Water in Agriculture

Proceedings of a CARDI International Conference on Research on Water in Agricultural Production in Asia for the 21st Century
Phnom Penh, Cambodia, 25–28 November 2003

Editors: Vang Seng, Eric Craswell, Shu Fukai and Ken Fischer

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The Australian Centre for International Agricultural Research (ACIAR) was established in June 1982 by an Act of the Australian Parliament. Its mandate is to help identify agricultural problems in developing countries and to commission collaborative research between Australia and developing country researchers in fields where Australia has a special research competence.

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Foreword

WATER makes a significant contribution to food security as it directly affects agricultural productivity.

Due to the significant growth in agricultural productivity over recent decades, the irrigated areas that comprise 17 per cent of agricultural lands produce nearly 40 per cent of food and agricultural commodities. The water used for irrigation in developing countries makes up over 80 per cent of fresh water use.

High risks of flood and/or drought make rain-fed systems difficult environments in which to increase crop productivity.

The extent to which agricultural production can be increased to meet food demands is limited by decreasing water availability and growing competition for water from the industrial and urban sectors.

In arid and semi-arid regions, water resources are fully exploited. Declining quality of water and soil resources has created new threats to food supplies. The great challenge in the 21st century will be to increase food production with limited water and land resources in both rain-fed and irrigated agriculture.

ACIAR supports a number of projects which have an emphasis on improving agricultural productivity and sustainability, particularly in Southeast Asia. The host country of this conference provides a good example. One of our projects focuses on Cambodia, where the most important crop is rice grown mostly under rain-fed conditions. ACIAR has made a commitment to improve production from the limited and unreliable rainfall by improving planting methods, direct seeding and the development of suitable rice cultivars.

We are pleased to publish these proceedings and hope that the book will be a valuable resource for researchers with an interest in the many aspects of water use in agricultural production.

Peter Core

Peter Core
Director
Australian Centre for International Agricultural Research

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Contents

Preface

THE AVAILABILITY of water and water quality are major concerns for everyone. Water plays a very important role in all parts of life and at all stages of crop growth and plant development. Generally, water is regarded as life—no water, no life.

Agriculture is the largest consumer of water. With increases in population, agricultural production also increases, which consequently leads to a significant increase in the quantity of water to be used, both for crop production and for urbanisation. Hence, the main question for us now is how to increase food production with limited water and land resources. The challenge becomes even more severe under irrigated conditions, where water availability is decreasing and competition for water is increasing between agriculture and industry. In these circumstances, as a result of increased water use, the incursion of saltwater from the sea or from subsurface layers to cultivated areas is alarming.

The International Conference 'Research on Water in Agricultural Production in Asia for the 21st Century', which was held at the Cambodian Agricultural Research and Development Institute (CARDI) in Phnom Penh, Cambodia, 25–28 November 2003, provided an important forum for researchers from around the world to discuss the issues and plan effective measures for the future. The themes: *(i) Agricultural Systems and Efficient Water Use; (ii) Water and Land Resources;* and *(iii) Improving Agricultural Productivity under Water Constraints with Emphasis on Agricultural Production in Asia,* were deliberately chosen to reflect the problems we are facing.

I want to congratulate the Conference Organising Committee chaired by Dr Seng Vang, and his team, Mr Hun Yadana, Mr Ty Channa, Ms. Sakhan Sophany, Mr Chea Marong, Dr Eric Craswell (CARDI-Assistant Project), Mr Mike Clark (CARDI-Assistant Project), Prof. Shu Fukai (University of Queensland, Australia), and Prof. Ken Fischer (University of Queensland, Australia) for the success of this conference. Appreciation also goes to all those who participated in the conference and to all donors for making it possible.

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It is hoped that these proceedings will provide valuable information to researchers and anyone else who takes an interest in this important subject.

Dr Men Sarom

Director, Cambodian Agricultural Research
and Development Institute (CARDI)

Challenges to agricultural production in Asia in the 21st Century

Per Pinstrup-Andersen[1]

DURING the past 50 years, Asia has made tremendous progress in food security and agricultural development. Nations with large populations that once experienced periodic famine, such as China and India, are now virtually self-sufficient in food production. Community-based nutrition programs in Indonesia and Thailand are frequently presented as models for developing countries. No longer does one hear the phrase 'basket case' when Bangladesh or India are mentioned. The achievement of peace in Cambodia and East Timor has greatly improved the prospects for overcoming hunger.

Asia has also made tremendous progress in agricultural development. Cereal production more than doubled during the past 30 years boosting calorie availability per person by 24% even as the region's population grew by a billion people. Virtually all of the increase in production resulted from yield gains rather than expansion of cultivated area. Increased agricultural productivity and subsequent rapid industrial growth in many countries of the region, along with a rapid expansion of the non-farm rural economy, contributed to almost a tripling of per capita incomes. While three of every five Asians lived in poverty some 30 years ago, less than a third do so today.

However, poverty remains higher in rural Asia than in the cities with nearly 700 million rural people still considered poor with low levels of health, education, and general well being. More than half a billion Asians are chronically undernourished and child malnutrition is widespread in parts of Asia, especially in South Asia. Famine is severe in North Korea and has been for about a decade. In South Asia, 88% of pregnant women suffer from anaemia, usually as a result of insufficient dietary iron.

Given that the centre of gravity of regional poverty and food insecurity remains rural, agriculture will continue to play a critical role as the region pursues sustainable food security for all. It is particularly important that strategies for future agricultural growth focus on equity, as well as redressing past environmental degradation that has often occurred in well endowed and irrigated areas, while recognising that environmentally friendly intensification of agriculture can offer sustainable livelihoods to the many poor people who live in less favoured rural areas. Public policies must strike an appropriate balance among agricultural, urban, and non-farm rural investments, and between well endowed and less favoured areas. Research and technology along with investments in rural infrastructure will play a major role in successful rural development and poverty eradication.

Current food security and nutrition situation

Nearly two-thirds of the 800 million people in the world who suffer from hunger and food insecurity live in Asia. The more than 500 million Asians affected account for about 17% of all Asian residents, down from 21% about 10 years ago. The number of food-insecure Asians has been dropping dramatically during the past 30 years, a trend that is expected to continue during the next 10 years and beyond (Figure 1). The prevalence of food insecurity is higher in South Asia than in the rest of the region, accounting for more than 20% of the South Asian population compared to about 10% in East Asia. FAO predicts that by year 2030, only 6% of the South Asian population and

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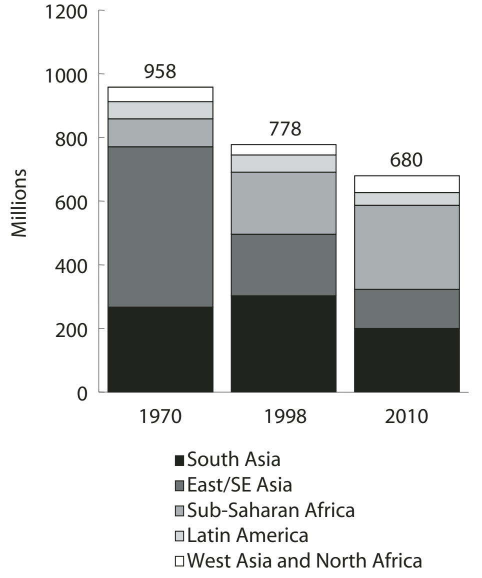
4% of the East Asian population will be food insecure. It is projected that there will be very little food insecurity left in South-east Asia by 2030 (Figure 2).

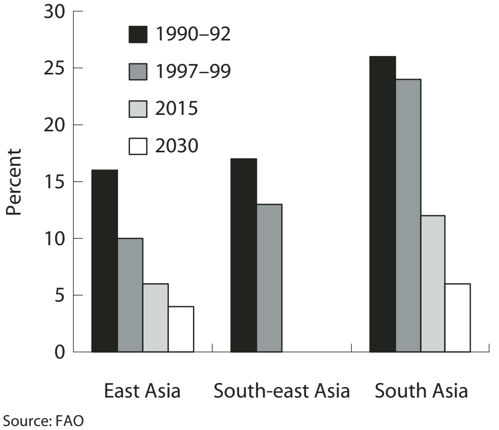
Malnutrition among pre-school children is of particular concern. The World Health Organization estimates that it is a factor in about half of all deaths of children under the age of five in developing countries. Every year, nearly three million children die from malnutrition in the following nine Asian countries: Bangladesh, Cambodia, China, India, Laos, Nepal, Pakistan, Sri Lanka, and Vietnam. Malnourished children who make it to their fifth birthday often suffer stunted physical and mental development and are at heightened risk of infection. As adults, they are likely to be less productive workers. As shown in Figure 3, there are more than 150 million malnourished preschool children in the world. More than 70% of them are found in Asia with South Asia accounting for more than half of the world's malnourished preschool children (Figures 4 and 5). At 44% of the South Asian population, the incidence of malnutrition in that region is higher than it is in any other developing region. Fortunately, both the incidence of child malnutrition and the number of malnourished children have been declining in Asia, in contrast to Sub-Saharan Africa where the number is increasing.

