.a., equivalent to doubling of investment over 10 years. Piesse and Thirtle (2010) were explicit in assuming a conservative output elasticity of 0.05 with respect to R&D expenditure.

The Global Harvest Initiative—a consortium of public organisations and private companies—estimated that exponential rates of global growth in TFP must increase from 1.4% p.a. in 2000–06 to 1.75% p.a. in the next few years in order to meet world food needs by 2050; doubling of TFP growth in Africa was also recommended (Global Harvest Initiative 2011). Like others, this group identified higher public and private spending on R&D as a top priority, but its 2011 annual report did not provide a target value.

71 This elasticity measures the ratio of the relative increase in output with respect to that in R&D investment. R&D investment for these estimates is usually measured as a stock by cumulating investments (knowledge) over time and assuming a depreciation rate for the knowledge.

The Food and Agriculture Organization of the United Nations (FAO) states that annual spending on public R&D in low and middle-income countries must increase by US\$6.3 billion⁷² (2009 US\$) in order to eliminate poverty and hunger by 2050 (FAO 2012); this figure is equivalent to an increase of ~40% relative to 2009 spending of around US\$15 billion (see below). Finally, using a partial equilibrium model and assuming elasticity of 0.3 between TFP growth and R&D investment,⁷³ Lobell et al. (2013b) estimated that spending of an extra US\$11 billion (in year 2000 US\$) in annual global R&D—on top of the baseline of US\$29 billion—between 2006 and 2026 would lift global yield progress to 2050 from 1.34% p.a. of 2006 yields to 1.64% p.a. (estimating a linear relationship).

In conclusion, it would appear that future global food security depends on at **least a 50% increase (but preferably more) of R&D investment in developing countries in the next decade**. However, the estimates are theoretical and approximate in response to predicted increases in future food demand. The sources, likelihood and efficiency of R&D investment will be affected by numerous factors, as discussed below. Note that the above studies all consider R&D, with scant explicit reference to research, development and extension (RD&E), yet high-priority yield gap closing in Sub-Saharan Africa and South Asia is most limited by lack of large and effective investments in extension and other gap-closing measures (see Section 13.3 on public investments).

Trends in public investment in agricultural research and development

Ambitious R&D targets will need to be set against the **general slowdown in spending on public R&D** that has been occurring since the 1970s in most countries—this includes a well-documented (Pardey et al. 2006) slowdown until 2000 in all major regional groupings of developing countries. However, available evidence suggests that **R&D spending beyond 2000 has been accelerating. Total public spending in developing countries rose to more than purchasing power parity (PPP) US\$15 billion in 2008**, to almost close the gap with developed countries in terms of total expenditure (Figure 13.1a) but not intensity of spending (Table 13.1).

China is the outstanding performer in terms of increased R&D investment (Figure 13.1b) and is followed by the rest of Asia (dominated by India). Latin America and Sub-Saharan Africa have also performed better in the past decade, although in each case, a few large countries (such as Brazil and Nigeria) have dominated regional trends and hidden poor performance in many smaller countries. Still, with the exception of China, the trends for increased investment remain well below the estimated requirement for spending to double within 10 years, and **R&D investments are certainly far too low in Sub-Saharan Africa to accelerate productivity growth to levels achieved in other regions**.

⁷² Billion means 1,000 million throughout this chapter.

⁷³ This elasticity is higher than values quoted earlier because a different function is used to relate R&D investment to the effect of TFP.

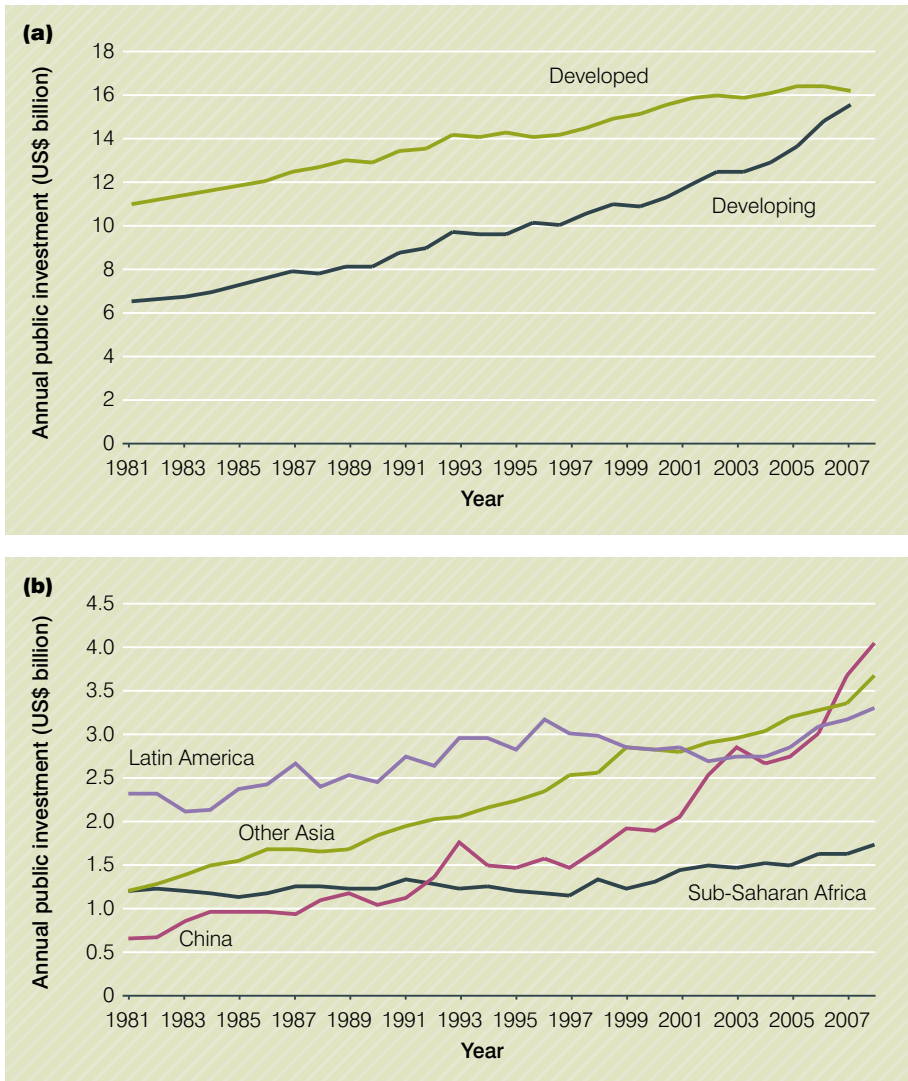


Figure 13.1 Trends in annual public investment (US\$ billion) in agricultural research and development (R&D) from 1981 to 2008, given in 2005 purchasing power parity (PPP) in (a) developing and developed countries and (b) major developing regions. Billion = 1,000 million. Source: Beintema et al. (2012)

Differences in **'intensity' of public spending on agricultural R&D** are also important. From this commonly used metric of spending as a percentage of agricultural gross domestic product (GDP), it is possible to compare differences and detect trends. Hence, data for major regions and countries presented in Table 13.1 reveal at least three clear features.

First, research intensity for low and middle-income (developing) countries in 2008 averaged 0.54%, which was equivalent to only about one-fifth of the intensity shown by high-income countries that year. Even when 'spill-in' of knowledge and technology (see Section 12.4 on case studies) from high-income countries has been properly accounted, developing countries appear to substantially underspend on agricultural R&D. At least an additional US\$30 billion of investment would be required to treble the research intensity of developing countries to approximately match that of Brazil and potentially achieve the TFP successes of that country (see Section 12.4).

Second, although research intensity in Sub-Saharan Africa is above the average for low and middle-income countries, it has declined since 1980. Note that higher research intensity in Africa reflects the large number of small countries; given the high fixed costs of R&D even in small countries, such countries generally have to spend more as a share of agricultural GDP to get the same results. Public–private partnerships (e.g. Section 5.4 on maize in Sub-Saharan Africa), public regional alliances and international agricultural research centres can all help in these situations, but a critical mass of national agricultural scientists is still needed.

However, there is good news in the final feature: agricultural research intensity has increased in the major developing countries Brazil, China and India, and in the rest of Latin America (Table 13.1), as these national governments begin to recognise its importance.

Table 13.1 Agricultural research intensity^a by regions and major countries

Country or region	Number of countries	1981 (%)	2000 (%)	2008 (%)
Sub-Saharan Africa	45	0.74	0.56	0.60
China	1	0.38	0.38	0.50
India	1	0.22	0.39	0.40
Asia excluding China and India	24	0.35	0.39	0.32
Brazil	1	1.15	1.86	1.52
Latin America ^b excluding Brazil	27	0.77	0.32	0.91
West Asia and northern Africa	13	na	0.65	0.68
Eastern Europe and Central Asia	21	na	0.28	0.51
Developing countries ^c	133	0.51	0.52	0.54
Developed countries ^d	46	1.52	2.63	3.07

a This is domestic public research spending as a percentage of agricultural gross domestic product (GDP).

b Latin America is the area of South America located south of the Rio Grande.

c IFPRI terminology is 'low- and middle-income countries'.

d IFPRI terminology is 'high-income countries'.

na = not available

Source: Beintema et al. (2012)

At the international level, investment in CGIAR also experienced a decline in real budgets⁷⁴ from the early 1990s to 2006. Investment in crop improvement programs at international research centres had declined even more sharply than overall CGIAR budgets during the 1990s. The budget for maize research at the International Institute of Tropical Agriculture (IITA) fell from US\$10 million in 1988 to US\$5 million in 2000 (Alene et al. 2009), while the wheat breeding budget at the International Maize and Wheat Improvement Center—otherwise known as *Centro Internacional de Mejoramiento de Maíz y Trigo* (CIMMYT)—fell by 60% in real terms from 1980 to 2002 (Byerlee and Dubin 2010).

The overall CGIAR budget since 2006 has, however, jumped by >50% in 5 years, from US\$450 million in 2006, to US\$706 million in 2011; in 2005 PPP US\$, the 2011 figure is equivalent to US\$620 million. Also, the reduced breeding budget trends have recently been reversed by growing investment in regional breeding programs, and reinvestment in breeding programs operated by international research centres; in particular, this investment has come from the Bill and Melinda Gates Foundation (Lynam et al. 2010).

Since developed countries are also major grain producers and dominate grain exports, **public R&D in developed countries** will continue to play a major role in upstream research for global food security, and provide important knowledge spillovers to developing countries. As shown in Chapter 12 (on trends in TFP) for the United States of America (USA) and Australia, a worrying slowdown in growth in agricultural TFP may have been linked to slow growth in public R&D investment. Furthermore, R&D resources have been reallocated to non-productivity issues (e.g. food safety and environment), which has reduced available resources for long-term strategic research of global reach, including efforts to push out the yield frontier (Alston et al. 2010b).

Trends in private investment in agricultural research and development

After a period of rapid increase, global private investment in crop-related R&D levelled off between 2000 and 2006. However, recent data indicate that an upward trend has been resumed, especially for seed and biotechnology R&D (Figure 13.2), totalling in 2010 almost US\$9 billion (in 2000 US\$ equivalent). Global R&D spending on crop protection—contained in the category of 'Chemicals' in Figure 13.2—has not increased. This is probably attributed to widespread adoption of genetically engineered (GE) resistance to insects in several major crops, which has reduced the requirement for insecticides, but has driven R&D in the seed and biotechnology sector. On the other hand, R&D into farm machinery has been rising, possibly as a result of the new tools for precision agriculture that are embodied in modern machines.

74 In other words, budgets in terms of purchasing power, hence corrected for inflation

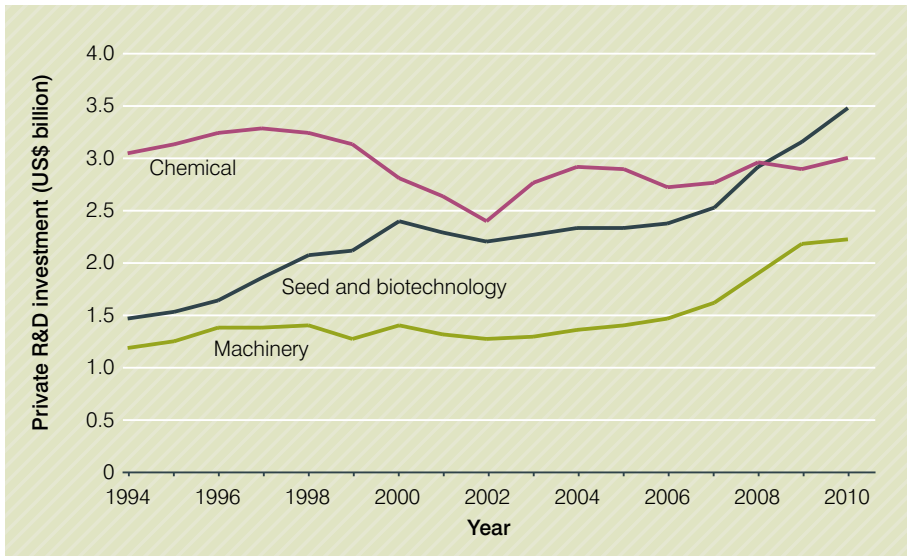


Figure 13.2 Trends in annual real global private investment (US\$ billion) in crop-related research and development (R&D) from 1994 to 2010, given in equivalents to year 2000 US\$ values. Billion = 1,000 million. Source: Fuglie et al. (2011)

About 95% of all private R&D invested in crop seed and biotechnology is undertaken in the USA and Europe (Figure 13.3)—although in Europe, continued negative public opinion about GE crops has prompted some such research to move elsewhere. Considerable spillover of this US and European research also occurs into developing countries (most notably in South America), because the major companies involved are multinational. Chemical and machinery research distribution is more balanced, as Japan plays a role. However, in no category is private research notable in developing countries.

Most private R&D in crop breeding is carried out by the ‘big seven’ seed companies, each with sales of more than US\$600 million per year (Fuglie et al. 2011). In order of market share in 2009, commercial seed sales (including vegetables) are Monsanto (34%), Dupont (22%), Syngenta (12%), Limagrain (6%), KWS (5%), Bayer (3%), Dow (3%) and others (15%). Monsanto, Dupont, Syngenta, Bayer and Dow also carry out R&D into crop protection. These large seed companies spent 16% of seed revenue on seed and biotechnology R&D in 2009, a sharp increase from ~4% in the 1980s (Byerlee and Lopez-Pereira 1994), undoubtedly because of the spread of plant variety protection laws and the opportunities provided by the new biotechnological tools.

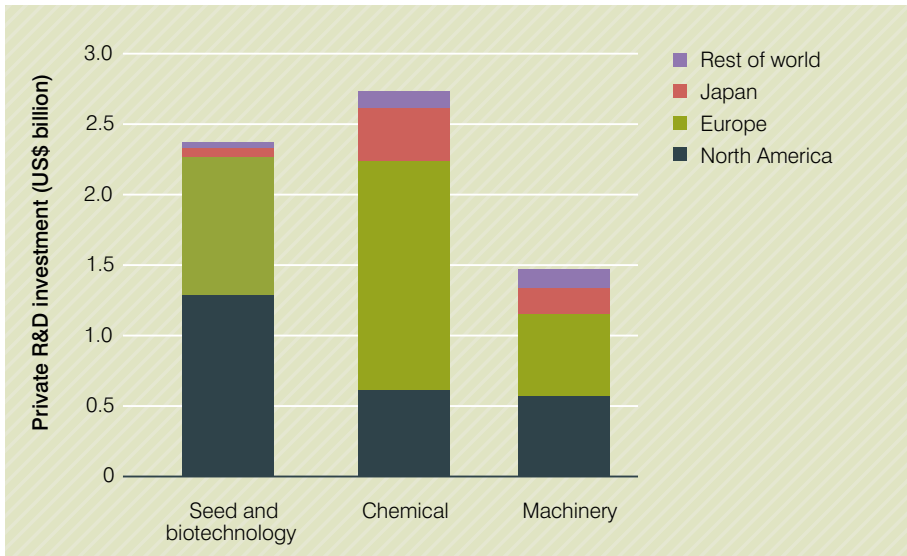


Figure 13.3 Distribution of private research and development (R&D) investment (US\$ billion) in 2006 by category and region. Billion = 1,000 million; Europe includes the Middle East. Source: Fuglie et al. (2011)

About 45% of private R&D into crop seed and biotechnology is dedicated to maize. This dominance is related to early success of the private sector in breeding hybrids. It has driven continued and impressive yield gains in the USA (Section 5.2) and other similar environments (such as Argentina; Section 5.5) where these companies and their subsidiaries operate (Fuglie et al. 2011). The spread of hybrid rice could result in a similar burst of private investment in Asia (Section 4.4), and hybrid wheat may be on the horizon (Section 9.8 on hybrid vigour). Further substantial private investment in food crops could be triggered if GE varieties of major food staples (such as rice and wheat) are accepted by the public, at least in countries where intellectual property (IP) protection enables breeders to capture part of the ensuing economic gain (see also Section 9.11).