In addition to calorie and protein deficiencies, micronutrient deficiencies are an important nutrition problem in Asia. In South and South-east Asia, 76% of pregnant women and 63% of preschool children suffer from iron deficiency anaemia (Figure 6). Around 50% of the world's anaemic women live in South Asia. Their risk of maternal mortality is 23% higher than that of non-anaemic mothers. Their



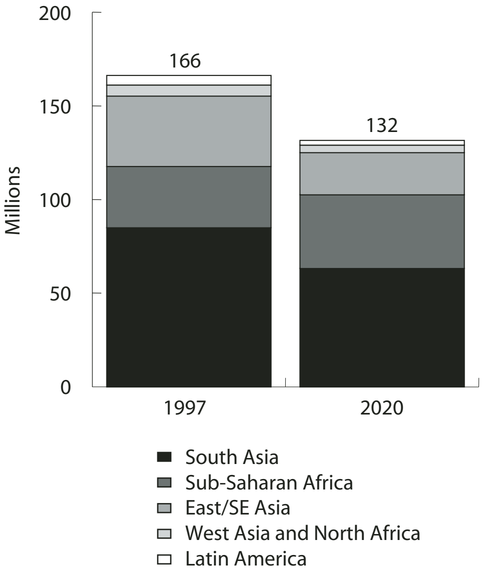
Source: FAO (2000, 2001)

Figure 1. Number of food-insecure people 1970, 1998, 2010.



Source: FAO

Figure 2. Percent of population that are food insecure.

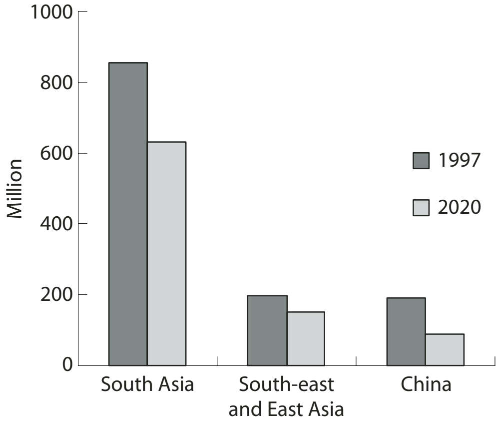


Source: Pinstrup-Andersen, Pandya-Lorch, and Rosegrant (1999).

Figure 3. Number of malnourished children 1997 and 2020.

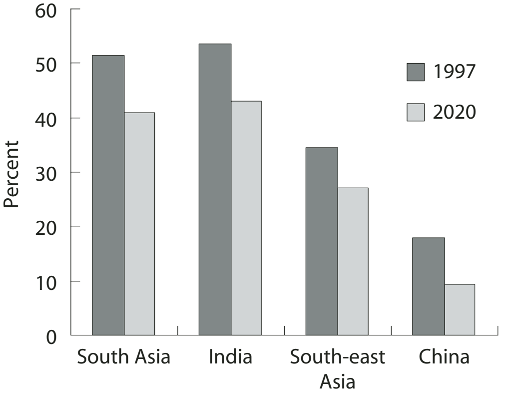
babies are more likely to be premature, have low birth weights, and die as newborns. The incidence of anaemia is also high among South Asian infants and children, who, as a result, face impaired health and development and limited learning capability. Other widespread micronutrient deficiencies include vitamin A, zinc, and iodine ones.

Overweight and obesity are gradually becoming serious nutrition problems in parts of Asia, particularly in countries experiencing rapid economic growth, such as China, where consumption of fat and sugar has increased rapidly (Figure 7). Overweight and obesity leads to increasing risk of diabetes, hypertension, and heart diseases. Recent research indicates that by year 2025, almost 40% of the Chinese population will be overweight or obese—an increase from about 10% in 1995 (Table 1). As shown in Figure 8, cardiovascular disease, diabetes, and cancer are expected to account for a rapidly increasing share of all deaths in China and India by 2020.



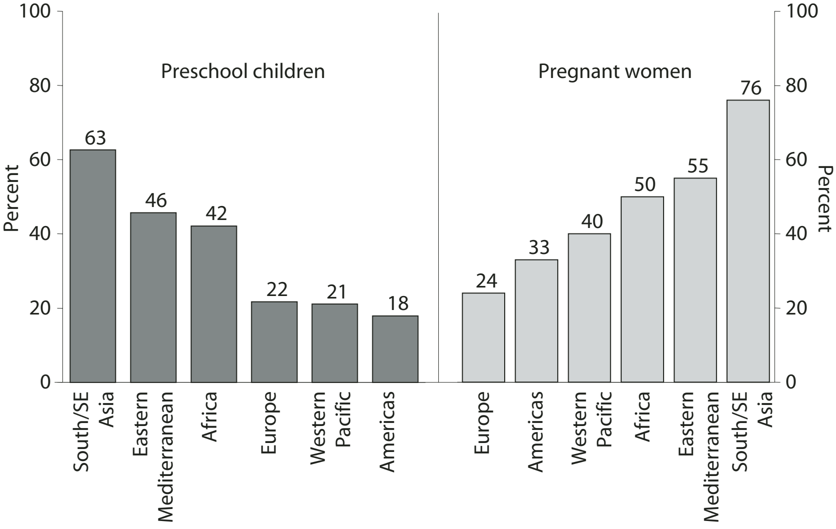
Source: IFPRI-IMPACT, 2000

Figure 4. Number of malnourished children by region, 1997 and 2020.



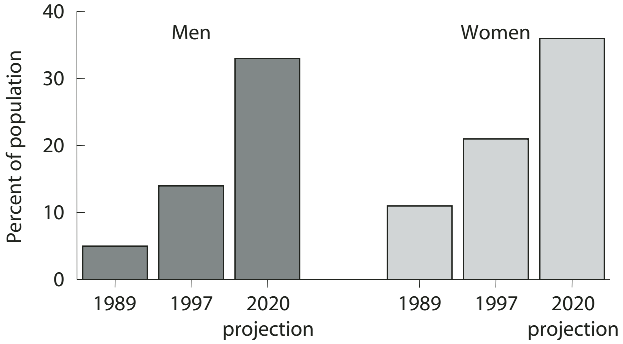
Source: IFPRI-IMPACT, 2000

Figure 5. Malnourished children as a percentage of total children under five years, by region, 1997 and 2020.



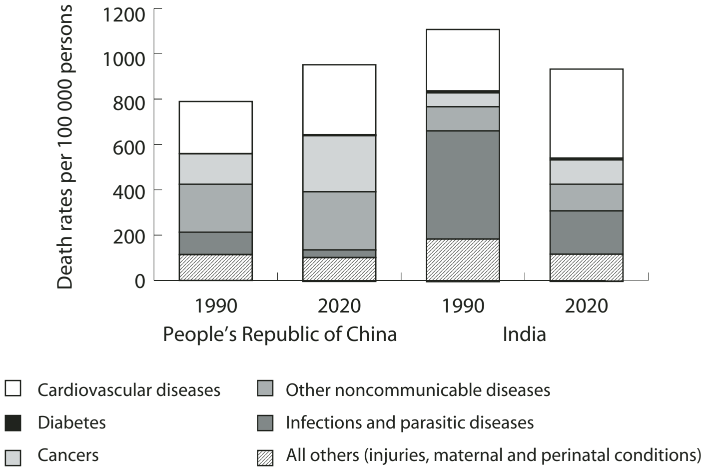
Source: UN-SCN/ACC (1999)

Figure 6. Prevalence of anaemia in preschool children and pregnant women by region, 1999.



Source: Gillespie and Haddad, "Attacking the Double Burden of Malnutrition In Asia," IFPRI, Washington, DC (2000).

Figure 7. Prevalence of overweight in China.



Source: Asian Development Bank Nutrition and Development Series (2001).

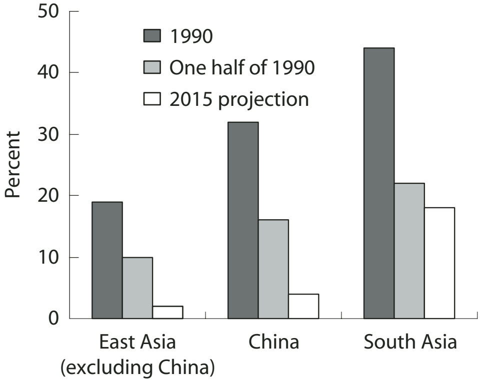
Figure 8. Actual (1990) and projected deaths (2020) by cause in the PRC and India.

Table 1. Overweight and obesity in China 1995 and projected for 2025[a].

	Number (million)		% Increase	% of Total population	
	1995	2025		1995	2025
Men	48	286	496	8	37
Women	71	309	335	12	40
Total	119	595	400	10	39

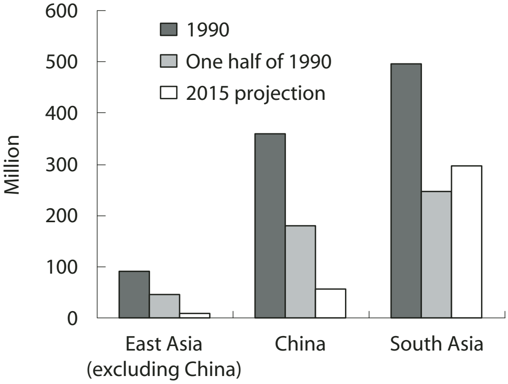
[a] Projected on the basis of one-half of the rate of increase during the period 1989–97.
Source: Estimated on the basis of Popkins, Horon, and Kim (2001).