Still, while private R&D is clearly central to future yield improvement, the growing **dominance of a few key players in the global seed industry is a concern**. When state-owned seed companies were included in the market calculation, the share for the top four seed companies increased from 21% in 1994 to 54% in 2010 (Fuglie et al. 2011). When only private commercial sales were considered (as above), the share for the top four companies increased further; in 2009 this market share was ~75%. Furthermore, this already substantial market share will increase even further if seed that is developed only by GE is considered (see Section 9.11 for a more detailed discussion of breeding privatisation).

Others have also pointed to weaknesses in the private R&D system, especially as seen in North America (Alston et al. 2012). Obviously private R&D is focused where benefits can be best appropriated by the investors—hybrid varieties, plant variety protection and

patents—and a considerable portion of the R&D investment is directed towards the food technology area to create patented food items. Royalty rates for seed technologies have been notably rising despite apparent fierce competition in the marketplace (see Section 9.11 on IP). Moreover, productivity-related agronomic research (especially input savings) and minor crops tend not to attract private investment.

Effective research and development—institutions, incentives, capabilities and partnerships

Effective R&D requires more than funding, so it is unfortunate that **institutional structures and incentives in public research systems of the developing world** have been slow to evolve to meet the needs of modern science and innovation (Byerlee et al. 2002). While there are islands of success, many (if not most) public institutes have failed to attract and keep funding and quality scientists. China and Brazil, with globally competitive incentive packages for top scientists, have been the exceptions.

More funding is flowing through competitive grants in many systems, but this is not appropriate for programs that require long-term strategic support, such as plant breeding or strategic research in agronomy. Grants usually do not cover core capacity for development of human and physical capital (e.g. laboratories). In regions with many small countries, such as Sub-Saharan Africa, mechanisms are still evolving to better link CGIAR centres, subregional organisations, regionally funded research and national systems.

A serious problem arising in public systems in both developed and developing countries is the ageing scientific cadre and consequent **training of the next generation of plant breeders**. Several authors have highlighted the looming scarcity of plant breeding staff, given that public universities increasingly specialise in more upstream biotechnology research (Morris et al. 2006; Miller et al. 2010). The FAO's database of plant breeding capacity⁷⁵ (while incomplete) reveals a decline in capacity for wheat, rice and maize in all regions, except for Sub-Saharan Africa and South Asia. In Sub-Saharan Africa, poor retention of senior staff has undermined public plant breeding programs. For example, two of the three maize breeding programs reviewed by Lynam et al. (2010)—in Ghana and Malawi—had lost all the senior maize breeders who were instrumental in earlier release of widely adopted maize varieties. Only Kenya—with six public maize breeding programs, and six Doctor of Philosophy (PhD) students in maize breeding—was judged as having substantial capacity in maize breeding.

No equivalent data are available on **capacity in crop agronomy** research. The experience of this book's authors indicates that much agronomic research is fragmented into subdisciplines and divorced from farmers' realities. Most research organisations still lack the disciplinary balance and multidisciplinary interactions that are needed to promote the required levels of effective crop system and resource management research.

⁷⁵ Available at <gipb.fao.org/Web-FAO-PBBC/>, but there are no data after 2009.

Ultimately, the capacity of public R&D organisations to learn and innovate in order to respond effectively to a rapidly changing environment—and the capacity and empowerment of farmers and their organisations to influence research—are keys to increasing the research impact. In recent years, public RD&E has been increasingly viewed as part of wider **innovation systems** that embrace private input industry, processors and others in the value chain (such as farmer organisations and civil society) to promote technological, managerial and organisational innovations (see Section 8.4).

Empowerment of farmers to co-finance and co-direct the research agenda is critical to the success of innovation systems; this is demonstrated in countries such as Uruguay (see Section 12.4 on case studies) and Australia, with potential in North America (Alston et al. 2012). Wheat breeding was privatised in Australia in the mid 2000s, to be financed by end-point royalties; prebreeding research was to remain a publicly funded activity, co-financed by growers and the government (Fischer 2012), but even this scenario is moving towards public–private partnerships. It is too soon to judge from the Australian experience whether this hybrid model of financing brings greater efficiency, but the model does raise the question as to the potential (or otherwise) to maximise breeding efficiency from a purely private system. In other words, do monopoly privileges that accelerate invention create wasteful secrecy, duplicate effort, build barriers against the public sector and/or cause excessive promotional and transactional efforts (Alston et al. 2012)?

Other forms of **public–private partnerships**—especially on seed and postharvest research—offer opportunities to improve market responsiveness. Examples include hybrid sorghum and millet delivery to farmers in India (see Section 7.2), and the tropical hybrid rice consortium run by the International Rice Research Institute (IRRI). The biggest challenges are to develop the capacity among key policymakers and stakeholders to promote institutional innovation in the R&D system itself, and furthermore, to learn from experience and make adjustments to meet changing demands and achieve greater public–private synergies.

13.3 Other public investments influencing productivity growth

Considerable evidence supports the key role of public investment in increasing agricultural productivity and reducing poverty (Fan 2008). Studies over several countries indicate that the highest pay-off arises from investment in agricultural R&D (sometimes including extension), generally followed by **investment in education and rural roads** (FAO 2012), although categories and coverage vary by study. Successful closing of large yield gaps in many countries (especially Sub-Saharan Africa) will depend on large public investments in infrastructure, institutions and farmer capacity building (see also Section 8.3 on technologies to alleviate yield gaps).

FAO (2012) estimated that in 2005–07, governments of developing countries annually invested about US\$40 billion in all aspects of agriculture, while foreign public investment added around US\$3 billion. Furthermore, FAO estimated that an additional 2005 PPP US\$50 billion of annual public investment will be needed by 2025 to eliminate hunger and poverty; rural infrastructure and market access represented the major areas for investment (37% combined) and R&D represented 13% of the recommendation. Some of this additional investment could be provided by foreign assistance, but most would have to be delivered by national sources. The most urgent increases are required in Sub-Saharan Africa and South Asia where the agricultural orientation index—that is, the share of public spending on agriculture relative to the share of agriculture in GDP—is very low relative to other regions. In 2003 the African Union set a target of 10% of spending to be allocated to agriculture, although only seven countries had reached the target by 2007 (FAO 2012).

Rural education

Low levels of education, low skills among ageing farmers and declining capacity of extension services have been identified as major determinants of the TFP 'efficiency gap' (see Chapter 12 on trends in TFP). **Rural education expenditure tends to deliver the second or third highest public investment returns** in terms of agricultural performance and poverty reduction (FAO 2012), and China has performed well in this area. A recent cross-country estimate is that one year of additional schooling of the total population increases agricultural productivity by 3.2% (Reimers and Klasan 2012). Rural educational levels for people aged 18–25 years joining the labour force in Sub-Saharan Africa, Latin America and South Asia (but not East Asia) are typically only about one-half of those in developed countries (Pardey et al. 2007; World Bank 2007). Educational levels are even lower for young women, even though they play an increasingly important role in farm labour and management, as men travel widely to seek extra family income.

Extension

Early studies looking to returns to RD&E separately found that extension delivered just as high a rate of return as R&D, averaging ~44% (Evenson 1997). Sheng et al. (2011) measured an internal rate of return of between 33% and 57% from public investment in extension in Australian broadacre farming. Although no comprehensive data are available on agricultural extension capacity, it is widely believed that, except in a few countries (e.g. Ethiopia), **public extension capacity has declined in terms of numbers, in operating budget and in effectiveness** in meeting the more complex informational and training needs of farmers. Further detail on this situation is provided in Section 8.4 with the case studies for India, and other approaches targeting the adoption of new technology. Even in the USA, spending on public extension peaked around 1980 and has steadily declined since (Alston et al. 2010b). Private extension—provided both by input suppliers and (more objectively) by private consultants—has moved to

fill some of the vacuum created by this decline in the USA, Australia (Fischer 2012), Argentina and Brazil, and probably other developed countries.

Many systems are moving towards **pluralistic approaches**, meaning that different models are often used within a country depending on the type of farmer and/or commodity targeted (Davis 2008). Although extension is still largely publicly funded, funds often flow through local governments, non-government organisations (NGOs) and farmer organisations that have a controlling interest in fund allocation. The National Agricultural Advisory Services in Uganda empower farmer organisations by co-financing grants to contract NGOs and private providers to deliver specific advisory services. Between 2004 and 2007, this program notably increased gross farm revenues, but the impact differed by region—it was greater for high-value enterprises and for male farmers (Benin et al. 2011).

The increase in contract farming has also given rise to **private advisory services** hired by agribusiness. **Better trained private input suppliers** can also provide valuable information, and the Alliance for a green revolution in Africa (AGRA) and others have included training programs in an effort to build private input dealer networks. Finally, **new information and communication technologies** can fill information gaps; thus many organisations provide mobile telephone services to identify pests and diseases, finetune fertiliser recommendations and provide the latest price information. The challenge is how to scale up these innovations to meet demands for information and to improve decision-making for millions of smallholder farmers.

Irrigation

Irrigation is an important factor driving yield increase and productivity growth. Bruinsma (2011) predicted that **a net 20 Mha of additional irrigated land** (all in developing countries) will be brought into production by 2050. Schmidhuber et al. (2011)—presumably using the Bruinsma prediction—calculated a requirement for net investment for irrigation to 2050 of US\$158 billion, a figure equivalent to about US\$8,000/ha or US\$4 billion annually. These investments are especially important in developing countries where ~60% of cereal production currently comes from irrigated areas.

Conversion of rainfed land to irrigation has been an important source of past crop yield increase (Bruinsma 2011). However, in the future, such conversion is expected to play only a marginal role in further cereal yield increase, as higher value crops begin to command a greater share of irrigated area. **Irrigation investments are especially important in Africa**—where less than 5% of cultivated land and only 2% of water resources are used. Africa offers considerable shallow groundwater reserves suitable for small-scale irrigation without huge investment in infrastructure (MacDonald et al. 2012). If high food prices since 2007 continue to prevail, more costly investments in large irrigation schemes should also be profitable, especially for rice. Larger schemes are also a likely area for private investment funds.

Rural roads

Investment in roads (especially rural roads) has been consistently documented as an important determinant of agricultural productivity (Fan and Hazell 2001). For example, although Brazil is a major exporter, long distances to port—around 1,500–2,000 km from the central Cerrado region in the state of Mato Grosso—and poor infrastructure meant that the cost to deliver export soybean (by truck and rail) was about US\$125/tonne in 2010, several times the cost for transporting US soybean from Iowa to gulf ports. The issue of road quality is particularly important in Africa where high transport costs are incurred because an estimated 75% of farmers are located more than 4 hours (by motorised transport) from the nearest market; in Asia, only 45% of farmers are affected by this proximity issue (Sebastian 2007). Freund and Rocha (2011) indicated that the costs of rural road transport is 3–5 times greater per kilometre than main road transport, so that 45% of transport costs are incurred in the first 28% of the distance transported from the farm. Foster and Briceño-Garmendia (2010) estimated that approximately US\$110 billion would be needed to provide and maintain 75% of the rural population in Africa with access (within 2 km) to an all-season road.

13.4 On-farm private investment

Private investment by farmers is the largest and most important source of investment in agriculture in developing countries (FAO 2012); in 2005–07 the annual amount averaged around US\$170 billion. This investment is not independent of public investment—the latter complements private investment by creating an environment that encourages farmers, input suppliers and produce handlers to invest.

To balance food supply with demand, the FAO has estimated the requirement for a total increase in private investment of US\$83 billion per year, not including depreciation of existing capital stock (FAO 2012). Most of the requirement is derived from on-farm private investment, especially for machinery—to substitute for increasingly expensive labour in (rapidly growing) developing countries—and for livestock and trees, and land improvement. Again the most urgent needs are obvious in Sub-Saharan Africa, where on-farm investment per worker has been falling, and in South Asia, where this investment has been stagnant (FAO 2012).

On-farm investments are in turn conditioned by the overall business environment. For example, the World Bank measures investment in its 'Doing Business Index', which includes factors ranging from public investments (discussed above), to macro-economic policies, rules and regulations required to start and run a business, and the prevalence of corruption. These factors are only now being assessed for agricultural investments, but are generally expected to be lowest in Sub-Saharan Africa and highest in countries of the Organisation for Economic Co-operation and Development (OECD).

Institutions in the form of property rights and financial markets are especially important for long-term investments (such as land improvement). For example, up-front investments in the 1980s to bring Brazilian Cerrado land into production—including land clearing and soil amendments to counter acidity and phosphorus fixation—amounted to about US\$1,000/ha at that time. Similar or even higher investments will be needed for the savanna areas of Africa, now being targeted for crop expansion. In other areas, investments are needed to simply maintain or restore productivity in the face of land degradation (such as soil erosion and fertility exhaustion). Secure property rights will be needed to stimulate these investments—a big challenge in Africa where land rights are generally not yet formally recorded.

13.5 Other policies influencing productivity growth

Price policies and regulations are also important factors in productivity growth.

Pricing policies

Appropriate price policies are especially important for providing incentives for intensification in regions such as Sub-Saharan Africa, and incentives to efficiently and sustainably use inputs in other regions. Both output and input pricing policies play roles in setting incentives.

Historically, developing countries have heavily penalised agriculture sectors (e.g. export quotas and taxes) in part to provide cheap food, and this has penalised overall rates of agricultural productivity growth. The situation was largely resolved under liberalisation policies of the 1990s, and the average tax on agriculture is now low (Anderson 2009). These reforms have provided a spur to productivity growth—see the case study for Egypt (in Sections 3.4 and 4.6)—but this is unfortunately a one-off opportunity. In Sub-Saharan Africa, Fuglie and Rada (2012) estimated that policy reforms that reduced taxation of the agriculture sector increased TFP by 5%, and further reforms could add another 5%. Progress in dismantling price distortions has been surprisingly much slower in developed countries where farm support programs have favoured a few crops and discriminated against adopting more sustainable cropping systems, especially rotations with alternative crops.

Nonetheless, yields of food crops are generally not responsive to prices, at least in the short term (Binswanger 1989; Rosegrant et al. 2008). For example, Hertel (2011) estimated a yield elasticity of 0.2 for maize in the USA—that is, a 1% increase in price would stimulate a yield response of 0.2%. However, this is a decline from 0.7 immediately after the World War II when input use was much lower and yields were

more responsive (see Box 2.2); this latter situation may be more representative of low-income countries today. The elasticity estimates also do not account for the effects of price incentives on investments with long-run pay-offs (such as R&D and irrigation), which are likely to raise the long-term elasticity. For example, there is evidence that public investment in rice research and irrigation in Asia decreased following the long-term fall in world prices of rice (Hayami et al. 1989; Rosegrant and Pingali 1994). Private research is likely to be even more responsive to prices, and the increases in food prices since 2007 probably explain the resurgence of private R&D spending. Thus, over the long term, yields may be much more elastic with respect to prices than they are in the short to medium term.