Poverty is also widespread in large parts of Asia. Close to one billion Asians lived on the equivalent of less than one US dollar per day in 1990, a number that has decreased to fewer than 800 million today. The Millennium Development Goal calls for a 50% reduction in the per cent of the population that falls into poverty. This goal will easily be achieved by Asia in general and by each of the sub-regions as well, although some countries may fall short (Figure 9). A somewhat more difficult goal would be to reduce the number of poor people by half, relative to 1990. Again, Asia as a whole is likely to achieve this goal although South Asia may fall short (Figure 10).



Source: Global Economic Prospects & Developing Countries, World Bank (2000).

Figure 9. Percent of people below $1/day.



Source: Global Economic Prospects & Developing Countries, World Bank (2000).

Figure 10. Number of people below $1/day.

Food demand and consumption

Forecasts in the 1950s and 1960s that population growth would outstrip food supplies in Asia fortunately did not materialise. On the contrary, during the past 30 years, cereal production doubled in South Asia and increased by about 120% in East and Southeast Asia. The cultivated area increased by only 4% and the green revolution technology accounted for most of the production gain. Although population growth rates in the region are considerably below 2% per year, the region will still experience large increases in the demand for food during the next 20–30 years, partly due to population growth and partly to income increases.

As shown in Figure 11, the rural population growth rate is expected to reach zero within the next five to 10 years. Growth in the urban population will continue to follow an almost straight-line trend. Per capita income growth during the 1990s was high in several Asian countries, notably China, Vietnam, and Myanmar, while they were low in Nepal, Indonesia, Cambodia, Pakistan, and the Philippines (Figure 12). Future growth in incomes is expected to be relatively high at about 5.5% for Asia. China, Cambodia, Vietnam, and India are expected to experience particularly high economic growth between now and 2020 (Figure 13). Past income growth, urbanisation, and changing lifestyles have resulted in dramatic dietary changes in Asia (Table 2). In middle income Asian countries the dietary change has been towards rapid increases in the consumption of dairy products, meat, fish, fruit, vegetables, and refined sugar. Somewhat similar dietary changes have taken place in low income Asian countries although the magnitude is much less. The net result of these dietary changes is a rapid increase in the consumption of calorie-rich food containing high levels of fats and sugar with the likely effect of increasing overweight, obesity, and related chronic diseases. The dietary changes have been particularly dramatic in East Asia as shown in Figure 14.

Agricultural production

Cereal yields continue to increase in Asia but at a lower rate than during the 1970s and 1980s. During the 1990s, cereal yields increased by 13% in Asia as a whole, with large variations among countries. Thus,

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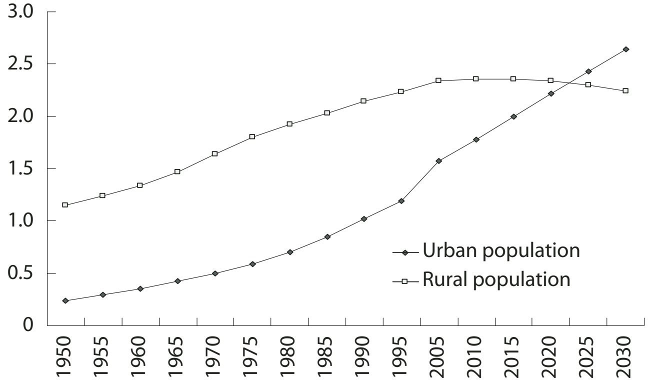
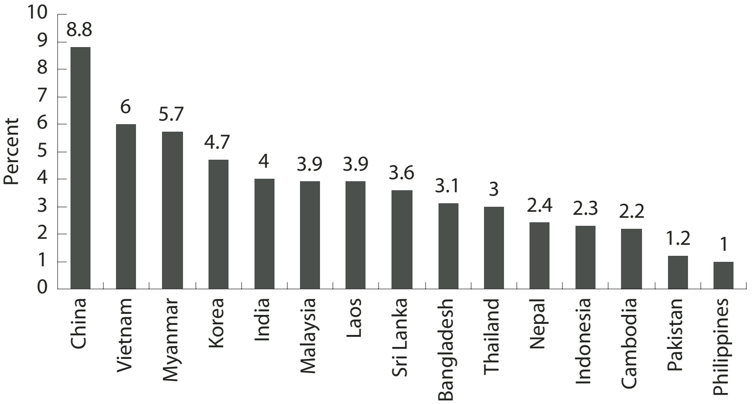


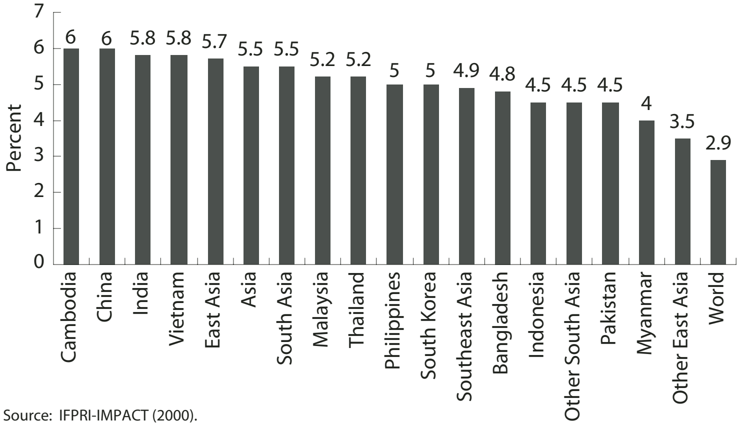
Source: UN Population Division (2001).

Figure 11. Urban and rural populations of Asia.



Source: UNDP, Human Development Report (2003).

Figure 12. GDP per capita annual growth rate (%), 1990–2000.



Source: IFPRI-IMPACT (2000).

Figure 13. Projected GDP growth rates, 1997–2020.

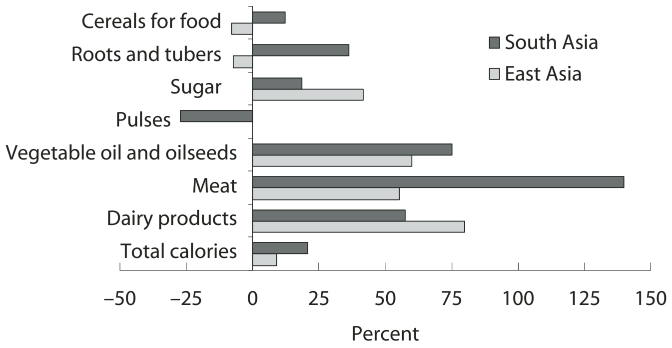


Figure 14. Projected percentage change in per capita consumption of selected foods in South and East Asia.

Table 2. Consumption of selected foods in middle- and low-income Asian countries in 1962 and 1996 (kg per capita).

	Middle-income		Low-income	
	1962	1996	1962	1996
Cereals and starchy roots	155	165	159	193
Dairy products and eggs	18	49	39	56
Meat	13	31	5	7
Fish	18	31	4	5
Fruits and vegetables	129	142	59	80
Added sugar	12	32	16	20

Source: Popkins, Horon, and Kim (2001).

yield increases in Cambodia during the 10-year period were 43% compared to a 1% increase in Indonesia (Table 3). The irrigated area in Asia is increasing but more slowly as shown in Figure 15. During the 30-year period, 1965–95, the irrigated cereal area in Asia increased by 58%. It is projected that it will increase by only 10.5% during the 30-year period, 1995–2025. The competition for water uses other than irrigation is increasing rapidly in Asia and it is projected that the percentage of the water used for irrigation will decrease from 87% in 1995 to 77% in 2025, leaving the total consumption of water for irrigation roughly constant during that 30-year period. The projected increase in total water consumption of 14% during the 30-year period will occur in non-irrigation for which water consumption is expected to double during that period.

Table 3. Average cereal crop yields.

Country		Average cereal crop yields	
		kg per hectare (1999–2001)	Change since 1989–91 (%)
1	Korea, Republic of	6,500	10
2	China	4,869	16
3	Vietnam	4,075	33
4	Indonesia	3,860	1
5	Bangladesh	3,322	31
6	Sri Lanka	3,270	12
7	Myanmar	3,082	13
8	Malaysia	3,075	13
9	Laos	2,978	33
10	Thailand	2,659	24
11	Philippines	2,571	27
12	India	2,321	21
13	Pakistan	2,305	29
14	Nepal	2,089	11
15	Cambodia	2,050	43
	Asia (excl. Middle East)	3,678	13
	World	3,096	15

Source: World Resources Institute, 2002, in collaboration with the United Nations Development Program, the United Nations Environment Program, and the World Bank.

One of the main reasons for the rapid yield increases in Asia is the adoption of improved crop varieties (Figure 16). About 90% of the area grown with potatoes and wheat use improved varieties. For rice, maize, soybean, and millet, the rate is around 70%.

As shown in Figures 17–19, the annual growth in cereal demand and production has decreased significantly during the past 30 years, a trend that is expected to continue during the next 20 years. Another past trend expected to continue is a faster growth in demand than in production leading to increasing net imports of cereals (Table 4). It is expected that Asia's net cereal imports will reach close to 100 million tons by 2030, up from less than 20 million tons during the 1960s (Figure 20). East Asia will account for more than two-thirds of the net cereal imports into Asia by 2020 (Table 4). As shown in Figures 21 and 22, maize prices are expected to stay constant in real terms over the next 20–25 years while most other food prices are expected to decrease.