Many inputs in Asia are commonly subsidised and pricing structures for inputs (especially water) are outmoded. Such policies helped stimulate adoption of inputs in the 1970s and 1980s from technologies developed during the green revolution (see Section 1.1), but current high levels of input use mean these now outdated policies undermine incentives for farmers to more efficiently manage inputs and sustainably manage natural resources. Another important influence for input efficiency will surely be support for institutional reform, with examples including greater devolution of water management decisions to users and a gradual shift to market-determined water allocation systems.

Sub-Saharan Africa is one region where further input intensification offers great potential for yield increase. Fertiliser nutrients (nitrogen, phosphorus and potassium) in Sub-Saharan Africa are used at a low rate of <10 kg/ha, a figure that is much lower than the ~100 kg/ha used in South-East Asia and South America, both of which are largely rainfed like Africa. The low rate of fertiliser use severely constrains yield, and in Africa, failure to sufficiently fertilise means that successions of crops will deplete soil nutrients over time. Low fertiliser use in Africa relates to many factors, but high fertiliser prices at the farm gate are the most important. Thailand depends on imported fertiliser, as do most African nations. Even so, retail prices for fertiliser are 25% higher in coastal African countries such as Ghana than in Thailand, and 60% or more higher where infrastructure is poorer, like coastal Mozambique, or transport distances greater, like Uganda (Figure 13.4). High fertiliser costs in Africa are caused by low volume procurement, high costs for shipping and inland transport and poor logistics (Morris et al. 2007).

Over the long term, investments in infrastructure will reduce these costs. In the meantime, there is a case for input subsidies to promote adoption of fertilisers and stimulate development of markets for inputs. In recent years, several African countries have reintroduced such subsidies that have meant large improvements to input use and yields; one example is given in Section 8.5 for maize innovations in Malawi (Dorward et al. 2011). However, high costs and displacement of commercial sales threaten the long-term sustainability and effectiveness of such programs. For example, in Zambia, where fertiliser subsidies are mostly captured by larger farmers, the government now spends >75% of the agricultural budget on subsidies and maize marketing operations, and only 0.5% on R&D (Jayne et al. 2012).

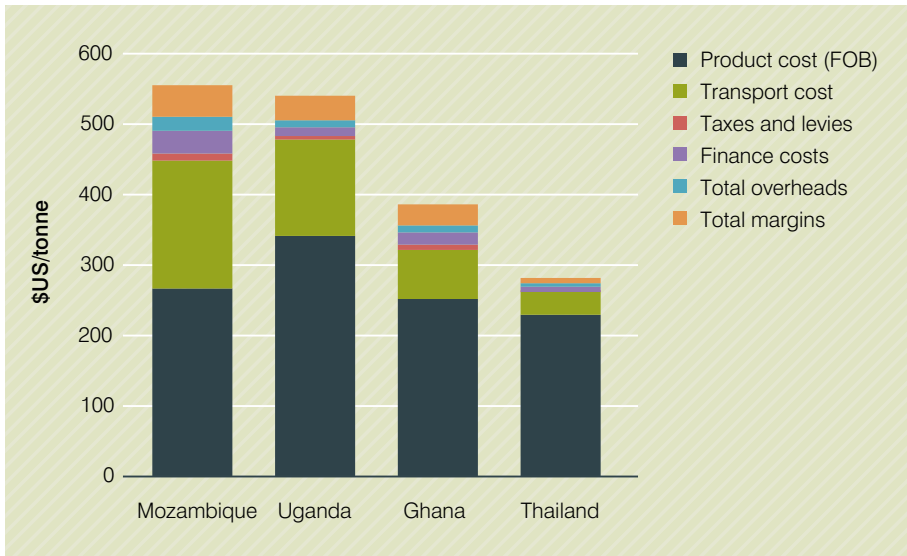


Figure 13.4 Comparison of urea value-chain costs in 2006 for countries of Africa (Ghana, Uganda and Mozambique) and Thailand. FOB = free on board, the price of urea loaded on board ships at the importing port, which is in Kenya in the case of Uganda. Source: IFDC and Chemonics Int. (2007)

Recent experience with input subsidies in Africa has diverged substantially from accepted 'good practice' (World Bank 2007), and this is partly due to the political dimensions of input voucher distribution. Ideally vouchers should be temporary, strengthen private input suppliers, target current non-users of fertiliser and not divert public funds from high-priority public investments such as R&D.

Finally, given the inherent challenge for agriculture from weather and/or market-related risks, institutions that mitigate this risk can provide incentives for farmers to increase yields. Farmers in developed countries widely use market-based risk instruments such as forward contracting and weather insurance, but these instruments are generally not available to most farmers in most developing countries. Weather-indexed insurance has been piloted in several developing countries and could have a role in reducing risks of relatively infrequent weather events that are damaging to yield. Government-run buffer stock programs have played an important role in stabilising prices in Asia, especially in the rice economies, but these programs now incur high costs (Rashid et al. 2008). Although buffer stock programs have been tried in Africa, generally without success, efforts such as investment in irrigation to reduce climate risks, and infrastructure and market information systems to reduce market risk, remain important priorities in Sub-Saharan Africa.

Regulations

Clear land tenure arrangements are vital, as already mentioned. However, elements of the regulatory environment can impede faster and wider uptake of technologies, in particular seed technologies. In view of the failure of state seed-industry models of the past, and with expansion of the private sector role in the industry, there has long been recognition that seed regulation in developing countries needs reform (e.g. Tripp 2002). Most developing countries have rigid varietal release and seed certification policies that delay the spread of varieties and importation of seed until after several years of in-country testing and approval. This is especially serious in Africa where private seed companies have to operate across several small countries in order to realise a profitable regional market size.

Although there have been many efforts over the past 20 years to introduce a common varietal registry across African countries (similar to that operating in the European Union), such a registry has not yet been implemented in any of the subregional economic zones. Further, lack of biosafety regulations (and/or capacity to implement them) continues to be an important hurdle to wider uptake of GE technologies in most developing countries. This is particularly problematic in Sub-Saharan Africa where regional agreements are needed to accommodate the many small and adjacent countries that share porous borders. Continuing European Union prohibitions on GE crops are probably directly limiting productivity growth in Europe, and indirectly so in developing countries that export to Europe.

Good governance is of course the overriding guarantor of the application of sound regulations (and other policies)—it is necessary to encourage productive investment and avoid abuse by powerful elites, which will inevitably exclude most nations' smallholder farmers. FAO (2012) pointed to the strong relationship between rule of law and the amount and growth of agricultural investment per worker.

13.6 Who will grow the food?

Food security is determined by a wide range of factors, including many that do not relate to crop yield. These factors include school feeding, which is an example of nutritional programs and social protection or safety nets for economically disadvantaged people. Even for crop yield, an important distinction is needed, on the one hand, between increasing global food supply to provide food at affordable and stable prices to people who are reasonably well connected to markets but experience food insecurity (e.g. urban and many rural dwellers) and, on the other hand, increasing food supply at the local and household levels for people with limited access to markets (such as most subsistence farmers). Thus, where the food is grown and by whom matters a lot to food security.

Global food security and trade

At a global level, undoubtedly trading increases food security and should deliver cheaper food, although there are availability limitations to imports by countries with large populations (China and India), and financial and logistical limitations for economically disadvantaged countries that lack foreign exchange. Moreover, producing at a local level means increasing agricultural productivity of subsistence farmers (especially women farmers). Thus, local production can increase food security directly through higher production for home consumption, and through freeing resources for the production of cash crops and livestock, which can be traded for staple foods.

With increasing urbanisation and more commercialisation, and the general move to freer trade, production of 'big four' crops (wheat, rice, maize and soybean) is expected to steadily move to regions of comparative advantage, with other regions depending more on imports. Exporting regions include five groups of countries:

1. traditional OECD exporters—USA, Canada, Australia and parts of western Europe, in particular France (although policy reforms and small yield gaps mean the role of European exporters may be declining)
2. current main exporters from the relatively land-abundant countries of Latin America—especially Brazil, Argentina, Paraguay and Uruguay—where increased investment in transport and logistics is likely to increase their export market share
3. South and South-East Asia, which continue to provide the world rice market—although with an increasing role for South American exporters (such as Uruguay) and the potential entry of new players such as Myanmar
4. potential new exporters from Sub-Saharan Africa, where there is considerable uncultivated land (which is now being tapped by a wide range of investors) and very large yield gaps, but where technology, transport and logistics seriously constrain investors and commercial smallholder farmers
5. emerging exporters of the Russian Federation, Ukraine and Kazakhstan (and to a lesser extent, Eastern Europe), which currently have large yield gaps and considerable land that could be brought back into production. These countries have already turned around from net imports of 31 Mt of grain and oilseed in 1992 to net exports of 56 Mt in 2009. With continued progress in these countries, the US Department of Agriculture forecasts that the Russian Federation will be the world's largest wheat exporter by 2020, although transport and logistics seriously constrains exports from inland locations.

Encouragement of free trade to allow efficient location of production should be an integral part of the solution to global food security and sustainable use of natural resources. Many countries with poor natural resources and growing coastal urban populations are unlikely to have a comparative advantage in grain production. FAO has projected that annual cereal imports by developing countries who are net importers will increase from ~160 Mt in 2005–07 to 300 Mt by 2050; an even larger relative increase is expected for vegetable oil imports (Alexandratos and Bruinsma 2012).

Reduction of ‘food miles’ is sometimes used to defend local production. However, energy costs of long-distance transport are only a fraction of total energy use in the food chain (Section 11.4 ‘Energy use efficiency’). Studies summarised by Desrochers and Shimizu (2012) have shown that in the United Kingdom about one-half of the energy in the food chain is consumed by shoppers driving to supermarkets, and only ~1% by each of airfreight and maritime shipment (the latter is the most efficient transport method). This does not include the energy cost savings from off-season cool storage of local produce that long-distance transport from a different climatic zone in the off-season often avoids. The Desrochers and Shimizu (2012) conclusion supports evidence in this book that ‘food miles’ represent nothing but a misleading distraction.

Countries unable or unwilling to depend on trade for food security

While international trade will likely expand steadily, there are limits to the extent that countries can depend on trade. Given their large size in relation to world markets, China and India will likely have to produce a large part of what they will consume (especially rice). There are also many countries in Africa—especially land-locked countries with very limited foreign exchange—that will necessarily have to produce most of what they will consume.

In addition, in the wake of the 2008 price shock, many countries have introduced policies to increase self-sufficiency in the name of food security. While these policies may well be self-defeating when measured by the internationally accepted definition of food security, it can be expected, as long as world price volatility remains high, that such policies will remain politically attractive (Anderson et al. 2012).

Farmers and farms of the future

FAO (2012) reports that in 2010 there were 1,300 million active workers in agriculture in the developing world and 17 million in the developed world. Farm data are less certain, but Nagayets (2005), also using FAO sources, estimates that around the turn of the century there were 525 million farms worldwide, of which around 400 million were less than 2 ha of owned or rented land. Most of these small farms were in Asia and Africa where the approximate average area was 1.6 ha, having decreased by about one-third in the previous 30 years. Data are unavailable but many millions of small farms (and some larger than 2 ha) will be subsistence farms with limited market access. Increased agricultural productivity—whether through yield of food or non-food commodities—is one of the most effective ways of reducing their poverty and generating income to provide better access to food. There is widespread evidence for this from Asia, where the efficiency of small farmers and their ability to respond to new technology was amply demonstrated by the green revolution.

However, there are nuances to these arguments for the 'big four' crops of this book (wheat, maize, rice and soybean). First, the world is rapidly undergoing urbanisation so that production for selling at markets will increasingly dominate production for home consumption. Second, agricultural labour becomes scarcer with urbanisation, and rural wages rise. These drivers will play out in different ways depending on the pace of urban growth and existing factor endowments, as described below for five major regions.

Emerging middle-income countries of Asia

These countries are now entering a phase of rising rural wages and rural population loss as occurred in Japan and South Korea 40 years ago; this situation now is more constrained by World Trade Organization rules. For example, Thailand has rapidly mechanised rice production, expanded farm size and maintained international competitiveness—although recently it exhibited a backward step, introducing unusual protectionist policies that will likely prove very costly. Elsewhere in Asia, as in Thailand, larger farms (>2 ha) with larger field sizes are likely to be the future grain producers, as smaller farms combine specialisation in labour-intensive horticulture and livestock industries with non-farm employment (Reardon et al. 2012).

Much of Asian agriculture is consolidating towards larger, specialised farms; the process is tracking the rapid development of land and farm machinery rental markets. In some parts of Malaysia and China, specialised companies are taking over farming on rented land (Yang et al. 2013). The main challenge for many countries (e.g. China) is to ensure well-functioning land rental and sale markets, which help to more efficiently consolidate small fields into larger fields (Otsuka and Estudillo 2011). Of course, as farm sizes increase, some (the more entrepreneurial) will benefit, but many will leave farming.

Africa

In Africa, there is much debate about future farm size, especially in countries with relatively abundant land. Some have argued for the promotion of Brazilian-style large commercial farms (Collier and Dercon 2009), while others urge a focus on making existing smallholder farmer agriculture more productive (Jayne et al. 2010). In the past there have been episodic bursts of productivity growth in maize for smallholder farmers, led by state provision of inputs and price guarantees, but these have not been sustainable, due to high costs (Smale et al. 2011). Recently, market-driven approaches to improving smallholder farmer productivity have been widely tested; the most popular of these (input vouchers, as discussed above) increased production, but high costs and poor targeting continue to challenge sustainability. Other recent approaches—such as innovative organisation (and management) of value-chains, and experiences with smallholder farmers and contract farmers (see Section 8.5)—have been promising, but are (as yet) too new to claim success.

On the other hand, investors are moving aggressively into biofuel and food production in Africa in large-scale ventures often exceeding 10,000 ha (and sometimes much more). In the past, such investments for food crops have generally failed miserably—examples include the large mechanised sorghum farms in Sudan and wheat farms in Tanzania and Nigeria (Deininger and Byerlee 2011). Schoneveld (2011) documents the new wave of foreign land investment in Sub-Saharan Africa since 2005, totalling about 18 Mha for 2005–10, and mostly targeting large-scale biofuel plantations. There is also some interest in food crops such as sugarcane (0.7 Mha) and rice (0.6 Mha); it is not known how much of this investment proceeded to completion. Clearly the high up-front costs of irrigation initially favour large operations—perhaps similar to those in Australia or Uruguay—but there is potential to add smallholder farmers, termed ‘outgrowers’, who receive support from and deliver to the adjacent farming corporation. A few established rice farms (e.g. ‘Tilden’ in Uganda) have achieved high yields and apparent profitability, and some recent investors—such as the Global Agri-Development Company (GADCO) in Ghana—have emphasised providing irrigation infrastructure for smallholder farmers as an integral part of investment in a large rice enterprise.

Even if large farms succeed in food production in Africa, it is difficult to see how such operations would contribute to food security at the local level; highly mechanised grain farming generates few jobs, and hence will contribute little to reducing widespread poverty there. For this reason, greater productivity of smallholder farmer agriculture, both for food and non-food products, has to be central to increasing food security.

Latin America

Contrary to earlier experience in Asia where smallholder farmers benefited greatly from modernisation of farming, there appears to be a widening gap in grain yields, favouring large commercial farms over smallholder farmers (Figure 13.5); in other words, larger farms have lifted yield notably over approximately 20-year periods, as shown for Brazil and Chile, but smaller ones have seen little progress. The primary reason for this appears to be the differing levels of access to financial and advisory services (see also Section 8.4).

Large private farms have also arisen in the Russian Federation, Ukraine and Kazakhstan, supplanting the equally large state and cooperative farms. Although smallholder farmers remain very important in horticulture and livestock production, the development of large farms has meant that smallholder farmers account for very little grain production there. In both this region and Latin America, companies with more than 10,000 ha (and sometimes hundreds of thousands of hectares) dominate (Byerlee et al. 2012). Yields on some such ‘superfarms’, which have used state-of-the-art technologies and management innovations, have been above average for each region; evidence of greater profitability has been less clear. The lack of public research and advisory services in the former Union of Soviet Socialist Republics (USSR) is proving to be a weakness in their farming model. Also it is too soon to be sure of the long-term viability of this new wave of corporate farms there and in Latin America.