Fish provides a different picture than that for most other food commodities in Asia. Fish production has increased rapidly during the past 30 years, particularly in China where the annual growth in fish production between 1985 and 1997 was 15.6% (Figure 23). The growth in fish production in Asia is expected to continue although more slowly (Table 5). Production increases that exceed the increase in demand in the region have resulted in a switch from the region being a net importer of fish to a net exporter, a trend that is projected to continue in the future (Table 6 and Figure 24). Contrary to most other food commodities, fish prices are expected to increase significantly during the next 15–20 years (Figure 25).

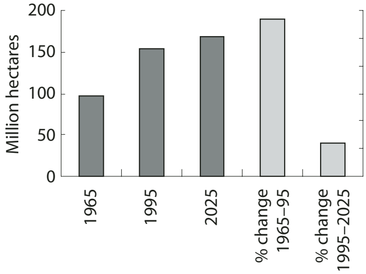
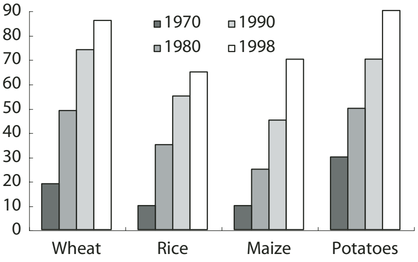
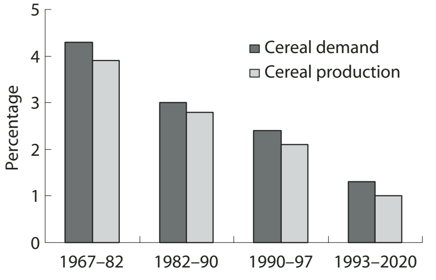


Figure 15. Irrigated cereal area in Asia, 1965, 1995, and projected for 2025.



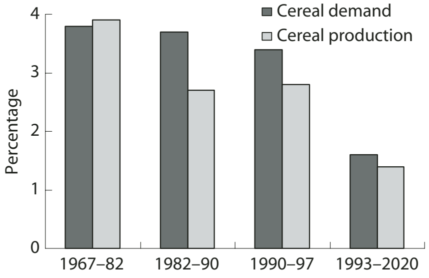
Source: Evenson and Gollin, Eds. (2003).

Figure 16. Percent of area planted to improve varieties in Asia.



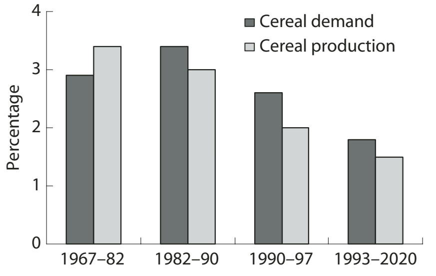
Source: IFPRI-IMPACT (for 1967–1997 data)
PNAS Online (for 1993–2020 data)

Figure 17. Annual growth rate (%) in cereal demand and production in East Asia.



Source: IFPRI-IMPACT (for 1967–1997 data)
PNAS Online (for 1993–2020 data)

Figure 18. Annual growth rate (%) in cereal demand and production in South-east Asia.



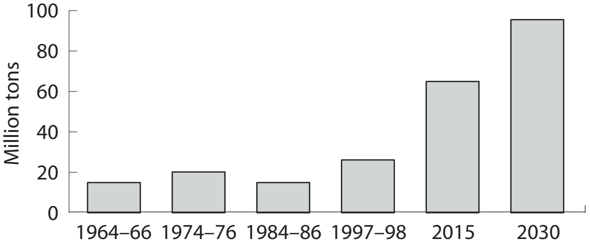
Source: IFPRI-IMPACT (for 1967–1997 data)
PNAS Online (for 1993–2020 data)

Figure 19. Annual growth rate (%) in cereal demand and production in south Asia

Table 4. Net cereal import in Asia, 1967–2020 (million tons).

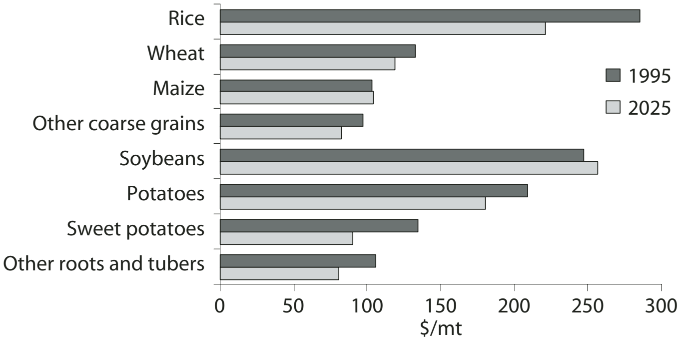
	1967	1982	1990	1997	2020
South Asia	12	3	3	3	21
South-east Asia	0	0	0	7	9
East Asia	6	30	26	21	67
Total	18	29	30	31	97

Source: IFPRI-IMPACT, (2002).



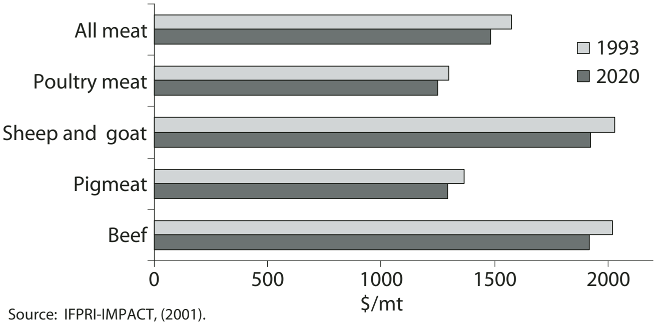
Source: FAO (2003).

Figure 20. Asian net cereal imports.



Source: Rosegrant, Cai, and Cline (2002).

Figure 21. World food prices, 1995 and projected for 2025 ($/t).



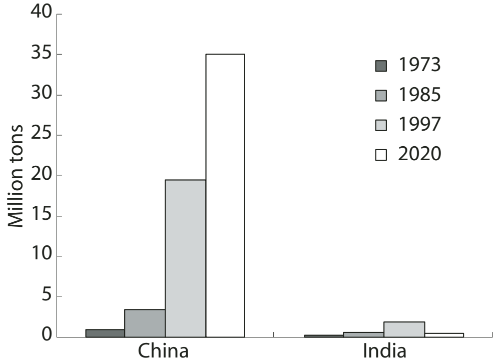
Source: IFPRI-IMPACT, (2001).

Figure 22. Real world market prices of selected commodities, 1993 and projected for 2020 ($/t).

Table 5. Production of food fish from aquaculture, 1973–2020.

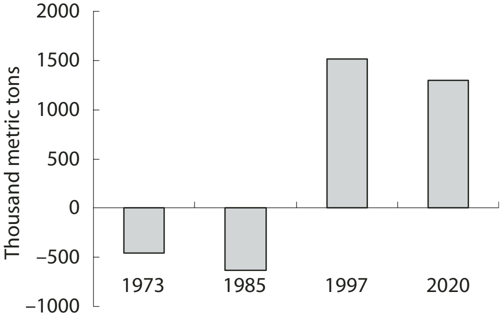
Region	Total production (million tons)				Annual growth rate (%)	
	Actual			Projected	Actual	Projected
	1973	1985	1997	2020	1985–97	1997–2020
China	1	3.4	19.5	35.1	15.6	2.6
South-east Asia	0.4	0.9	2.3	5.1	7.6	3.6
India	0.2	0.6	1.9	4.3	9.6	3.7
Other South Asia	0.1	0.1	0.5	1.2	10.5	4.0

Source: IFPRI-IMPACT model (Rosegrant et al. 2001)



Source: IFPRI-IMPACT model (2002), FAO (2002).

Figure 23. Production of food fish from aquaculture, 1973–2020.



Source: Delgado, et al., (2003).

Figure 24. Total Asian net exports of food fish, 1973–97 and 2020.

Table 6. Total net exports of food fish, 1973–97 and 2020.

Region	Total net exports (thousand metric tons)			
	Actual			Projected
	1973	1985	1997	2020
China	–108	–284	181	543
South-east Asia	–324	–145	1,131	482
India	–49	–109	122	426
Other South Asia	26	–97	84	–157
All Asia	–455	–635	1,518	1,294

Source: Delgado et al. (2003).

Challenges to Asian agriculture

A number of challenges are facing Asian agriculture. They include accelerated globalisation, and further trade liberalisation, sweeping technological changes, degradation of natural resources and increasing water scarcity, emerging and re-emerging health and nutrition crises, rapid urbanisation, and changing structure of farming and agribusiness.

Accelerated globalisation including trade liberalisation

The failure of the WTO meeting in Cancun to move towards more trade liberalisation of agricultural and food commodities was a major blow to the world community in general and to developing countries in particular. Failure by the OECD countries to reduce trade-distorting behaviour is severely harming developing-country agriculture and the rural as well as urban poor in those countries. Harmful policies include agricultural subsidies linked to quantity produced, dumping of surplus production on developing country markets, and offering subsidised food commodities on the international market at prices significantly below production costs.

According to Oxfam estimates, the world market prices for maize are only 80% of the production cost in the US from where wheat is sold on the international market at roughly half the production costs. Sugar prices on the international market are only about one-fifth of the EU production costs and the cotton market is badly affected by US subsidies. It is virtually impossible for developing country farmers to compete in the international market at those highly subsidised prices. Furthermore, except for special and preferential treatments, it is virtually impossible for developing countries to enter the OECD markets with commodities such as sugar, rice, meat, cotton, dairy products and groundnuts because of extremely high import tariffs. There are large differences between the trade positions of the various countries in Asia, with some, such as Vietnam and Thailand, being major exporters of rice and others net food importers. Others, such as South Korea and Japan, maintain high levels of trade-distorting protection of their agriculture. In spite of these differences, I believe the region would benefit greatly from reductions in the trade-distorting OECD policies. The challenge to Asian agriculture is to develop the infrastructure, technology, and institutions that are needed to support not only increasing productivity but also the ability to change the production patterns and commodity portfolio in response to relative price changes on the international market. Ability to meet existing and emerging non-tariff barriers in OECD and Asian countries, such as increasing quality standards and new food safety demands, is also a major challenge.