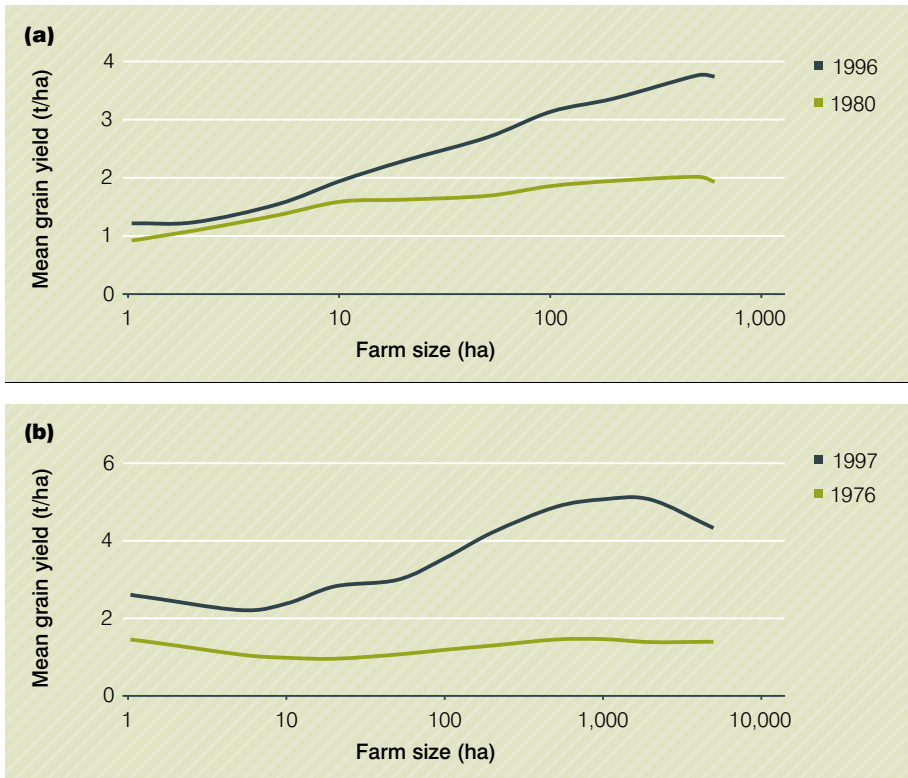


Figure 13.5 Relationship of farm size (ha) to (a) maize yields in Brazil and (b) wheat yields in Chile. Farm size is shown on a log scale. In Brazil, farm size is estimated as harvested area of land. Source: World Bank (2007)

OECD countries

Almost all broadacre farming in OECD countries is owned and managed by families, and farm size is steadily increasing. In the USA, for example, the weighted median wheat area per farm for wheat growers increased from 163 ha in 1987 to 368 ha in 2007 (MacDonald 2011), although this disguises a non-normal distribution of size, with many small farms and fewer large ones. In Australian wheat farms, the average cropped area per farm has increased from 500 ha to 900 ha in the past 20 years (Bell and Moore 2012). These changes reflect efforts to maintain farm incomes in line with non-farm incomes; there is only weak evidence of a statistically significant relationship between yields and profitability, and farm size. Farm area has partly increased by purchase but also by renting land to enable further expansion of operational units; this is seen in the USA, Australia, and very probably elsewhere. Some of the largest farms have evolved into family-owned companies that hire considerable labour. Recently in Australia, new business models have emerged for farmers to work with companies who provide working capital and professional management advice, and absorb some of the risks.

13.7 Conclusion for policies and people

The overall outlook on policies and investment conducive to crop yield increase and TFP growth is becoming more positive. Investment in R&D has risen sharply in most developing countries and especially in the largest grain producers (China, India and Brazil), but with the clear exception of Sub-Saharan Africa. Stronger commodity prices (since 2008) have stimulated increased private investment in agriculture, and have probably also influenced the recent rise in public investment.

However, while both public and private investment in the R&D sector is rising, it is still not enough to ensure global and local food security. Except for few star performers (such as Brazil), estimates discussed in Section 13.2 suggest that public spending on agricultural R&D in developing countries should roughly double over the next 10 years (as well as accelerate in high-income countries) to achieve sufficient yield increase. Moreover, public and private investment in other key areas related to agriculture will need to show similar relative increases. The biggest challenge remains in Sub-Saharan Africa, followed by South Asia, where yield gaps are large and both public and private investment fall far short of requirements for food security. Sub-Saharan Africa still seriously lacks both public and private investment, but the trends have been positive with evidence of rising yields in some countries for some crops—for example, rice in the Sahel region; maize in Malawi, Zambia and Ethiopia; and cassava and cowpea in Nigeria.

Unintended consequences of poor policy have declined with general improvements in policy design and implementation; this has occurred in developing countries through reforms to reduce taxation of agriculture, and in developed countries by withdrawal of domestic price subsidies to better align with world prices. Although removing subsidies in some developed countries has followed from recent rises in world prices, it does of course dampen yield increase.

There is considerable scope to use trade to balance supply and demand to improve global food security. There are, however, limits to this strategy, especially for very populous countries and the many countries in Africa where increased domestic production is essential. Further, for millions of subsistence farmers and others not well connected to markets, one of the most effective ways of reducing poverty and hunger is to increase farmers' productivity.

Important structural changes in the farm sector with respect to food staples are likely (see Section 13.6). Generally, scaling up grain production delivers limited economies of scale, either through increased yield or reduced costs, but these may be emerging when comparing the extremes. On one hand, the very small farms now common in Asia and densely populated areas of Africa and Latin America, are not likely to become efficient producers of grains, although they may well be productive with other more labour-intensive agricultural commodities. Still, increased productivity of food staples for home consumption can free resources so other products can be sold at a market to bring in an income, doubly improving food security. At the other extreme, the upper limit

of efficiency has been pushed out by new technologies and management innovations. However, true 'superfarms' for cropping have emerged only where distortions in input, product and capital markets provide favourable incentives relative to family farms. Policies that level the playing field for family farms by making markets work better will likely ensure these farms' futures.



Summary and conclusion

14



Key points

- To ensure that real food price increase does not exceed ~30% over the record lows of 2000–06, published modelling suggests that staple crop production must increase by 60% between 2010 and 2050.
- It therefore follows that, after accounting for likely increases in crop area, farm yield (FY) must linearly increase by a rate of 1.1% per annum (p.a.) (relative to 2010 yield). This is the minimum rate required, and a higher target of 1.3% p.a. is recommended to offset risk. Unfortunately, the current average global rates of progress for FY in wheat, rice and soybean are each only 1.0% p.a.
- Progress in FY is influenced by two components: (1) progress in potential yield (PY)—or water-limited potential yield (PY_w), depending on which is appropriate; and (2) closing of the yield gap between FY and PY (or PY_w).
- Progress in PY averages between 0.6 and 1.1% p.a. for most crops, and progress these days is largely attributed to breeding. The yield gap is closing or reducing, but at a rate of change (range of -0.8% p.a. to -0.2% p.a. for staples) such that its influence on FY is somewhat less than that of the change in PY. Yield gaps exceed 100% of FY in many developing countries.
- The most feasible and fastest way to lift global FY will be to close large yield gaps. This will require huge investment in research, development and extension, and in rural infrastructure and institutions.
- Continued progress in PY (and PY_w) is also important and largely dependent on investment in basic and applied breeding, both in the public and private sectors, but boosting progress will be difficult to achieve. Conventional breeding can be assisted by new molecular tools. Biological limits are not yet foreseen.
- As always, new crop management (agronomy) complements breeding advances. Agronomic improvements are also vital in yield gap closing and building sustainability.
- This book strongly supports the intensification of cropping as the means to deliver higher yield and feed a hungry world. Intensification can occur sustainably if based on scientifically determined ‘best-practice’ management that improves input use efficiency and soil quality. The biggest positive environmental consequence of crop intensification will be the reduced pressure to clear new land for cropping.

Summary and conclusion

14.1 The question unpicked

The title of this book asks whether crop yield increase can continue to feed the world, and throughout the preceding chapters, this running theme has been approached from the various facets that must be considered in order to determine an answer. Food production increase over the past 50 years has occurred faster than population growth, with notable increases in per-capita food production (see Section 1.2 on demand for crop products). Yield progress—measured as output per area of land (Section 2.1)—accounts for ~80% of the increase in food production, while the remainder is derived almost equally from expansion of arable land area and increases in cropping intensity (see Box 1.1 and Section 1.4 for further definitions).

The food supply required to 2050 will also be a function of growth in demand. As for all commodities, agricultural product supply and demand are balanced by price (see Section 1.5 on crop yield, pricing and trade). Although it is unlikely that the world will ever again see the record low real grain prices of 2000–06, various predictions suggest that affordable food could be guaranteed for all if further price increases did not exceed 30% beyond the 2000–06 base.

Table 1.6 summarised a range of predictions of supply and demand growth from published partial equilibrium modelling that included allowances for some growth in grain for biofuel. It was then estimated that total grain supply must increase by 60% by 2050 (relative to 2010) in order to meet the aforementioned price condition. It is also clear that the most critical period will be the next 20 years, during which population growth rate (and hence demand growth) will be greatest in the overall period to 2050.

The past pattern of contributions to production increase is expected to continue through to 2050. Thus yield progress will remain dominant, contributing 80% (or even more) of the production increases of the future. The balance will come from increases in crop area, both through greater arable area and greater cropping intensity. This book, in Section 1.4, considers various estimates and suggests that, by 2050, there will be a net increase of at least 100 Mha in the global area of arable land. This is equivalent to a further 7% on top of the 2010 global area of 1,400 Mha; to account for losses, new arable land will increase more (~200 Mha) and without doubt will be associated

with some additional environmental stress. Cropping intensity is expected to continue increasing slowly, along with the growth in arable area. These factors will result in an increase of 10% in crop area between 2010 and 2050.

Taking into account these predicted area changes, and the demand estimates and price goals, Section 1.5 estimated that feeding the world in 2050 will require a 45% increase in yield from 2010 levels.⁷⁶ To translate to an annual rate in terms of linear growth—as is consistent with the shape of current yield progress seen in Figure 1.5 and elsewhere in this book—the target for global yield increase for the staple crops should thus be 1.1% p.a. relative to 2010 yield.⁷⁷

Section 1.5 also argued that this target rate of progress should be a minimum goal. Thus, it would be wiser to aim for a higher rate of yield progress to better protect against unanticipated shocks. Although individually improbable, many shocks would be likely to be adverse for food prices (and the welfare of economically disadvantaged people). Thus a target for yield progress set closer to 1.2% p.a. (or even 1.3% p.a.) would better offset risks.

Importantly, some acceleration in yield progress will be required to meet the proposed target rate. Measured over the past 20 years, current rates of yield progress (relative to 2010 yields) are only 1% p.a. for wheat, rice and soybean, but higher at 1.5% p.a. for maize (see Section 1.5).

14.2 Assessing prospects for increased global grain yields

Section 14.1 refers to increases in on-farm yield—abbreviated throughout this book as farm yield (FY) progress. As outlined in Chapter 2, FY progress depends on two factors:

1. plant breeding and/or new agronomy contributing to progress in potential yield (PY) or water-limited potential yield (PY_w)
2. on-farm adoption of improved crop varieties and/or new agronomy contributing to progress in FY—thereby closing the yield gap between FY and the higher PY (or PY_w). This gap is expressed as a per cent of FY.

Thus FY is PY less yield gap. Also, for growth or relative rates of change (% p.a.), FY change is PY change less change in yield gap, with the closing of yield gap equivalent

76 A 10% increase in area multiplied by a 45% increase in yield delivers a 60% increase in production.

77 Throughout this book yield growth rates are considered to be linear, not compound or exponential as used by many in the past, but are summarised as per cent per annum (% p.a.) relative to the most recent yields available (around 2010 usually).

to a negative rate of change. Importantly this approach assumes that a relative change in PY leads to the same relative rate of change in FY when the technology is fully adopted (see Section 2.2 on measuring progress in FY and PY).

Using a sample of countries and/or regions and targeting key 'breadbaskets', Chapters 3 to 7 presented analyses of measured changes in FY and PY, and calculated yield gap change in key commodities over the past 20–30 years. To assist interpretation of progress, sample yields were grouped (wherever possible) into relatively uniform and crop-specific mega-environments.

While FY progress can be influenced by many factors (such as weather trends, price and policy change, and/or area shifts), this book particularly sought to determine how new technology (breeding and/or agronomic) has influenced PY, and how subsequent adoption of that technology by farmers has contributed to FY progress and closing of yield gaps. The focus has been on the immediate past (20–30 years) as an indicative prediction of future progress towards 2050, and special consideration has been given to any evidence for exhaustion of past technical sources of yield progress.

14.3 The story of crop yield change

Each commodity considered in this book (Chapters 3 to 7) has revealed a somewhat different story.

Looking first at the demand side, continuing growth in demand for wheat is likely to be stronger than that for rice. This likelihood is attributed to recent trends that show that per-capita demand for rice tends to decline as per-capita incomes rise, and it can be expected that this trend will continue (Section 1.2). Growth in demand for both maize and soybean will be even stronger than that for wheat, attributed to the role these crops play in animal feeding and biofuel production, and the importance of soybean as a source of vegetable oil.

In addition, as consumer wealth increases, rapid growth in demand is foreseen in several other crops—sources of vegetable oil (e.g. oil palm, canola and/or sunflower), sugar (e.g. sugarcane), and fruit and vegetables. Oil crops are also in demand for biodiesel, and similarly sugarcane is in demand for ethanol. The growth in demand for higher value crops will to some extent squeeze resources (e.g. land and water) available for the staples.

Wheat yield change summarised

Looking at the supply side, Chapter 3 presented a balanced picture across studied countries for wheat; production is equally divided between developed and developing countries. In summary, and using estimates weighted by area and production of each

wheat mega-environment (WME), world average wheat PY progress over the past 20 years is calculated to be only 0.6% p.a., and the change in yield gap is -0.4% p.a., making FY progress 1% p.a. (Table 3.7). There is no obvious difference in progress between irrigated and rainfed situations, which each comprise about one-half of the world's wheat area.

The average global yield gap across the 12 WMEs is 50% of FY. Compared with the other staple crops, this yield gap is considered to be relatively small; it is not much larger than the minimum gap that would be expected from the economic objectives of farmers (estimated to be ~30% of FY; see Section 2.1). The implication of this small yield gap is that more pressure will be directed towards continued PY progress as the main mechanism by which future wheat FY increases can be achieved.

Despite unabated PY progress in north-western Europe, it is surprising that parts of this region experienced little or no progress in FY (see Section 3.8); this result reflects several factors, including policies that have driven lower use of agricultural chemicals. This result appears to be an exception to general trends in global wheat FY progress. However, wheat is likely to be the first major crop to suffer globally at the expense of higher value food crops, particularly when water shortages reach the major irrigated regions of the developing world (thereby displacing irrigated wheat).

Rice yield change summarised

Rice is almost entirely produced in the developing world (mostly under irrigation) and Chapter 4 revealed greater variability in yield results for rice than seen for wheat in Chapter 3. In summary, the world average rice PY progress, weighted by rice mega-environment (RME), is 0.7% p.a. and the change in yield gap is -0.3% p.a. (Table 4.6), noting that there are fewer solid rice PY progress studies than there are for wheat. The estimated average global rice yield gap is 72% of FY, with many rainfed situations revealing much larger gaps (>100% of FY).

For low latitudes, it is anticipated that future PY will be boosted by rapid development of new tropical rice hybrids, and this PY progress will be followed by a corresponding boost to FY on adoption. However, progress in FY remains constrained in many situations. Agronomic constraints (inadequate soil fertility, pest weeds and diseases, and poor water management) limit FY progress, especially in rainfed areas of Asia. In other areas (e.g. Japan, North-East Thailand), FY is constrained by demand for lower yielding varieties that deliver better eating quality grain.

China is the biggest rice producer (28% of world production), almost entirely of irrigated rice. Rice production is associated with a unique combination of tiny field size, excessive use of agricultural chemicals, constraints to labour, poor agronomic management, and policies to control supply so as not to exceed demand. There is some scope for yield gap closing but more for input efficiency gains. India is the second largest rice producer (21%), but in contrast to China, >40% of the Indian rice area is rainfed; throughout India yield gaps are larger than in China but there is good scope for yield gap closing.

Maize yield change summarised

Chapter 5 reveals that one-half of the world's maize area lies in moist temperate areas of the United States of America (USA), China, Europe and southern South America; these areas exhibit high PY values. Most of the rest of the world's maize area occupies the generally hotter and drier subtropics and tropics of Sub-Saharan Africa where PY_w is more appropriate. USA dominates world production (38%).

Progress in maize appears to be about equal for both PY and PY_w . World average PY progress—weighted by maize mega-environment (MME)—is 0.8% p.a., with higher rates in the non-temperate areas (Table 5.8). With a world average rate of change of -0.7% p.a., maize yield gap closing has been relatively strong in most areas, notably in Brazil, Argentina and the US Corn Belt (Table 5.7). However, the great range in yield gaps across the MMEs implies that little interpretation can be drawn from the global weighted average yield gap of $\sim 100\%$ of FY. Estimated yield gaps varied from a low 36% in Iowa (in the US Corn Belt), widening to 96% in China, and extending to as much as 400% in eastern Africa (Table 5.7).

The yield gap figures present a very clear message that huge scope exists for yield gap closing in all developing world MMEs. Concerted effort for improved farm agronomy (increased fertiliser use, weed and pest control, and conservation agriculture) is the top priority. Also PY progress and yield gap closing in such regions will no doubt be influenced by increasing private sector investment into research and development (R&D) for maize breeding, and the promotion of maize hybrids suited to environments subject to abiotic stress.

Soybean yield change summarised

Chapter 6 revealed that soybean is unique among the 'big four' staples, in that crop area has expanded over the past 20 years (particularly in North and South America) at a rapid rate of 2.6% p.a. (Table 6.1). At the same time, across the three case studies examined, soybean PY has advanced at an average rate of 0.5% p.a. while yield gap changed at -0.8% p.a. (Table 6.2). However, since world average FY increase for soybean is only 1.0% p.a., the rate of yield gap closing has likely been overestimated by the absence of case studies from less progressive soybean regions (e.g. southern China and central India).

On the basis of sampled growing regions (dominated by the Americas, 66% of production), average world soybean yield gap is only 31% of FY (Table 6.2). Similar to the current situation for wheat, this particularly low yield gap suggests that future FY progress will depend on PY progress through breeding gains. It is noteworthy that this situation should have arisen so quickly; the remarkably successful soybean story has been equally driven by breeding and agronomic innovations that have been rapidly adopted by growers. Compared with all other crops, soybean likely exhibits the highest percentage of global crop area planted to genetically engineered (GE) glyphosate-resistant varieties (81%; see Section 9.9 on genetic engineering), and the highest percentage sown under zero-till.

Despite a progressive approach to innovation, lack of diversity in current soybean cropping systems continues to instil risk, particularly from herbicide-resistant weeds (see Section 11.5 on sustainability in modern intensive agriculture) and other biotic stresses. With little apparent new agronomic technology on the horizon, breeders will have to work hard to maintain the current rates of PY (and FY) progress.

Summary of yield change in other crops

The other crops considered in Chapter 7 add further diversity to the global scene. In terms of global dynamics in crop area:

- canola, sugarcane, sunflower and oil palm are expanding rapidly
- cassava is expanding moderately
- pulses are stagnant
- coarse grains (barley, sorghum and millet) are stagnant or declining
- sugar beet is rapidly declining
- potato is shifting from Europe to Asia.

PY progress in some of these crops has been very high over the past 20 years, with rates of 1.4% p.a. in rapeseed (canola) (Section 7.4), 1.6% p.a. in sugar beet (Section 7.6), and 1.3–1.8% p.a. in cassava (Section 7.7). The high rates for rapeseed (canola) and sugar beet have been heavily influenced by development of hybrid varieties and strong involvement from the private sector.

Except for millet in western Africa, little FY progress has been observed in the important coarse grains. With one exception (moderate progress in barley), coarse grain data on PY progress are unavailable, but there has been notable breeding success with the advent and adoption of hybrid millet in India (Section 7.2). PY progress and FY progress for pulses appear to be low (Section 7.3), perhaps because of disease and pest challenges, but there have been some cases of moderate progress such as with cowpea in western Africa and peas and lentils in western Canada. PY progress in sugarcane and sunflower is intermediate (Sections 7.5 and 7.6), while PY progress in potato (at least in the developed world) has been stymied by quality requirements of the market (Section 7.9).

Yield gaps are generally high in pulses in the developing world (>100% of FY), and also in sorghum, millet and cassava; more moderate yield gaps are estimated for the more 'dynamic' crops of oil palm (Section 7.8), rapeseed (canola) and sugarcane. In the case of oil palm and sugarcane, systems for large-scale plantation production have increased the adoption of new technologies and closed yield gaps.

Conclusions on yield change

The overall lesson seems to be that strong PY and FY progress will follow demand and investment—even in crops where area has rapidly expanded—and the above summary of global yield analyses lends itself to two further findings:

1. none of the examined cases showed zero progress in PY or PY_w
2. progress in PY (and PY_w) these days largely reflect efforts from breeders, although PY (and PY_w) growth often builds on positive genotype-by-agronomy interactions.

It must be emphasised that the rates of progress in PY (or PY_w) for all crops considered by this book—except rapeseed (canola), sugar beet and cassava⁷⁸—are well below 1.0% p.a., implying that moderate yield gap closing explains the greater rates of FY progress observed in almost all situations studied. Furthermore, despite the difficulties of breeding for water-limited environments, there is no tendency for the rate of PY_w progress in any crop occupying both types of environments to be less than that for PY, although progress in PY_w is generally lower on an absolute basis (i.e. in terms of kilograms of increase in harvested grain per hectare per year).

Small yield gaps (<30% of FY) indicate situations where future FY progress will entirely depend on further PY increases. These gains will no doubt be derived from breeding, because it is hard to envisage new agronomy to further lift PY or PY_w . It can, however, be expected that there will be incremental changes to existing agronomic technologies, and it cannot be ignored that agronomic innovations have historically surprised forecasters.

In the past, the developing world (particularly Sub-Saharan Africa and parts of South Asia) has failed, for many reasons, to deploy existing modern varieties and agronomy. Large yield gaps for rice, maize and most other crops in these developing regions have thus made the effect of this failure especially apparent. Fortunately, when it comes to tackling global food security, this past failure can now be exploited. Large yield gaps offer 'easy win' opportunities to progress global FY—the task for both science and policy is to facilitate prospects for yield gap closing, as discussed below.

14.4 Prospects for yield gap closing and progress in potential yield, including under climate change

Two routes for achieving FY increase are yield gap closing and either maintaining or preferably increasing the progress rate for PY (and PY_w). At the same time, climate change, especially temperature increase, is seen as a threat to yield prospects, notwithstanding the recognised positive effects of rising levels of carbon dioxide (CO_2) for C_3 crops.

⁷⁸ Another exception may be tropical maize, but the global average PY progress for maize was reduced by temperate maize, which currently dominates the global production.

Yield gap closing

The most assured and rapid way of increasing FY rates of gain will be closing the yield gap to bring FY more in line with current PY levels (Chapter 8). This approach to FY progress will remain especially relevant during the aforementioned critical period of rapid increase in demand over the next 20 years. As mentioned, yield gaps are greatest with rainfed rice in Asia, and maize and cassava in Sub-Saharan Africa, but are also relatively high with irrigated rice, and with pulses and other coarse grains throughout much of the developing world.

Given that a component of yield gap can be explained by poor pest and disease control, breeding for greater tolerance of biotic stress can directly aid yield gap closing. New molecular markers will assist breeding for host-plant resistance, and good prospects exist for delivering novel fungal disease resistance through GE technologies, as has been seen with GE insect and virus resistance. In addition, breeding for abiotic stress tolerance may help with some aspects of agronomic management. For example, breeding for acid soil tolerance could reduce the requirement for liming, and breeding for adaptation to conservation agriculture would encourage farmers to adopt this practice. Of course, breeding specifically for drought tolerance (under the definitions used throughout this book; see Section 2.1), will be a matter of raising PY_w (see below).

Notwithstanding the role for breeding, the most obvious strategy for rapid yield gap closing is to improve the level of agronomic management practised by the millions of smallholder farmers involved in underperforming systems. Clearly, adoption of the latest technology, and consequential yield gap closing, has been a feature of FY progress in the developed world where family farms overwhelmingly dominate production. In addition, through the green revolution (see Section 1.1) and household reforms in China, Asia has shown that under the right conditions, family farms—in this case, smallholdings—can modernise farming practices and commercialise the resultant surpluses with huge benefits for all. In another success story, larger scale (and often corporate) farming has underpinned the FY revolution in Brazil and Argentina—corporate development that is now also unfolding in Eastern Europe and the former Union of Soviet Socialist Republics (USSR). However, this latter approach can be appropriate only where a sparse population of indigenous farmers operates on suitable arable land.

Large yield gaps remaining in parts of Asia, and widespread throughout Sub-Saharan Africa, are associated with smallholder farmer systems. These systems can learn from earlier progress seen with smallholder farmers elsewhere in Asia. However, effective adaptive research, development and extension (RD&E) for these farmers will depend on both a revamping of traditional systems and willingness to embrace new approaches. Also, closing of large yield gaps will not occur without attention to the many off-farm constraints involving rural infrastructure and institutions. This in turn calls for huge investments in areas ranging from rural roads and land tenure, to education and health, and of course, adaptive RD&E—all of which must be supported by a favourable policy environment.

The difficulty is that most components of yield gap closing are necessary—at the agronomic level on the farm, and in the rural economy—and none is sufficient alone. This is why it has proven difficult to drive yield progress in areas that are largely dominated by smallholder farmers who are economically disadvantaged, poorly organised, and experience weak infrastructural and institutional support.

Some strong governments with favourable policies (e.g. Vietnam) have recently shown the way forward. However, if rural infrastructure and institutions are to be upgraded, and RD&E sufficiently revamped to create farm environments conducive to major yield gap closing, there will be no escaping the substantial investments (both public and private; see Section 13.3) that will be required in most of the developing countries that currently show very large yield gaps.

If these investments are forthcoming in affected areas (especially Sub-Saharan Africa), yield gaps could close much more rapidly than has occurred in the immediate past. Then FY rates of gain for the staples could easily double to reach 2–3% p.a. with huge benefits for people on low incomes.

Raising or maintaining progress rates for potential yield

Maintaining, or better, raising, the progress rate for PY (and PY_w) is the second route for FY increase. Nowadays this is largely a question of plant breeding, as agronomic interventions for raising PY are not obvious, although several possibilities deserve more research attention (see Section 9.7 on new agronomy).

Where small yield gaps exist—for example, in developed countries where agronomic management is nearly optimal—breeding is increasingly becoming the main route for FY progress. Improved varieties are usually, and relatively quickly, adopted by commercial farming to directly benefit FY. Unfortunately, modest recent rates of PY progress suggest that breeding for higher yield is becoming increasingly difficult. Furthermore, success with new varieties in commercial farming should not overshadow the institutional problems in seed systems that remain to be overcome in many developing countries.

From a crop physiological perspective, PY is fully determined by the product of three components:

1. cumulative interception of photosynthetically active radiation (PAR)
2. radiation use efficiency (RUE)
3. harvest index (HI).

Section 2.6 provides definitions and further detail on these and other crop physiology terms used below.

Some scope appears to remain for improvement in each component, although there are firm limits to PAR_i and HI, which considered alone constrain prospects for further gains in PY to $\sim 20\%$. However, RUE—a measure linked largely to maximum leaf photosynthesis (P_{max})—offers more scope for future PY increase. Past breeding has modestly improved RUE (Section 9.4), but known genetic variation in P_{max} needs to be better understood and therefore exploited. However, because of the complex genetic control of traits affiliated with P_{max} (see Section 9.4 on increasing RUE), it appears unlikely that GE technology will be able to raise RUE by improved P_{max} inside 20 years or more.

In the water-limited environment, breeding for greater PY_w faces many of the same problems as breeding for PY. However, there is some evidence of higher relative rates of progress (e.g. in maize; Section 5.4), and more opportunities to sustain that progress given the apparent sensitivity of reproductive processes to water stress (Section 9.6 on physiological components of PY_w).

Just as PY is determined by three components, PY_w is determined by three components, one of which (harvest index) is shared in common with determinants of PY. It is no surprise that the other two components of yield determination in the water-limited environment relate to water. Thus PY_w is fully determined by the product of three components:

1. water transpired by the crop
2. crop transpiration efficiency (TE)
3. harvest index (HI).

Crop transpiration is ultimately limited by water supply, which (in rainfed situations) is largely controlled by soil type, rainfall and crop rooting depth, but considerable scope remains for improved agronomy to lift the proportion of the total water supply that is transpired. TE is dominated by the prevailing vapour pressure deficit, yet there remains some genetic variation with which breeders can work, and sometimes traits for greater TE appear without negative trade-offs (like reduced P_{max} and/or lower growth rate). As previously mentioned as a goal for increased PY, TE could also benefit from improved P_{max} .

There is also more scope to lift HI under water-limited conditions. HI under drought is often well below the genetic maximum due to the sensitivity to water shortage of seed number determination. Considerable natural genetic variation has also been observed in this trait (Section 9.6). However, breeding for reduced sensitivity to water stress has been complicated by environmental interactions related to variation in the timing and degree of water shortage. Such interactions are dominated by unpredictable annual weather variation, but improved measurement and simulation modelling is enabling breeders to better quantify these environmental effects.

Just as with determination of PY, there are indications that the complexity of genetic determination of PY_w is too great, and the present state of knowledge too limited, for

GE technology to offer a route to future improvements. However, brighter prospects for breeding for both PY and PY_w should be found among the extensive and largely untapped genetic variation in landraces and close (and distant) wild relatives of modern crop varieties.

Molecular techniques (such as genomic selection) will facilitate the search for new genetic variation and will independently speed rates of conventional breeding progress. Even within modern breeding gene pools, these molecular techniques are better able to access the remarkable level of as-yet unexploited genetic diversity and gene recombination. Some anticipate that these breeding techniques will sustain increased rates of PY progress, but it is too early yet to predict the longevity of this outcome (see Box 9.1 on genomic selection).

By definition, PY and PY_w are measured in the absence of biotic stresses, but the incorporation of adequate host-plant resistance consumes a large proportion of all breeding resources. As mentioned in the subsection on yield gap closing, above, new techniques for breeding resistance—such as molecular markers and likely new transgenes (especially targeting fungal diseases)—present the possibility of efficiency gains in resistance breeding, which will free up resources for more attention to increase PY.

As with conventional breeding, large-scale and accurate phenotyping (trait and yield measurement) remains a critically important part of new molecular approaches to breeding; phenotyping is now used to predict breeding decisions through marker–trait associations. Development of remote-sensing techniques promises to further accelerate phenotyping throughput. Furthermore, there are advantages of scale in applying new breeding techniques that the private sector has been quick to embrace. This fact and the rise of hybrids and plant variety protection have facilitated a rapid privatisation of crop breeding in developed countries and more recently in developing countries (see Section 9.11 on intellectual property).