Sweeping technological changes

Achieving equitable and sustainable rural growth will be an important challenge for the 21st Century. Agriculture will play a prominent role, particularly in countries where it provides a large percentage of the national incomes, such as Myanmar, Laos, Nepal and Cambodia. The importance of agriculture as the driver of economic growth and poverty alleviation is due not only to its large share of national incomes and employment but also to the large multiplier effect associated with agricultural growth. Studies in Asia have shown that for every dollar of additional agricultural income, incomes in society as a whole are likely to increase by between two and three dollars. The most powerful illustration of this multiplier is found in China beginning in the late 1970s. These multipliers are important not only in the above mentioned countries where more than one-third of the gross national product comes from agriculture but also in countries such as Pakistan, India, Bangladesh, Vietnam and Sri Lanka where roughly one-quarter of the national income is from agriculture. The key to agricultural growth in Asian countries is productivity increases from land, labour, and water. Producing more per unit of each of these three scarce resources is of critical importance not only for agricultural growth but for general economic growth and poverty alleviation. Agricultural growth is also needed to meet future food demands and to help protect natural resources.

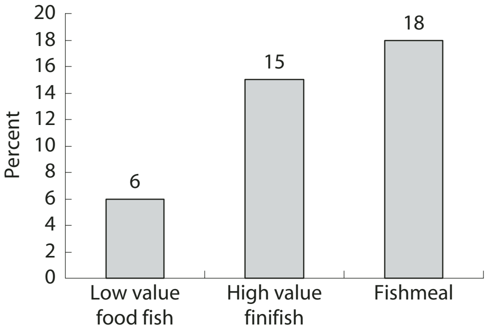


Figure 25. Projected real price change of fisheries commodities, 1997–2000 (%).

Although an increasing share of the agricultural research that is needed to generate the productivity increases needed will come from the private sector, there is an urgent need for accelerated public investment in the kind of agricultural research that is needed to produce the public goods type technology needed by small farmers in Asia. Benefits to society from such research generally exceed 20% per year compared to long-run real interest rates of 3–5% for government borrowing. Modern biotechnology can contribute to the development of the technology needed for Asian agriculture. When used in conjunction with traditional agricultural research methods, biotechnology can be a powerful tool to increase agricultural productivity and reduce poverty. It should be used where appropriate to develop solutions for problems faced by small-scale farmers.

A number of different modern biotechnology methods are being used in Asia including marker-assisted breeding and tissue culture. Genetic engineering is being applied in only a few countries. Among Asian countries, only China and India have a significant area planted to genetically modified crops. In China, more than 100 genetically modified crop varieties have been authorised for release while commercial production of genetically modified crops in India is limited to Bt cotton. Thailand and the Philippines have modest research efforts in progress although, except for Bt maize in the Philippines, no GM technology has been approved for commercial production. In addition to the new technological advances in molecular biology, Asian agriculture could benefit greatly from increased use of new information and communications technology, particularly to improve sustainability in production and to obtain better market information.

Degradation of natural resources and increasing water scarcity

Degradation of natural resources is rampant in many resource-poor areas of developing countries, particularly those with fragile soils, irregular rainfall, a relatively high population concentration, and stagnant productivity in agriculture. Natural resource degradation is also occurring in agricultural areas of Asia that have been exposed to misuse of modern farming inputs. While natural resource degradation is often a consequence of poverty, it also contributes to poverty. Such a downward spiral is found in many parts of Asia where low income people reside. Investments in rural infrastructure and institutions as well as appropriate policies and technologies are needed to identify win–win situations where productivity can be increased without doing damage to natural resources. Such win–win scenarios are plentiful and there is no reason to believe that productivity increases can only be obtained at the expense of natural resources. In fact, much of the natural resource degradation that occurs in Asia is a result of low productivity and resulting unsustainable survival behaviour coupled with government failure to invest in the so-called ‘low potential’ areas where a large share of the world’s poor people live.

Unless properly managed, fresh water may well emerge as the most important constraint to food production in an increasing number of areas including parts of Asia. Water is poorly distributed across countries as well as within countries and between seasons. As shown earlier in this paper, the demand for water other than for irrigation will grow rapidly in Asia. The costs of developing new sources of water are high and rising and non-traditional sources such as desalination, reuse of waste water, and water harvesting are unlikely to add much to Asian water availability in the near future, although they may be important in some local or regional ecosystems. The rapidly growing domestic and industrial demand for water will have to be met with reduced use in the agricultural sector. Reforming policies that are contributing to wasteful use of water offers considerable opportunity to save water, improve efficiency in water use, and boost crop output per unit of water. Policy reforms needed include establishing secure water rights of users, decentralising and privatising water management functions, and setting incentives for water conservation—including markets in tradeable water rights, pricing reform, and reduction in subsidies.

Emerging and re-emerging health and nutrition crises

The devastating effects of HIV/AIDS on the well-being of millions of people and the grim prospects for its rapid expansion in parts of Asia have serious implications for future agricultural development and food security. While HIV/AIDS has historically been viewed as an African problem, it is spreading rapidly in many parts of Asia. In those African countries such as Uganda where governments recognised the increasing prevalence of HIV/AIDS and put in place effective interventions, the spread of AIDS has been brought under control. In other countries such as South Africa, where the government is more hesitant to recognise the importance of the problem, it is out of control. The lesson for Asia is to pursue transparency, foresight, and appropriate interventions instead of failing to recognise the problem until it is out of control. Preparing for the impact of HIV/AIDS on the agricultural and rural labour force and on health care expenditures would be an appropriate action.

A number of other health problems including chronic diseases resulting from overweight and obesity may play an important role in future agricultural development and food security in the region.

Rapid urbanisation

As already discussed, while the rural population of Asia is expected to reach a growth rate of zero within the next five to 10 years, the Asian urban population will continue to increase at significant rates. The rapid increases in urbanisation will mean new challenges to the Asian agricultural sector partly because of the new demands on transportation, processing, storage, and other marketing activities and partly because of the above mentioned dietary changes that tend to follow urbanisation. Policies will be needed for improved infrastructure, markets, and institutions to meet the rapidly increasing food demand from urban centres.

Changing structure of farming of agribusiness

Rapidly changing structure of farming and agribusiness pose a serious challenge to Asian agriculture. Partly in response to increasing globalisation and partly because of the stagnation and expected decrease in the rural population, the small farms typical of many of the Asian countries are likely to be less viable. This is so partly because of the higher marketing costs associated with the collection of products from many small farms and partly because these small farms are unlikely to be able to provide the desired income levels for the farm family. Rapid concentrations in the agribusiness will further push the structure of farming towards larger and more specialised farms simply because that is expected to reduce unit costs in production and marketing. Past trends of rapidly increasing off-farm income among small farmers is likely to continue. It is less clear whether many small farms will in fact be merged into larger farms or whether small farming will coexist with an increasing share of off-farm employment. Undoubtedly, the changes that do occur will vary with location.

Concluding comments

There is great variation among Asian countries and attempts to derive uniform policies for all of Asia would not be useful. Clearly, the policies needed for agriculture in Korea and Taiwan are different from those needed in Laos and Cambodia. Therefore, the challenges I have discussed above may be more relevant to some countries than others. Similarly, policy priorities will vary widely. However, at the most general level, I believe that six policy areas should be considered by most Asian countries to further accelerate economic growth, reduce poverty and hunger, and achieve sustainable management of natural resources. These policy areas are, in my opinion, the following:

1. Investment in human resources through primary education, primary health care, and access to clean water, with emphasis on neglected rural areas.
2. Improving access to productive resources and employment for the rural as well as the urban poor.
3. Policies to promote pro-poor technological change in agriculture as already discussed.
4. Policies and institutions that would facilitate the capture of benefits and reduce the risks associated with globalisation including trade liberalisation.
5. Investments in rural markets and rural infrastructure.
6. Further policy guidance to improve the rural capital and labour markets.

Asia has made tremendous economic progress during the past 30 years instigated in most, but not all countries, by rapid productivity increases in agriculture. The role of agriculture as the driver of economic development in low income countries is extremely important but frequently overlooked. We need to constantly remind policy makers of the importance of agricultural growth not only to produce more food, but to generate income within and outside agriculture and to hopefully eradicate poverty and hunger.

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Sustainable agriculture and efficient water use in Monsoon Asia

Kunio Takase[1]

Abstract

The world knows little about Monsoon Asia's agriculture even though it feeds 54% of the world's population but uses only 14% of the world's land. Within 30 years from when the International Rice Research Institute (IRRI) and the Asian Development Bank (ADB) were established in Manila, most Asian countries had achieved self-sufficiency in rice by using the green revolution technologies of irrigation management, high-yielding seeds and fertilisers. It also built up the foundation of the 'East Asian Miracle' in early 1990s, through integration of agricultural processing and marketing.

Irrigated rice is an engine of life, which sustains high-yield, abundant, high-nutritional elements and a long history of cultivation. The networks of irrigation and drainage provide life-supporting water to every kind of creature and so contributes to biodiversity and environmental protection. However, different rainfall and soil conditions have led to unique and efficient water management systems to meet the local people's traditional socioeconomic choices. This paper highlights seven such examples in the Philippines, Thailand, Indonesia, China, Sri Lanka, Cambodia and Syria.

After successfully increasing food production, Monsoon Asian countries are now challenging much broader targets for human welfare through crop diversification and agro-industries for higher income and sustainable rural development. At the beginning of the 21st Century, one of the most difficult problems is how to sustain efficient irrigation management. 'Participating Irrigation Management (PIM)' initiated by the World Bank in 1995 has encountered a vicious circle. It appears that this now needs to be extended to 'Community Owned Management (COM)' which will give stronger incentives to farmers and, at least, land cultivation and water use rights.

Finally, the tragic event in the USA on 11 September 2001 demonstrated that 'narrowing the gap between the rich and the poor' is more important than simple 'Poverty alleviation'. The United Nations is asked to seriously consider this aspect and initiate a comprehensive study leading to global structural reform, beyond the Millennium Development Goals (MDG).

Historical review of agriculture in Monsoon Asia

THE ASIAN DEVELOPMENT BANK (ADB) was established in 1966, coinciding with the time of the major technical breakthrough in rice production led by the International Rice Research Institute (IRRI) that laid the foundation for the green revolution and spurred considerable socioeconomic growth in the Asian region. In 1967, the ADB took its first technical assistance entitled 'Asian Agricultural Survey', which visited 15 Asian counties for six months, by 18 world-renowned agricultural experts including ones in livestock, forestry, fisheries, processing, marketing and institutions. It published a comprehensive report (787 pages) in 1969.

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Figure 1 summarises the progress in rice production in Monsoon Asian countries compared to historical development in Japan. The ADB recognised three unique features of agriculture in Monsoon Asia:

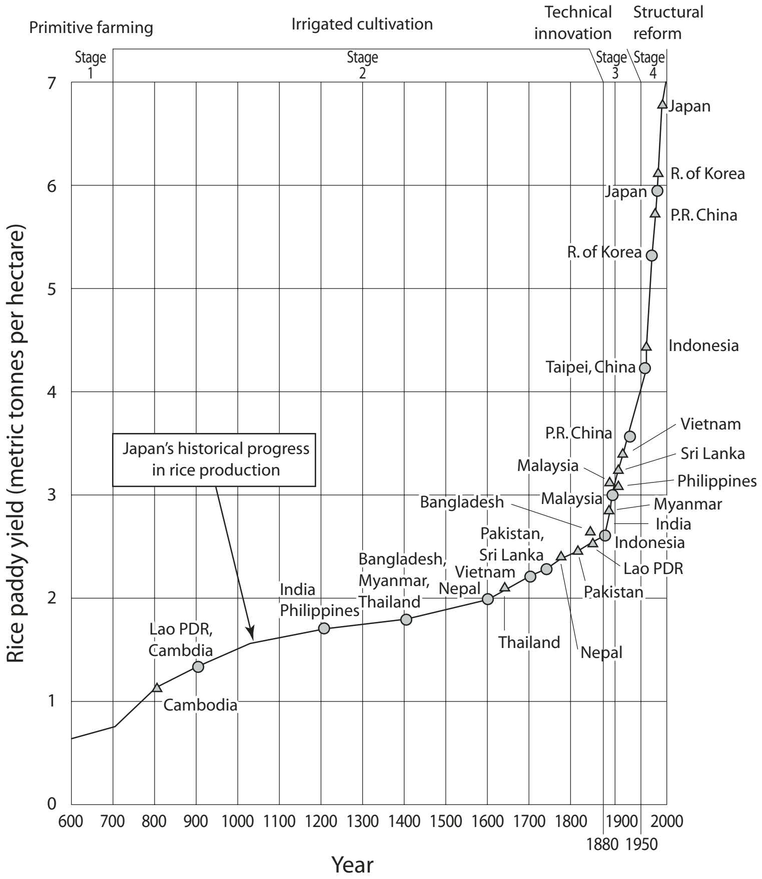
- heavy monsoon rainfall in most areas, averaging 1500–2000 mm a year
- rice as the single major crop
- the predominance of small-scale subsistence farming with an average farm size being one hectare or less.

As well demonstrated in Japan's 1200-year history, there were the three development stages of:

- irrigation
- technical innovation (seed and fertiliser)
- structural reform.

The ADB, together with other donors, after a strong request from member countries, placed massive investments during the past two decades into irrigation coupled with other inputs. Most Asian countries doubled their rice yield in 15–20 years and this formed a sound basis for the rapid industrial expansion, which became known as the 'East Asian Miracle', in the 1990s.

Monsoon Asia is roughly defined as East Asian countries having more than 1000 mm of annual rain and being affected by year-round seasonal winds (Figure 2).



Source: Takase, k. and Kano, T., 1967, "Development Strategy on Irrigation and Drainage", Asian Development Bank, Asian Agricultural Survey (Tokyo, University of Tokyo Press, 1969), p.520.

○ : updated by Dr. W. David Hopper, Vice President of the World Bank, 1976

△ : further updated by IDCJ, based on FAO Production Yearbook, 1994

Figure 1. Progress in rice production in Monsoon Asia.

Figure 2. Rainfall distribution in Monsoon Asia.

Efficient water use in Asian countries

Irrigated rice is an engine of life

Rice can be grown in upland areas, but the introduction of irrigated rice can substantially increase yields, if enough water is available. Irrigated rice allows repeated cultivation, while upland rice cannot be repeatedly cultivated. The Asian monsoon region sustains 54% of the world's population with only 14% of the world's land. This is possible because of efficient water use for irrigated rice.

Rice typically contains 76% carbohydrates, 7% protein, 1% fat, and various other nutritional elements including vitamins B_1 and B_2, and a variety of amino acids. Polished rice contains 356 kilocalories per 100 g. In other words, rice is an outstanding food. It also has higher yield and carrying capacity per harvest area than any other cereal.

With a long history of irrigated rice cultivation, the Asian monsoon region has networks of irrigation and drainage canals that transport nutrition to the land, working in a manner similar to arteries and veins. Some drinking and industrial water is also transported and stored in these networks. Thus, the networks provide life-supporting water to every kind of creature nurturing the environment and rich biodiversity. Irrigation systems in different rainfall and soil conditions, however, developed their unique features.

Irrigation water management in the Philippines

The Asian Agricultural Survey, undertaken by ADB in 1967, identified and recommended that effective water management should be the top priority for increasing rice production in Monsoon Asia.

The Angat Dam in the Philippines was built in 1927 and covered more than 30,000 ha; however, water management was not effective. A 140-ha pilot farm was established with ADB's technical assistance in 1968–69 with the farm ditch density being increased from 16 to 62 m/ha. Demonstrations and training sessions were followed by the application of IRRI's high-yielding variety and fertiliser. Yield under the pilot scheme increased from 2.3 tons/ha in 1968 to 3.1 tons/ha in 1969. Farmers willingly paid their irrigation service fees to the government (Figure 3).

Chao Phraya River Basin, Thailand

The vast delta region of the Chao Phraya River Basin in Thailand used to be historically unsuitable for agricultural production and was wasteland. Today, however, with progressive paddy field development, it is now the principle granary region of Thailand. With improved irrigation and drainage systems, there has been a shift from single crops of paddy rice to diversified farming including vegetables and fruits. Agricultural water now provides a regional water supply that is used widely, for example, for irrigating upland fields, rearing domestic ducks and domestic water supply (Figure 4).

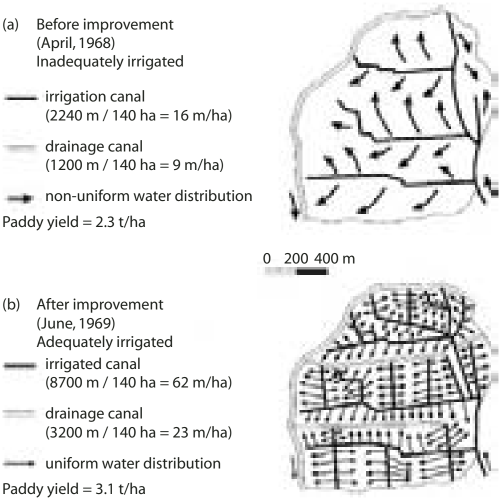


Figure 3. Irrigation improvement in the Angat Pilot Program, the Philippines (RWIWM 1973).

Subak irrigation system, Bali, Indonesia

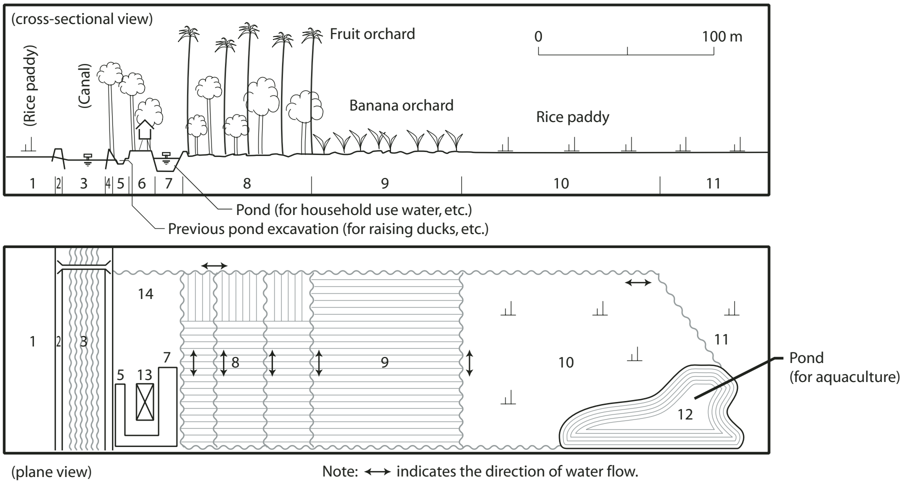
Balinese irrigation is organised under the cooperative subak system (The 3rd World Water Forum 2003). Irrigation is designed and operated so that it is:

- environmentally sound
- fair
- transparent
- accountable.