Privatised crop breeding is a positive development that encourages greater investment into breeding and promotion of improved varieties. However, it remains vulnerable to monopolistic practices and inefficiencies (such as high transactional costs, limited knowledge sharing, and possible underinvestment in any long-lasting host-plant pest resistance that cannot be patented). Furthermore, private breeding continues to depend heavily on underpinning strategic public sector research, and it avoids unprofitable breeding of many smaller ‘orphan’ crops (which consequently demand public sector support).

In the case of both PY and PY_w progress, one-off yield gains of 10–20% have been achieved from hybrid vigour effects in maize, rapeseed (canola), millet, and temperate and tropical rice—the last-mentioned is now spreading into South and South–East Asia (Section 9.8 on hybrid vigour). Other crops could achieve similar results if such exploitation of hybrid vigour were expanded. Wheat is the next target. There is a reasonable likelihood that viable hybrid wheat systems can be attained within the next decade (see Section 3.7 on wheat in China and Section 9.8).

Taking all these developments together, it seems likely (and fortunate) that private sector investments into crop breeding will continue to increase. However, a critical ongoing, more strategic and 'gap filling' role will remain for the public sector. Judging from recent signs (Section 13.2 on R&D investment), public investment should grow from the lows observed a decade ago provided world economic growth returns to 'normal'. Building an efficient interface between public and private research investments in breeding in particular remains a challenge as various public–private models are tried. However, both these private and public developments should be sufficient to maintain current rates of PY and PY_w progress for the next several decades. Unfortunately, given large lag times—generally more than 20 years from breeding investment to peak adoption (see Section 12.4 on case studies)—it may prove difficult to boost the rate of PY progress now, when it is needed most.

Climate change

Chapter 10 described how rising levels of CO₂ and associated global warming⁷⁹ will exert opposing effects on the yields of C₃ crops like wheat, rice and soybean. The balancing effect is such that, out to 2050 and without adaptation, the likely outcome from these environmental changes will be limited to small (<5%) net global effects on PY and FY (see Section 10.3 on direct measurements and crop modelling). However, under the same terms, C₄ grain crops (like maize), which gain much less benefit from increased CO₂, may suffer up to 10% yield loss, other things equal. Furthermore, negative yield effects in some currently warmer locations (i.e. South Asia for wheat and Sub-Saharan Africa for maize) are likely to be larger than elsewhere and associated with more frequent hot spells (1–2 days of extreme heat).

In contrast to projected changes in CO₂ and temperature, projected shifts in rainfall patterns are considered to be very uncertain in most regions. Thus, given that different climate change predictions include either increase or decrease in rainfall (Section 10.1 and Section 10.2 on time series and climate change), the possible effects on global yields from change in rainfall to 2050 are considered to be small.

In all crops examined, considerable scope exists for both agronomic and genetic adaptation to a slowly warming climate; CO₂ rise will benefit yield, and opportunities exist to adapt agronomy to changing rainfall patterns. Thus, the priority for climate change research should be pre-emptive targeting of improved genetic tolerance to chronic warming and increasingly frequent hot spells, plus a search for photosynthetic adaptation to higher CO₂. However, most other research investments related to climate change adaptation would be better directed towards the 'normal' agricultural R&D agenda, rather than into specialised research under the climate change banner.

79 This book considers a CO₂ rise of 26% (100 ppm) and warming of 2 °C from 2000 to 2050.

14.5 Socioeconomic and policy perspectives

Chapter 12 demonstrated that intensification of cropping produced steady increases in total factor productivity (TFP), particularly over the past 30 years. Reduced real cost of food has been driven by growth not so much in yield as in TFP, which in turn depends on two critical activities:

1. researchers pushing out the technological frontier—the product of R&D
2. farmers adopting more inputs and particularly becoming more efficient with those inputs to more closely approach the shifting technological frontier—the product of farmer skill, extension and incentives.

There is little evidence that TFP growth is slowing anywhere, although it is possibly slowing for cereals in the developed world and for several crops in India (see Section 12.4 on case studies). TFP is growing strongly in China and Brazil, but growth in Sub-Saharan Africa remains dismal as renewed growth in agricultural output over the past decade has been achieved largely through land area expansion (rather than yield gain).

Chapter 12 argues that changes in TFP have been strongly related to changes in R&D investment, as a comparison across developing countries reveals, but the latest estimates suggest a time lag of ~24 years for peak impact. Thus, evident situations of slowing growth in TFP (e.g. USA and Australia; see Section 12.4) may be related to slowing growth in public investment in agricultural R&D over the past 25 years. Reduced public investment may be partly compensated by the recent increase in private sector investment that is dominated by a handful of multinational crop life and machinery companies (Section 13.2). However, substantial shifts in R&D to the private sector are largely limited to developed countries.

In developing countries, public R&D remains inadequate, although there have been exceptions with notably greater investments in China, India and especially Brazil (see Section 13.2). Unfortunately, even in these leading examples for developing countries, public investment remains barely adequate compared with developed countries. Private agribusiness investment in developing countries is beginning to unfold, especially in the area of breeding and seeds.

Questions arise as to whether the current level of R&D investment is adequate to drive further sustainable intensification of cropping and TFP growth as will be needed to feed the world in 2050. This theme underpins this book. Judging from past intensities of public R&D investment (see Table 13.1), the answer is an emphatic ‘no’. Successful agriculture sectors in developed countries currently spend ~3.0% of agricultural gross domestic product (GDP) on R&D—this figure is termed ‘research intensity’. In contrast, the low levels of spending in developing countries (currently totalling about US\$15 billion annually) amount to an average research intensity of only ~0.5%. The effect of this low figure is exacerbated by efficiency weaknesses in R&D in many countries.

However, two factors suggest that developing countries may not require the level of R&D spending that has previously driven success in developed countries. First is the obvious spill-in of research results from developed to developing countries, but this is largely limited to strategic research. Second is the opportunity to improve efficiency in the RD&E system through smarter approaches and public–private partnerships and other collaborations at both regional and global scales (see Section 13.2). Even so, when looking at the current low research intensities in developing countries, substantial increases in investment seem warranted. In fact, a full doubling of investment in developing countries would lift research intensity to only ~1%, a figure that is less than one-half of the rates sustained by developed countries for decades.

FAO has argued for an annual increase of at least US\$6 billion (in 2005 PPP US\$)⁸⁰ in public RD&E expenditure in developing countries (see Section 13.2). In addition, it is critical—and fortunately, it seems likely—that the private sector will move to fill some of the gap in research investment in developing countries, just as has been done in developed countries. At the same time, public RD&E must streamline the delivery of innovation to farmers, in order to maximise the impact on farm practices. This pursuit should include efforts towards capacity building, as has been well provided in developed countries by the public sector over the past century (during which agriculture modernised).

Apart from RD&E, other essential rural investments needed by developing countries remain very difficult to estimate. In order to eliminate hunger by 2050, FAO recommended that annual domestic public investment into rural infrastructure and institutions should be increased by about US\$45 billion (in 2005 PPP US\$), a figure equivalent to at least doubling of current rates of investment (see Section 13.3). Unfortunately, movement towards this investment goal—and towards the aforementioned target for RD&E investment—has been slow in those countries that are most in need (such as in countries of Sub-Saharan Africa).

Finally, to deliver world food security, comparative advantages and trade opportunities will need to be exploited (as far as possible) to increase crop yields. Although the developed world dominates cereal exports, a number of middle-income countries—in South America, Eastern Europe, the former USSR and South-East Asia—are increasing in importance as exporters, especially for wheat, rice, maize and oilseeds. The role for these countries is likely to grow as their relatively high yield gaps are closed, and as more land is brought into production in some cases.

However, even with wise use of trade opportunities, much of the focus on yield gap closing will need to be directed towards domestic production by economically disadvantaged developing countries, which do not have the means (or the infrastructure) to rely on imported food. This is a common situation in Africa, where countries exhibit huge potential for intensification of agriculture to raise incomes of smallholder farmers, reduce poverty and increase food security.

80 Purchasing power parity (PPP) is an exchange rate based on the equivalent purchasing power between two countries. It is published by the World Bank and the International Monetary Fund (IMF) and is approximately equivalent to 2005 US\$.

14.6 Resource use efficiency, sustainability and environmental effects

Evidence presented in this book suggests that cropping intensification, meaning more physical as well as managerial inputs, is feasible for meeting growing demands to 2050, and is the best way to minimise expansion in cropland. In much of the developed world and in East Asia, the main focus of intensification should be on more efficiently using existing inputs, and in some cases (like much of China) reducing excessive input levels. However, in many other situations that exhibit significant yield gaps, intensification generally (although not always) relies on greater use of physical inputs.

The important point, developed in Sections 11.1 to 11.4 on resource use efficiency, is that productivity (output per unit input) generally increases with intensification of agriculture, provided that modern management practices and modern crop varieties are used. This rule seems to apply for all major inputs (water, nitrogen, phosphorus and energy) assuming that farmers have the means, skills and incentives to avoid supply in excess of crop demand. Through greater dry matter production and higher HI, modern varieties have been developed to be more input efficient. Also, inputs are generally used more efficiently when supplied together to the crop at close to optimal levels. While modern agronomy has developed ways of achieving this optimum (e.g. site-specific nutrient management), there is scope for more progress in the efficient supply of inputs.

The most challenging input efficiency issue is probably management of nitrogen. Substantial losses of nitrogen occur through denitrification and leaching of nitrate in humid environments, particularly where optimal crop yield is targeted and when water input cannot be controlled or anticipated (as in much rainfed farming). Biological nitrogen fixation (e.g. rotation with legumes used as green manure) cannot generally be relied on to reduce the risk of nitrogen loss, and it carries a large opportunity cost in terms of land area needed to replace reliance on fertiliser nitrogen. Much more research is needed and the solution will undoubtedly call for greater farmer skills (and care) than is currently common. Regulation and higher world nitrogen fertiliser costs (which are closely associated with energy prices) may eventually drive improvements in nitrogen use efficiency (NUE), but will also increase food costs.

As with nitrogen, management of biocides—another vital chemical input for intensive cropping—is environmentally risky and demands skill. However, host-plant resistance (including that attained through GE) offers potential to gradually reduce the need for biocides, as has already been seen with GE pest resistance. Integrated management of pests, diseases and weeds uses all available tools in a critical effort to avoid biocide resistance evolving in target organisms. Integrated management is probably the most complex task faced by agronomists and modern farmers, and the challenge is currently exemplified by the upsurge in glyphosate-resistant weeds.

Maintaining the long-term productivity of the soil and water resources, and the related biodiversity (both agrobiodiversity and native remnant biodiversity) are the principles of sustainable farming (see Section 11.5). The key soil issues involve its physical, chemical and biological status. Reduced tillage, and in particular conservation agriculture (zero-till, crop residue retention and/or crop rotation) provide a proven approach to sustainable farming. However, these practices must be accompanied by special activities that build soil fertility where it has been seriously depleted; thereafter nutrients need only be added to balance those removed in harvested produce.

Soil chemical fertility balance can be achieved through good management, but more understanding is needed to optimise biological fertility, and to avoid soil compaction from modern machinery in situations prone to such damage. Organic agriculture cannot achieve the soil nutrient balance on the scale needed to feed the world (Box 11.2). It relies on an ample supply of nutrients from nearby sources, and those nutrients that arrive in the form of manure come at the cost of nutrient depletion wherever the animal feed is grown. As with conventional farming, incorporating legumes can close the balance for nitrogen in organic agriculture, but as always, the extra land requirement is a heavy opportunity cost.

The issue of water sustainability in irrigated cropping relates to working within the sustainable water yield of aquifers and other water supply systems. Serious aquifer depletion has occurred, and is continuing, particularly in the north-western Indo-Gangetic Plain of India and Pakistan, the North China Plain and parts of the Great Plains of the USA (see Section 11.5 on sustainability in modern agriculture). Cropping system changes are inevitable in these currently highly productive systems, and yield and production are likely to fall when pumping depths become excessive. However, in canal systems there is good scope for better management and infrastructure to improve the quantity of water delivered to fields relative to that extracted from rivers.

Sustainable biodiversity in cropping refers to the available genetic diversity of the world's crops and especially as to how this diversity is deployed in time and space across cropping landscapes (Section 11.5). For the staples, and most minor crops, the genetic diversity is now largely conserved in gene banks. Moreover, the definite need to better evaluate and use these genetic resources in breeding can be aided by new genotyping tools.

Monoculture (i.e. the growing of a single uniform crop at any one time) dominates in modern agriculture, and this is likely to remain the case for practical reasons despite popular but ill-informed criticism. Crop diversity in a given landscape, however, remains important (Section 11.5). Continuous monoculture heightens risks from soil-borne biotic stress agents, but risks can be somewhat reduced if crops are separated by severe winters or long dry seasons, or—as in the case of the widespread continuous flooded rice at lower latitudes—by short intervals of soil drying. However, even in the binary crop rotations that appear widespread in modern agriculture (e.g. maize–soybean and rice–wheat), soil-borne biotic stress risks persist.

Hence it seems desirable to introduce more crop variety in many systems, even to the extent that pastures, fodder production and/or grazing animals may form part of the sequence. Introducing new crops is possible, but it requires markets and (in most cases) substantial R&D effort starting in the public sector. Linked aspects of cropping diversity are the spatial distribution and scale of crops in a landscape at any one time. Modern cropping, with its dependence on large machines and fields, limits diversity in this respect, but the extra risk this entails remains unclear.

Countering the above risks from poor diversity in time, space and scale, the most important measure of crop biodiversity is derived from the number and nature of host-plant resistant genes found in the varieties of the crops grown, and in how crop management protects this genetic defence (Section 11.5). Such harnessing of genetic diversity has generally been very effective and constitutes the foundation of most of the integrated disease and pest management systems that modern agriculture will need to embrace. Breeders are probably slowly gaining ground with host-plant resistance diversity, but there is concern that the strong incentives that drove publicly funded breeding to deliver host-plant resistance are weaker in the private sector, especially if ownership of such traits cannot be protected.

Off-site environmental effects from cropping intensification often form the target of criticism relating to environmental pollution (Section 11.6). Pollutants include:

- emissions of greenhouse gases, such as:
 - CO₂ from consumed fossil fuel energy and net losses from the soil
 - nitrous oxide (N₂O) from highly fertile soils and/or nitrogen fertiliser application
 - methane (CH₄) from irrigated rice
- leached chemicals and nutrients (biocides, nitrate and sometime phosphorus)
- smoke from burnt crop residues.

As mentioned, product per unit energy consumed generally improves in 'best-practice' farming. Also pollution risk can be noticeably reduced when overuse of inputs and misuse of biocides are avoided. As applies with standards for best practice in advanced nations, better management of inputs can be achieved through better regulation and (preferably formalised) training of farmers and machinery operators.

Continuing (and particularly challenging) objectives for crop researchers and managers will be to reduce the two most potent greenhouse gases emitted by cropping, N₂O and CH₄ (Section 10.5). N₂O emissions are fortunately reduced by the same best management practices that improve the efficiency of nitrogen fertiliser use. Scope for more widespread application of best practices is large, and scope for further gains by improving these practices is also evident.

Carbon sequestration in untilled soils offers a potential counterbalance to greenhouse gas emissions, but has its own substantial costs in other nutrients sequestered along with carbon. Importantly, emissions from modern cropping pale into insignificance when

compared with the emissions caused by the clearing of new land (especially forest) for cropping—such clearing can be largely avoided through increased crop yields (along with better regulation).

Modern cropping, with its large cleared fields, is also often criticised for the inevitable reduction in indigenous biodiversity. There is limited scope to counter this effect in existing croplands under commercial farming. The solution is to minimise new clearing for cropping, but where clearing must happen, greater attention should be given to sensitive areas, and appropriate buffers and corridors should be left uncleared (for example, as required by regulations governing the Brazilian Cerrado). Sensitive clearing will often require enforcement of generally stronger regulations and better governance of currently unfarmed lands than has been the case in much of the world, both developing and developed.