To satisfy these principles, the irrigation system is designed and operated for a particular hydrologic area with a clear relationship between locations of a farmer's land and their irrigation network including separate feeding and drainage channels. The system uses the width of a weir as a measurement and this is proportional to the amount of water allocated to an irrigated area. One share of water allocation is called a tek-tek.

The simple subek design allows all members to:

- get a volume of irrigation water proportional to their land area and its distance from the water source
- recognise their obligations and responsibilities for maintaining irrigation structures in their irrigated area
- implement crop diversification on their own land with certain conditions.



Source: History of rice in Asia, Yoshihiro Kaida, et al.

Figure 4. Diversified agricultural production, Thailand (JIID, 2003).

The system is also designed to adapt to flow changes whether excessive flow during flooding, or limited flow during the dry.

Source: Sahid Suanto, Sigit Supadmo Arief, Gadjah Mada University

Sixth industrialisation of agriculture, China

The model shown in Figure 5 summarises a philosophy agreed to by an IDCJ Mission visiting in 1997 and the Chinese Government. It contains both agriculture industrialisation (the combination of agricultural production, processing and marketing) and effective linkages among agriculture (including livestock), forestry and fishery sectors. The key strategy of the Chinese government for developing a market economy and sustainable rural development is expressed in this model. The three merits are that:

- agriculture, forestry, livestock and fisheries can co-exist while mutually benefiting each other by maximising their contribution to human life, including food, building materials and fuel
- this model serves best for natural resource management, which includes environmental conservation, and contributes to sustainable rural development through tourism and cultural and historical development
- it adds substantial values by processing low-value primary products through secondary and tertiary industries such as marketing, which results in the compounding of the sixth highest income industry in rural society.

Tank irrigation for multi-purposes, Sri Lanka

The special feature of the ancient civilisation of Ceylon was its irrigation works. Two different systems of irrigation were adopted: rivers were diverted along excavated channels which conveyed water to more distant lands, or water was impounded in reservoirs from which it was gradually released to paddy fields. Small village reservoirs were a unique feature of the ancient hydraulic civilisation in Sri Lanka. These small reservoirs were called tanks and formed the nucleus of the village hamlet. From the tanks, the water was conducted to paddy fields through networks of canals and the tanks were arranged in cascades, so that the lower ones collected run-off from those upstream. There could be over 50 tanks in a single cascade system. Some of the ancient tanks in Anuradhapura in Sri Lanka are now under the world heritage sites of UNESCO.

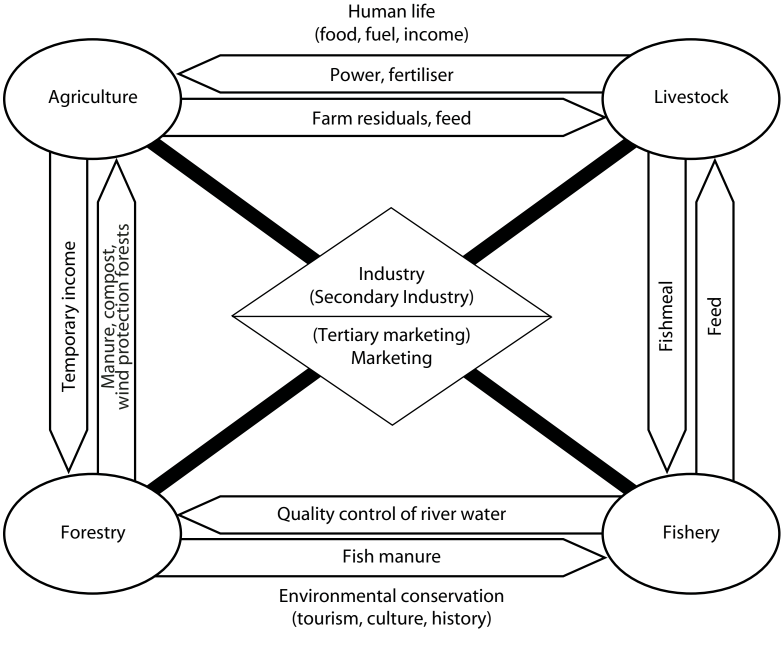


Figure 5. A new era for agro-industry, China.

The multiple roles of irrigation are:

- efficiency
- food security
- prevention of urbanisation
- other domestic needs.

Source: G.T. Dharmasena, Department of Irrigation, Sri Lanka

Multi-functional *colmatage*, Cambodia

Agriculture is the backbone of Cambodia's economy and society, and paddy rice is the most important single crop. It occupies about 2 million ha (70% of the cultivated area), accounts for 11% of gross domestic product (GDP), and represents about 70% of average daily calorie intake. Achieving food security for all is a basic goal of the Royal Government, which places considerable emphasis on rural and agricultural development.

The three principal rice production systems in Cambodia are:

- rainfed (non-irrigated) agriculture
- full irrigation
- recession rice cultivation.

A distinctive aspect of the recession rice cultivation is *colmatage* farming, in which canals lead water from the major rivers during the flood season, into the lower elevation land behind the levees (The 3rd World Water Forum 2003).

The principal benefit of irrigation and drainage is, of course, water control, which helps farmers avoid the effects of lack of water or excessive water. The *colmatage* system also provides sediment control, replenishing soil fertility and allowing land reclamation. However, traditional practices also help:

- maintain Cambodia's biological diversity
- conserve seasonally flooded forests, shrublands and associated ecosystems
- conserve natural fish habitat, and support a large capture fishery
- provide opportunities for field-based aquaculture
- mitigate flooding downstream from irrigated areas
- provide drinking water for people and livestock
- provide tracks and roadways that are above flood level
- recreation
- preserve Cambodia's cultural heritage
- create a distinctive and attractive landscape
- maintain social relationships in rural areas
- provide off-farm employment, for example, in the construction industry.

Source: Theng Tara, Pich Veasna, Paul Mosley; Ministry of Water Resources and Meteorology, Cambodia

Semi-arid land-use patterns, Syria

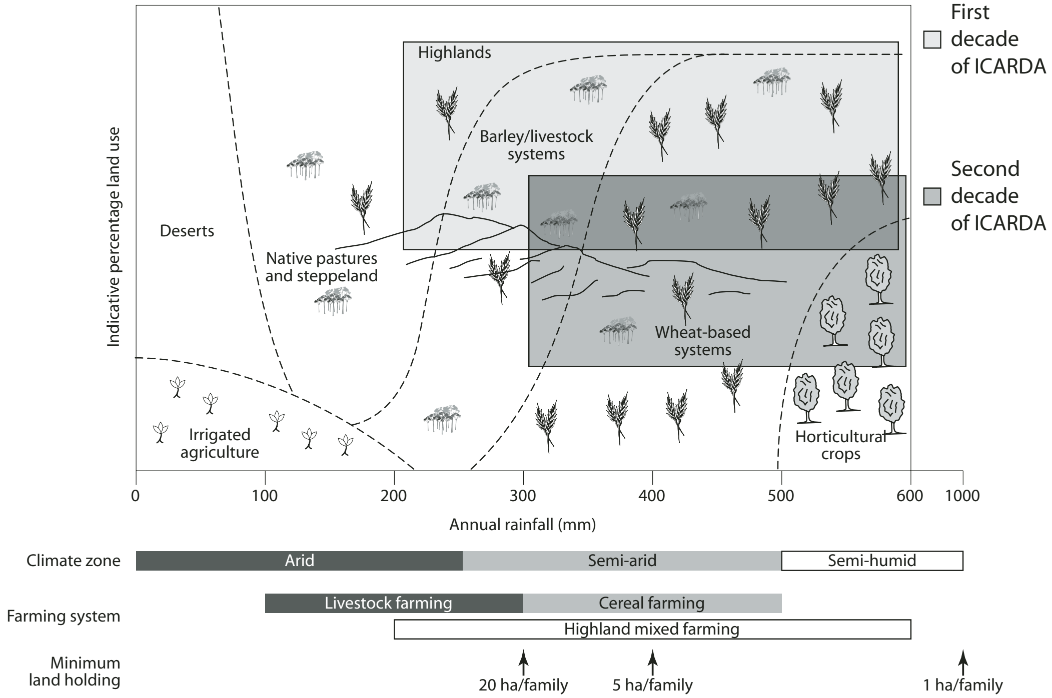
An IDCJ mission visited ICARDA (International Center for Agricultural Research in the Dry Area) in 1992 looking at alternative land uses in semi-arid areas where annual rainfall is less than 500 mm. The share of the agricultural sector in GDP decreased from 29% to 22% during 1965–89. Major crops are barley (1.5 Mha, average 1982–87), wheat (1.2), olive (0.3) and cotton (0.15), the latter being Syria's biggest cash crop. About 55% or 10.2 Mha of the land is classified as desert and steppe which is not suitable for rainfed planting. Thus, the share of the livestock sub-sector in agricultural production is large (33%).