14.7 Overall conclusion

Notwithstanding considerable uncertainty, this book has collected evidence that supports the notion that FY progress of 1.1% p.a. (relative to 2010 yield) is the minimum needed to feed the world in 2050 at real prices close to those in 2010 and not too far above the 2000–06 record low prices.

However, Section 1.5 presents an argument to aim for an even higher rate of yield progress to better protect against unanticipated shocks that (although individually improbable) are likely to disadvantage people of lower socioeconomic status through food prices rises (especially price spikes). Clearly, a higher target for yield progress would accommodate greater demand pressure and allow for the unanticipated negative effects. For these reasons, this book concludes that the target for FY progress should be set closer to 1.3% p.a.

Across the major crops, the average rate of current FY progress is ~1.0% p.a., and rates have been falling. However, depressed rates of progress are not due to biological limits in the system. At least in some cases, rates of yield improvement have been reduced by product quality considerations (e.g. rice in Japan), by policies on input use (e.g. wheat in western Europe) and by surplus avoidance (e.g. wheat and rice in China). Although slowing of yield progress in some situations (e.g. western Europe) is derived from pro-environmental regulation, these cases do not appear to reflect the beginning of a global phenomenon.

About one-half of current FY increases are achieved through progress in PY (and PY_w); the other one-half occurs through yield gap closing. In terms of PY, it has always been difficult to foresee new agronomy, and future prospects for PY improvement through this avenue appear less evident than ever. Rather, the expectation is that future PY progress will be derived more through breeding gains.

Conventional breeding is continuing to deliver improvements in PY, although at an increasing cost per unit gain. However, in contrast to its long-heralded power, there is little evidence that modern biotechnology, including GE, has yet significantly directly influenced PY progress (but it has had other benefits for breeding and has indirectly helped yields such as through pest resistance). However, genome-wide applications of marker-assisted selection can be expected to improve PY progress in the near future. In summary, new breeding technologies may assist the progress of PY to increase a little from the current rates of 0.5–0.8% p.a. in staple crops; however, it appears unlikely that PY progress will reach 1.0% p.a. despite untapped genetic resources.

The greatest opportunity for boosting FY lies in the hastening of yield gap closing. Assuming the appropriate mechanisms of support are in place, yield gap closing can relatively easily accelerate FY progress because this channel uses existing technology, rather than (as for PY) creating a need to discover and develop new technology. Importantly, developing countries (especially in Asia and Sub-Saharan Africa) offer significant opportunities to close large yield gaps; doing so will benefit the world's developing nations and its most economically disadvantaged people. Finally, despite generally smaller yield gaps in developed countries, some opportunities still exist for gap-closing technology and improved farmer skill to make gains in this domain.

The way forward on yield gap closing is relatively clear, but in the developing world large investments are required in infrastructure, institutions, RD&E and training. While the role for the public sector (especially with respect to proper policy) remains undisputed, there is a critical and increasing role for the private sector in sourcing and managing the needed capital. This role could prove difficult in the present global economic climate, but sustained higher food commodity prices can be a strong incentive, as has already been seen since 2008 (see Section 13.2 on R&D investment). Unfortunately, increased participation from the private sector will not help the resource-poor consumer, including subsistence farmers, in the short term. Thus the world should be prepared to accept targeted food safety nets while waiting for global cropping systems to modernise.

In conclusion, no calamity is foreseen—but there is no room for complacency, especially of the kind invoked by some advocates of biotechnology. Multidisciplinary agricultural science remains the key to success. With complementary investment in infrastructure and institutions, and relative freedom from civil unrest, the world should manage to sufficiently feed its growing population. The solution to the food security challenge can never be ideal—some level of environmental cost is always unavoidable—but the pursuit of 'perfect' should not discourage or deter effort from those outcomes that are scientifically feasible, pragmatic and broadly accepted by an informed society.



Special recognition and acknowledgments

This book has benefited from many generous contributions to bring it to publication, and we acknowledge these people, their persistence and their skill, later in this section. However, well before this came the inputs from some outstanding thinkers and activists, each of whom mentored one or more of us, the authors, through the early stages of our careers. We first offer these pioneers special recognition.

Special recognition

It has been difficult to limit our special recognition to the short list below, but we are confident that many of our colleagues, past and present, will join us in expressing our gratitude to the following scientists to whom we, the authors, personally owe a great deal. Global agricultural science has advanced on the strengths of these outstanding colleagues, and as a result of their enduring efforts, opportunities have emerged for the world to one day achieve food security for all.



Norman Borlaug (1914–2009)

Wheat breeder and advocate for agricultural development

International Maize and Wheat Improvement Center (CIMMYT), Mexico City, Mexico

A United States citizen, Dr Norman Borlaug was a wheat breeder in Mexico from 1945 supported by the Rockefeller Foundation. The wheat varieties he developed, complemented by his efforts in training young scientists and advocating sensible wheat policies, revolutionised wheat production, first in Mexico (see Section 3.2), and then in South Asia and elsewhere as the green revolution unfolded in the mid 1960s. In 1970 he was awarded the Nobel Peace Prize for his efforts in combating hunger. A recent and engaging biography covers the inspiring story of this great agricultural scientist (Vietmeyer 2011).

Norm Borlaug led the Wheat Program at CIMMYT, Mexico, from its inception in 1966. In 1970, the first author of this book (Fischer) joined CIMMYT and developed his career in physiology and agronomy under Borlaug's leadership. He was among the many whom Borlaug inspired through his dedication, work ethic and commitment to delivering improved varieties to farmers.

Later Edmeades and Byerlee joined CIMMYT, where, as an emeritus scientist, Norm Borlaug continued to share with all comers his experience and wisdom in many fields of development, especially crop agronomy and rural policy. He was always a strong advocate of agricultural science and development, and openly expressed concern for the complacency generated by the success of the green revolution, and for the general ignorance of agriculture that had arisen with food abundance in increasingly urbanised, wealthy countries.



Kees (C.T.) de Wit (1924–93)

Crop ecologist

Wageningen University, Wageningen, The Netherlands

Professor C.T. de Wit was a giant in European crop science. He contributed substantial knowledge to the areas of interplant competition, agricultural resource use planning and efficiency, and (especially) to simulation modelling of crop growth and yield, with a focus on useful impact. Professor de Wit led the Wageningen University Department of Theoretical Production Ecology, which through training and the travel of its staff significantly influenced advances in agriculture around the world, but especially in developing countries.

One of us (Fischer) first met Professor de Wit in the early 1970s at a failed attempt to attract interest in crop modelling organised by the Food and Agriculture Organization. Professor de Wit was adept at uncovering the simple limiting functions driving crops, and the originality of his observations never ceased to stimulate. For example, when the scientific world was enthralled by energy balances in agriculture in the mid 1970s, from his Dutch perspective Professor de Wit simply asked, 'Who wants to burn roses?'. His visit to CIMMYT in the early 1990s as part of the Technical Advisory Committee (TAC) of CGIAR (then known as the Consultative Group on International Agricultural Research) was equally iconoclastic.



Colin Donald (1910–85)

Agronomist and crop physiologist

Waite Agricultural Research Institute, Adelaide, Australia

Professor Colin Donald is recognised as one of the outstanding Australian agronomists of the 20th century. His research achievements in south-eastern Australia ranged broadly from soils to pastures and on to crops, embracing disciplines of genetics, plant nutrition, physiology and ecology. In 1951 he led Australia's first plant collecting mission to the Mediterranean. Located at the University of Adelaide from 1954, for more than 25 years Professor Donald was an outstanding teacher (Byerlee was one early student), and mentor (for Fischer). Professor Donald was always concerned with the big picture of sustainable agricultural development in Australia and nearby South-East Asia. His elucidation of the basis for wheat yield change in Australia was hugely influential (and finds its way into this book; see Figure 3.4), as were his original ideas on intraspecific competition in crop stands and the physiology of yield improvement, concepts that also often appear here and were the cause of endless debate between one of us (Fischer) and breeders at CIMMYT. His most influential concept, that of the minimally competitive crop ideotype, was embraced by rice breeders at IRRI (see Section 4.2), but was also serendipitously realised by maize breeders in the USA (see Section 5.2).



Don Duvick (1924–2006)

Maize breeder

Pioneer Hi-Bred International, Johnson, Iowa, USA

Dr Don Duvick, as a maize breeder and as Vice President for Research at Pioneer Hi-Bred International, left his mark on an array of hybrids produced by that company and marketed from 1960 to 2000. He emphasised the need for stress tolerance, focusing particularly on the stresses of increased plant density. During his tenure at Pioneer and after his retirement, Don almost singlehandedly led the choice and systematic evaluation of a time series of vintage hybrids, baptised the ERA set, under an array of environmental challenges. He published these results in several classic papers that highlighted the striking changes in stress tolerance that occurred in the US Corn Belt germplasm. We authors met Don for the first time in the early 1990s when he was a member of CIMMYT's Board of Trustees. He was a quiet and thoughtful supporter of research that one of us (Edmeades) was leading on improving

the tolerance to drought and low soil nitrogen status—two stresses that affect maize throughout the developing world. Later when Edmeades joined Pioneer after Don had retired, Don generously provided advice on evaluating the ERA set under drought, and was always available to discuss these hybrids from the 1930s through to the 1990s, or to discuss potential yield. His broad interest in germplasm and how it could be manipulated to create stable high-yielding varieties spanned both temperate and tropical environments. All benefited from his practical scholarship and thoughtful insights.



Carl Eicher (1930–)

Agricultural economist

Michigan State University, East Lansing, Michigan, USA

Carl Eicher has been a tireless advocate for over 50 years on the importance of investing in agricultural research and higher education in Sub-Saharan Africa. After gaining a PhD in economics from Harvard University in 1961, he returned to his native Michigan, where he remained a faculty member of the Department of Agricultural, Food and Resource Economics at Michigan State University until retiring as Distinguished University Professor Emeritus in 2000. Carl's passion has been training students, building institutions and developing applied agricultural research capacity throughout Sub-Saharan Africa. He has been a life-long mentor to Byerlee, who joined Michigan State as an assistant professor in 1971, and to dozens of young agricultural economists, mostly from Africa.

Carl was a leading scholar of African agricultural development long before it became fashionable. The book 'Agricultural development in the third world', which he edited with John Staatz, was a standard textbook for many years. Co-authored with Doyle Baker, Carl's 1982 report 'Research on agricultural development in Sub-Saharan Africa: a critical survey' has been widely cited. His publications 'Institutions and the African farmer' and 'Africa's emerging maize revolution' (co-edited with Byerlee) have been influential in stressing the importance of agricultural research, extension and education in Africa.



Lloyd Evans (1927–)

Plant and crop physiologist

CSIRO Plant Industry, Canberra, Australia

Dr Lloyd Evans was at CSIRO for almost 50 years. His first achievement was to plan and oversee construction of the Ceres Phytotron, an artificially controlled environment facility, which in 2013 celebrated 50 years of helping unravel the influence of environment on plant and crop growth and development. He led the Division of Plant Industry, became President of the Australian Academy of Science and Fellow of the Royal Society, and for many years was active on the Technical Advisory Committee of CGIAR (along with C.T. de Wit). His research publications and book on crop science (Evans 1993) reflect the breadth and depth of his interest in and understanding of the subject. His publications culminated in a delightful celebration of the history of innovation in agriculture, 'Feeding the ten billion' (Evans 1998), published on the 200th anniversary of the gloomy essay of Thomas Malthus on world population and food supply. Lloyd was strongly supportive of the early physiology research at CIMMYT, including the efforts of one of us (Fischer) in wheat, and at the International Rice Research Institute (IRRI). He served on the Board of Trustees of both centres, and his comments as a Board member of CIMMYT between 1990 and 1995 were at the time eagerly anticipated by all of us.



Bob Loomis (1928–)

Crop physiologist

University of California, Davis, California, USA

Bob Loomis is an Emeritus Professor in the Department of Plant and Environmental Science at the University of California, Davis, where he was a professor for over 40 years. He became a leading US crop physiologist, with research publications on sugar beet, maize, potato and alfalfa. His interests ranged from plant hormone activity, to plant carbon, nitrogen, water and energy balances, to crop modelling, and finally to agricultural systems and their history and current importance. With these broad interests and his enthusiasm, he was a powerful stimulus for many graduate students, including two of the authors of this book (Edmeades and Fischer) for whom he was the first such crop physiologist encountered 'in the flesh'. His thinking on limits to potential yield, and ground-breaking work on canopy architecture in the late 1960s, strongly influenced the thinking of maize physiologists and breeders. The text 'Crop ecology:

productivity and management in agricultural systems', which he co-authored with David Connor in 1992 (and which was later revised, adding Ken Cassman to the team; Connor et al. 2011), has been an essential 'go to' reference for the past two decades. Bob's graduate students have provided a continuing legacy of innovative thinking in crop and stress physiology.



Vernon Ruttan (1924–2008)

Agricultural economist

University of Minnesota, St Paul, Minnesota, USA

Vern Ruttan was for decades the leading light in agricultural research and technical change both in the USA and globally. He spent most of his career at the University of Minnesota, becoming Regents Professor in the Departments of Economics and Applied Economics in 1986. As a 'farm boy', Vern always had his feet firmly on the ground and, as an economist, he had a strong ability to communicate with agricultural scientists. He was the first social scientist posted to the CGIAR system, occupying this post in IRRI from 1963 to 1965, and paving the way for the hundreds of social scientists in the system.

After IRRI, he continued to contribute to the system as a member of the Technical Advisory Committee and of several Center Boards of Trustees. Ruttan's paper, 'The green revolution: seven generalizations', published in the *International Development Review* in 1977, arose from his early encounter with Asia and is still a standard reference.

But his most influential contribution was the book co-authored with Yujiro Hayami, 'Agricultural development: an international perspective', first published in 1971. In this book it is argued that technical and institutional change is induced through responses of scientists to relative resource endowments, helping to explain the contrasting US, European and Asian experiences in agricultural development. Another highly influential book, 'Agricultural research policy', published in 1982, provides a commonsense guide to not only the importance of investing in research but also institutional and managerial arrangements for improving the efficiency and effectiveness of those investments. Always humble, even in greatness, Vern was a mentor to hundreds, including Byerlee who spent a sabbatical leave at the University of Minnesota in 1986 synthesising his thoughts on maintaining the momentum in post – green revolution agriculture.



Dr M.S. Swaminathan (1925–)

Wheat breeder and statesman

M S Swaminathan Research Foundation, Chennai, India

Dr Swaminathan was a plant breeder working on wheat and other crops at the Indian Agricultural Research Institute when the Mexican semi-dwarf wheats first reached India in 1963–64 season. He was quick to see their potential and, against much conventional wisdom and opposition from local scientists, moved without delay to promote their widespread testing and use. In this task he worked closely with Norman Borlaug; both were fully committed to a vision of hunger banished by agricultural science. M.S., as he is fondly known, was equally supportive of the new semi-dwarf rices from IRRI, and in time became known as the 'Father of the green revolution in India'. From 1970 to 1980 when he was Director-General of the Indian Council of Agricultural Research, Indian wheat production increased 60% (and rice production 27%). He inspired the gathered CIMMYT wheat staff, including Fischer, when he spoke on these issues at a seminar in north-west Mexico in 1971.

With his concern for the smallholder farmer, especially the smallholder woman farmer, and his vision for what new technology can bring when properly used, M.S. has continued to lead and inspire people in agriculture. This he achieved as Director-General at the International Rice Research Institute (IRRI) in the 1980s, and subsequently in key roles in the plant genetic resource and intellectual property debates in India and internationally. But, true to his origins, it is his commitment to the small rural village communities of the world that endures and which encourages and inspires all who know of him.



Derek Tribe (1926–2003)

Animal scientist and research advocate

University of Melbourne, Melbourne, Australia

Professor Derek Tribe taught one of us (Fischer) animal science in the Faculty of Agriculture at the University of Melbourne. From that early contact, Derek's concern about world hunger and the role of agriculture science in increasing food production was clearly evident and infectious. He was later heavily involved with setting up the International Laboratory for Research on Animal Diseases (ILRAD) in Addis Ababa, Ethiopia, subsequently to become part of the International Livestock Research Institute

(ILRI). He went on to champion the cause of international agricultural research in Australia, helping set up in 1982 the Australian Centre for International Agricultural Research (ACIAR), and in 1987, the Crawford Fund. His 1991 book 'Doing well by doing good: agricultural research feeding and greening the world', was part of his advocacy and the thesis contained in its title continues to drive the public awareness efforts of the Crawford Fund. The rise in Australian expenditure on international agricultural research in the past 30 years is in no small part due to Derek's pioneering efforts.

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Many scientists were consulted when preparing the book and we are most appreciative of their quick responses to our often-repeated queries, and for providing sometimes unpublished data. These scientists include Khalid Aisawi, Shigemi Akita, Karim Ammar, Fernando Andrade, Senthold Asseng, Michael Bange, Filipe Barrios-Masias, Sarah Battenfield, Anita Boling, Ken Boote, Bas Bouman, John Bradshaw, John Brennan, Flavio Breseghello, Jelle Bruinsma, Pep Canadel, Ken Cassman, Grace Centeno, Scott Chapman, Ignacio Colonna, Greg Constable, Wallace Cowling, Abelado de la Vega, Ron DePauw, Abdelsalam Draz, Jesse Dubin, Michael Duffy, Roger Elmore, Olaf Erenstein, Thomas Fairhurst, Robert Finger, John Foulkes, Brian Fowler, Madhur Gautam, Mohammed Gharbi, Ken Giller, Patricio Grassini, Richard Gray, Raj Gupta, Antonio Hall, Tony Hall, Graeme Hammer, Jerry Hatfield, Zhonghu He, Paul Heisey, Clair Hershey, Gene Hettel, Tadashi Hirasawa, Svi Hochman, Takeshi Horie, Liz Humphreys, Phillip Jackson, Peter Jamieson, Jin Jian, Boonrat Jongdee, David Jordan, Motohiko Kondo, Alice Laborde, Tanguy Lafarge, Claudia Lange, Weili Liang, Bruce Linqvist, Verity Linehan, Mike Listman, Rick Llewellyn, Chunji Liu, Mike Livingstone, Sergio Lopes, Alice Maitia, Ian Mackay, Tadahiko Mae, Graciela Magrin, R.K. Malik, Susan McCouch, Peter McIntosh, Alex Morgounov, Paul Morris, Moussa Mossad, Francisco Moura Neto, Piedad Moya, John Mullen, Lanier Nalley, Gerald Nelson, Nasser Nsarella, Rodomiro Ortiz, Ivan Ortiz-Monasterio, Maria Otegui, Phil Pardey, H. Partak, Pirjo Peltonen-Sainio, Mark Peoples, John Porter, Curtis Pozniak, Philip Pritchard, Larry Purcell, Arnel Rala, Magno Ramalho, Mike Raupach, Howard Rawson, Matthew

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Abbreviations and glossary

This glossary defines the units, abbreviations and terms used frequently in this book.

Units

Abbreviation	Explanation ^a
kg	kilogram = 2.205 pounds
t	tonnes = 1,000 kg
Mt	megatonnes = 1 million tonnes
ha	hectare = 10,000 m ² = 2.471 acres
ML	megalitres = 1 million litres
s	second
hr	hour
d	day
yr	year
Pa	pascal, unit of pressure; 100 kPa = 1 bar = 14.5 pounds per square inch (psi)
MJ	megajoule = 1 million joules; 1 joule = 0.239 calories; 1 MJ = 948 British thermal units (BTU)

- a Metric units and abbreviations are used throughout (k = kilo or 10³, M = mega or 10⁶, G = giga or 10⁹, m = milli or 10⁻³, μ = micro or 10⁻⁶).

Weather, soil and crop characteristics, and economic terms

Abbreviation	Units	Explanation
Weather		
DTR	°C	Diurnal temperature range ($T_{\max} - T_{\min}$)
GSR	mm	Growing season precipitation (rain + snow)
PAR	MJ/d	Incident photosynthetically active radiation = $0.5 \times R_s$
PTQ	MJ/°C	Daily solar radiation divided by mean temperature or mean temperature less a base temperature
R_s	MJ/d	Incident solar radiation
T_{\max}	°C	Maximum daily temperature
T_{mean}	°C	Mean daily temperature = $(T_{\min} + T_{\max})/2$
T_{\min}	°C	Minimum daily temperature
vpd	Pa or kPa	Vapour pressure deficit (0.1 kPa = 1 mbar)
Soil and fertiliser		
K	kg or Mt	Elemental potassium ($\times 1.21$ for K_2O)
N	kg or Mt	Elemental nitrogen
P	kg or Mt	Elemental phosphorus ($\times 2.29$ for P_2O_5)
PAWC	mm	Plant available water-holding capacity of fully developed crop root zone in a particular soil/crop combination
S	kg or Mt	Elemental sulfur
SOC	%C, w/w	Soil organic carbon = soil organic matter $\times 0.58$
Crop		
DM	g/m ²	Above-ground weight of crop dry matter (or biomass), or of crop part (e.g. leaf, spike, grain)
ET	mm	Evapotranspiration (observed water use by crop = transpiration plus soil evaporation)
ET_p	mm	Potential evapotranspiration (water use by crop without soil water limitation), calculated from weather; largely independent of crop
F_{PAR}	% or fraction	Fraction of incident PAR intercepted by green crop
GDD	°Cd	Growing degree-days (duration of development stage in degree days above a base temperature)
GN	/m ²	Grain number per square metre (often calculated from GY/GW)
GNC	% or w/w	Grain nitrogen concentration
GW	mg	Average weight per individual grain
GY	g/m ²	Dry grain yield (100 g/m ² = 1 t/ha)

HI	ratio or %	GY/DM at maturity
K	unitless	Extinction coefficient for PAR in crop canopies
k	Pa	Crop specific constant relating TE to 1/vpd
LAI	unitless	Leaf area index (alternatively, green area index), leaf area relative to land area
NHI	% or w/w	Grain nitrogen amount relative to total nitrogen uptake by crop at maturity
NUE_t	kg grain/kg N	Nitrogen use efficiency (yield per kilogram of nitrogen fertiliser applied)
PAR_t	MJ/m ² /d	Daily intercepted PAR by green crop
$\sum PAR_t$	MJ/m ²	Cumulative PAR_t across days or weeks or more
P_{max}	$\mu\text{mol CO}_2/\text{m}^2/\text{s}$	Maximum leaf photosynthetic rate in full direct sunlight
PUE_t	kg grain/kg P	Phosphorus use efficiency (yield per kilogram of phosphorus fertiliser applied)
RUE	g/MJ	Radiation use efficiency, given in grams of DM produced per megajoule of intercepted PAR
TE_1	kg/ha/mm	Transpiration efficiency (DM produced per unit crop transpiration)
TE_2	dimensionless	Transpiration efficiency (DM produced per unit weight of water transpired)
WUE	kg/ha/mm	Water use efficiency (yield per unit water used)
Economics		
internal rate of return	% p.a.	Annual internal rate of return is a discount rate that equates the discounted value of future output with the discounted cost of the investment. Discounting takes into account changes in the value of money with time
PPP	US\$	Purchasing power parity is an exchange rate based on the equivalent purchasing power between two countries, published by the World Bank and the International Monetary Fund (IMF); approximately equivalent to 2005 US\$
real price	US\$	Observed prices corrected for general cost of living change, expressed in constant dollars of a given year when the real and observed prices were assumed to be the same
technical efficiency	% or ratio	Relates to a sample of, say farmers, and where their average performance sits relative to the best, as delineated by the performance frontier
TFP	unitless	Total factor productivity (in agriculture or specific commodity) = index price-weighted physical outputs divided by similar index of inputs
SFA	(not applicable)	Stochastic frontier analysis is an economic technique for relating the performance, in terms of output versus input levels, of individuals (e.g. farms) relative to an upper performance frontier set by considering all individuals in the sample

Other scientific terms and abbreviations

Term	Explanation
agronomy	Management of crops as distinct from breeding new crop varieties
anthesis	Appearance of first burst anthers (male part of flower); essentially flowering
attainable yield (AY)	Yield attained by a farmer with average natural resources, and adopting economically optimal practices and levels of inputs, and prudent avoidance of market and weather risk
<i>Boro</i> rice	Term specific to irrigated rice grown in the dry winter/spring season in Bangladesh
C ₃ /C ₄	Refers to the fundamental photosynthetic system of crop species—with C ₃ the first products of CO ₂ fixation is a C ₃ sugar; with C ₄ the first product is a C ₄ acid
cisgenesis	Genetic engineering with most or all of the inserted genetic material coming from the same species
CO ₂ equivalent (CO ₂ -e)	Refers to the global warming potential of an atmospheric gas relative to that of the equivalent weight of CO ₂
conservation agriculture	This recent term has come to mean cropping that combines minimal or zero soil tillage with retention of crop residue on the soil surface along with crop rotation. It is an aspirational goal that can bring benefits even when only partially achieved
control variety	The crop variety against which other varieties are compared in experiments
crop area	Area of crop that is harvested—definition used by the Food and Agriculture Organization of the United Nations (FAO)
cropland	All land in the world dedicated to cropping including arable land plus permanent crops— definition used by the Food and Agriculture Organization of the United Nations (FAO)
c.v.	Coefficient of variation
decile	Top decile has two meanings, specified accordingly: (1) yield value on moving from the ninth to tenth decile (also known as 90th percentile); and (2) the average of the top 10% of the group of individuals
DNA	Deoxyribonucleic acid
double cropping	Two crop harvests produced in 12 months = 200% cropping intensity
F ₁	First cross hybrid, derived from crossing two inbred lines
facultative wheat	Flowering is mildly responsive (accelerated) with vernalising cold, but no obligate requirement for cold as in true winter wheats
farm yield (FY)	Field, district, regional or national average yield in kilograms (kg) or tonnes (t) per hectare, as reported in surveys or local or national statistics; main yield figure used in this book
farm yield index	For a region, a sum of the proportion of each main variety grown multiplied by the relative potential yield of each; can be plotted against time to measure breeding progress caused by variety change in farmers' fields
frontier value	Mathematical term defining the upper (or lower) boundary of a cluster of points showing some relationship of a dependent variable (<i>y</i> axis), like yield, and some independent input (<i>x</i> axis) such as rainfall

gene banks	Repository for seeds of all genetic variants of a plant species
genetic engineering (GE)	Artificial insertion of DNA, either from sources that would not normally cross with the target species (transgenesis) or from the same or related species (cisgenesis)
global warming potential (GWP)	Related to the warming effect of an activity in terms of the gases it contributes to global atmosphere, expressed as weight of CO ₂ equivalent.
greenhouse gas	Gas that contributes to global warming, considered here as carbon dioxide (CO ₂), nitrous oxide (N ₂ O) or methane (CH ₄)
green revolution	Refers to the dramatic increase in wheat and rice yields in Asia beginning in the mid 1960s with the introduction of high-yielding semi-dwarf varieties of these crops along with adding fertiliser and irrigation
hybrid vigour	The improved or increased function of any biological quality (e.g. grain yield) in a hybrid offspring relative to that of its parents
intercropping	Two crop species growing simultaneously in the same space in the field (for at least some period of overlap, often at different stages of development)
<i>Kharif</i> season	Crops grown in the rainy season in a monsoonal climate (South Asia), e.g. <i>Kharif</i> rice
landrace	Unique crop plant variant selected and grown by farmers before the impact of modern plant breeding; may still be grown in some regions
masl	Altitude as metres above sea level
OPV	Open pollinated variety e.g. as distinct from F ₁ hybrid in maize
<i>P</i> -value	Statistical probability of erroneously declaring a treatment effect; in this book, an upper limit of $P = 0.10$ indicates effects worthy of comment
paddy rice	Two meanings: (1) irrigated rice; and (2) harvested rice before hull removal. After hull removal, 80% by weight remains for brown rice, while after hull removal and polishing, 67% by weight (of the paddy) remains for white rice, all at the same moisture content
panel data	Econometric term for multidimensional datasets, here used to comprise locations (cross-sectional data) plus years (time series data)
potential yield (PY)	Yield to be expected with the best adapted cultivar (usually the most recent), the best management of agronomic inputs, and in the absence of manageable abiotic and biotic stresses
protected	Sprayed with fungicide etc. to protect from biotic stresses; best trials for measuring PY and PY progress are protected
<i>Rabi</i> season	Dry cropping season in monsoonal South Asia; also coincides with winter/spring cropping as in <i>Rabi</i> maize or sorghum
rate of FY increase	Per annum (p.a.), as a percentage of FY for defined year, or kg/ha/yr
rate of PY increase	Per annum (p.a.), as a percentage of PY at year of release, or kg/ha/yr
R^2	Coefficient of determination = square of the correlation coefficient in simple correlation
SNP	Single nucleotide polymorphism

standard error	Standard deviation of the sample mean of a variate, or of the slope in a relationship between two variates; follows the Student's <i>t</i> distribution
theoretical yield	Yield that modelling suggests could result if certain physiological processes could be altered within realistic bounds
transgenesis	Genetic engineering with all or most of the inserted DNA coming from unrelated species that do not in nature exchange DNA with the host species
water-limited potential yield	Yield obtained with no other manageable limitation to the crop apart from the water supply
mega-environment	Commodity-specific term that refers to broad areas facing similar agroecologies in terms of weather, abiotic and biotic stresses, and cropping system requirements for the crop under consideration
yield gap	Difference between farm yield and potential yield, here expressed as a per cent of current FY
yield-scaled emissions	Emissions of greenhouse gases expressed as global warming potential per unit of production, as in CO ₂ -e/kg grain
zero-till	Using the least possible soil disturbance to place seed under soil, typically involving discs to create a slot for the seeds

General abbreviations

Abbreviation	Explanation
AAPRESID	<i>Asociación Argentina de Productores en Siembra Directa</i> , or Argentine Association of Direct Drill Producers
AIS	agricultural innovation systems
BBRO	British Beet Research Organisation (UK)
<i>Bt</i>	<i>Bacillus thuringiensis</i>
BW	bread wheat
CENEB	<i>Centro Experimental Norman E. Borlaug</i> , or Norman E. Borlaug Experimental Centre (Mexico)
CGIAR	Formerly the Consultative Group on International Agricultural Research, but now named in its own right
CIAT	<i>Centro Internacional de Agricultura Tropical</i> , or International Center for Tropical Agriculture (Colombia)
CIMMYT	<i>Centro Internacional de Mejoramiento de Maíz y Trigo</i> , or International Maize and Wheat Improvement Center (Mexico)
CIP	<i>Centro Internacional de la Papa</i> , or International Potato Center (Peru)
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
DW	durum wheat
Embrapa	<i>Empresa Brasileira de Pesquisa Agropecuária</i> , or Brazilian Agricultural Research Corporation
FAO	Food and Agriculture Organization of the United Nations (Rome)

FAOSTAT	Database of the Food and Agriculture Organization of the United Nations
GDP	gross domestic product
GRDC	Grains Research and Development Corporation (Australia)
HGCA	Home Grown Cereal Authority (UK)
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics (India)
IFPRI	International Food Policy Research Institute (Washington, DC, USA)
IIASA	International Institute for Applied Systems Analysis (Austria)
IITA	International Institute of Tropical Agriculture (Nigeria)
IP	intellectual property
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
IRRI	International Rice Research Institute (Philippines)
ICT	information and communications technology
IWMI	International Water Management Institute (Sri Lanka)
MME	maize mega-environment
NARS	National Agricultural Research System
OECD	Organisation for Economic Co-operation and Development (Paris, France)
PMCA	participatory market chain approach
PROSOJA	<i>Profesionales especialistas del cultivo de soja</i> , or Professionals specialised in soybean production (Argentina)
R&D	research and development
RD&E	research, development and extension
RME	rice mega-environment
SMEs	small to medium-size enterprises
WME	wheat mega-environment



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A

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