The minimum land area needed to support a family is 1 ha in an area with more than 1000 mm/year rainfall. The minimum area increases to 5 ha/family with 400 mm/year, and 20 ha/family with 300 mm/year. With 600 mm/year or more, families depend on sedentary agriculture. In an area with less than 100 mm/year rainfall, no agriculture is possible without irrigation (Figure 6).

Sustainable rural development strategy

'Food production' is, of course, the most important necessary condition of human welfare, but 'socioeconomic' fairness is equally important for welfare. In other words, not only agriculture, livestock, forestry and fisheries production, but also water, health, education and environment are important factors contributing to sustainable rural development.

After World War II, most East Asian countries progressively changed their rural development strategies (Table 1). Food self-sufficiency was the top priority, except in Malaysia, where low-price rice can be easily imported from Thailand. The green revolution in rice production, which started at IRRI in the 1960s, spread rapidly to most Asian countries and made them self-sufficient in rice by the late 1980s. Crop diversification then became the main aim of most countries. The incidence of poverty sharply decreased from 53% in the 1970s to 12% in the 1990s. However, equitable income distribution including land reform has not yet been satisfactorily achieved.



Source: ICARDI (with some additional information by the mission)

Figure 6. Semi-arid land use patterns, Syria (Takese 1993).

Table 1. Agriculture and rural development in Monsoon Asia.

Year	Strategy				
	Food[a]	Income	Equity (land reform)	Diversification[b]	Environment[c]
1945					
	Thailand		(Japan)		
			(Korea)		
1950			(Taiwan)		
1960	Japan			Thailand	
		Japan			Japan
	Taiwan		(Philippines)	Malaysia	
1970		Korea			
	Korea				
	Philippines	Taiwan		Taiwan	
1980		Malaysia	(China)		Taiwan
	Indonesia		Malaysia	Indonesia	
	China	Thailand		China	Korea
1990			Thailand		
		Philippines	Indonesia	Philippines	
		Indonesia			
2000		China			China

[a] Malaysia has never achieved self-sufficiency in rice.
[b] Japan and Korea did not achieve crop diversification mainly due to cold winters.
[c] Four other countries did not enforce a strong environmental policy.

Participating irrigation management (PIM) is not enough

Over the past 20 years or so, most of the world's irrigation authorities have been working hard to turn some of their responsibilities for facilities and water allocation over to farmers in an effort to reduce government supervision and expenses. The World Bank took the initiative in creating an international PIM network together with a number of participating countries in 1995. However, there is a vicious circle of 'insufficient facilities', 'inadequate water management', 'insufficient cost recovery' and 'insufficient facilities'.

At the request of the JBIC (Japan Bank for International Cooperation), the IDCJ in 2002 evaluated intensively eight irrigation projects financed by JBIC that had previously been evaluated in 1992. They include three projects in Indonesia, and one each in Sri Lanka, Jordan, Tanzania and the Dominican Republic, all of which were built during 1978–85. The IDCJ Mission was surprised to find that most of them required 'rehabilitation' within 5–6 years due to improper operation and maintenance. Properly maintained, they should last 30–50 years. The mission recommended not to use the word 'rehabilitation' which so easily justified obtaining funding from JBIC, but 'renovation' which means 'qualitative improvement of institutional and physical sustainability'.

In conclusion, the acronym 'PIM' is not enough and needs to be replaced by 'COM' (community owned management). This will encourage farmers to take responsibility for establishing a system, at least for land-cultivation and water-use rights. In Japan, the 'Land Improvement Law' was established in 1947 and, under it, farmers can ask the government to construct an irrigation system with a 2/3 majority consensus of more than 15 farmer members. Land ownership and full operation and maintenance responsibility of irrigation water including costs, rest in the irrigators' association.

Global vision in the 21st Century

Inequality between rich and poor

Major donors stress 'poverty alleviation' as the top priority of development. The World Bank President, MacNamara, emphasised this point in his historic Nairobi speech in 1973, but, unfortunately, since then the gap between the rich and the poor has widened. Limited global resources are rapidly being destroyed by the rich, and this is preventing sustainable development for the poor (Figure 7). The poor have no option but to survive, while the rich have many options to modify their life styles and unsustainable consumption patterns.

A proposal to the United Nations

During the post-cold war period, most insurgencies arose from poverty, and a feeling of inequality emerged in people within the same country when they compared themselves to people living in other countries. These inequalities are now readily conveyed by media like television. The tragic event in the USA on 11 September, 2001 demonstrated that 'narrowing the gap between the rich and the poor' is more important than simple 'poverty alleviation'. The author would like to propose the following global structural reform to the United Nations.

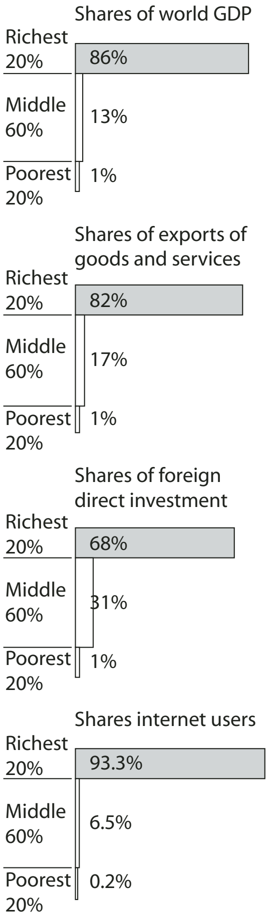
The present gap between 'developed' and 'developing' countries (23:1) could be narrowed down to 10:1 in 50 years if the population growth were controlled to the levels of 0.6% and 1.1% and the GNP annual growth were adjusted to 2.4% and 4.6%, respectively (Table 2).

This proposal may be too simple and deficient in many aspects; however, it is a starting point to reach a meaningful global strategy to quantify influential factors including population and GNP growth. The United Nations is requested to seriously consider this aspect and to initiate a comprehensive study leading to global structural reform, beyond the Millennium Development Goals (MDG).

Acknowledgment

The author would like to record that the substantial part of this has already been published on 15 February 2003, under the title of 'Kunio Takase: Japan, Monsoon Asia and the Global Agricultural Revolution in the 21st Century', ©Springer-Verlag 2003, Paddy Water Environ (2003). Major changes to it include: (i) expansion of efficient water use systems in several Asian countries; (ii) less emphasis on Japanese and African agriculture; and (iii) more activities by IDCJ. The title of this paper is also changed to 'Sustainable Agriculture and Efficient Water Use in Monsoon Asia'.

(1)



(2)

Category	Products	Developed/ Developing
Food	Cereals	3
	Milk	8
	Meat	6
Forest	Sawn wood	11
	Paper, etc	14
Industrial	Fertilizers	5
	Cement	3
Metals	Copper	19
	Iron & Steel	13
	Aluminium	19
Chemicals	Inorganic	20
	Organic	17
Transport	Cars	24
	Commercial vehicles	125*
Energy	Solid	10
	Liquid	19
	Gas	13
	Electricity	10
	Emissions	8
Average		12–18*

Figure 7. Global shares and consumption patterns (UNDP,1999; Parikh 1995). (1) Global shares in 1997 (2) Consumption patterns/cap in 1987–88.
* Indicates the higher value obtained when commercial vehicles are included.

Table 2. Evolution of Japan's Strategy on Global Agricultural Development[a] (Takase 1994).

Development factors		Unit	Year		Annual growth	
			1990	2040		
Population	(Total)	Million	5000	8200	1.0	Absolute GNP annual growth (%)
	(Developed)		900	1100	0.6	
	(Developing)		4100	7100	1.1	
GNP per capita	(Total)	$	3800	10 000	2.0	
	(Developed)		18 700 (23)	45 000 (10)	1.8	2.4
	(Developing)		800 (1)	4500 (1)	3.5	4.6
World Total GNP		$ Trillion	19.0	82.0		3.0[b]

[a] World Development Report (1991). There are 25 'developed' countries with a GNP per capita of $6000 or more, while 99 other countries are still 'developing'.

[b] This was the same target as suggested in 'Our Common Future' (1987).

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The economics of rice double-cropping with supplementary irrigation in the rainfed lowlands of Cambodia: a survey in two provinces

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Abstract

The use of small-scale, supplementary irrigation is seen as a potential method to overcome a severe constraint in rainfed lowland rice production, permitting a move from single- to double-cropping and thus improving food security and farm incomes. In Cambodia, a single rice crop grown on infertile soils under unfavourable climatic conditions is the most common practice. With poor yields and low levels of land use, farmers regularly experience food shortage and poverty. Based on supplementary irrigation from privately owned tube-wells or on-farm reservoirs, farmers in some areas have been able to grow an additional, short-term rice crop at the start of the wet season using modern varieties. In this study, the effect of double-cropping on farm incomes and on the use of farm resources were assessed, and farm-level constraints to the adoption of double-cropping identified. A survey was conducted in two locations in southern Cambodia, one in Takeo Province where conditions were favourable for supplementary irrigation, and one in Kampot Province where conditions were less favourable. Data about production practices and the costs and returns of single-cropping and double-cropping were collected by interviewing 115 randomly selected farmers. It was found that moving to double-cropping could increase food supply by 75% in Takeo and 22% in Kampot, and farm family income by 37% in Takeo and 25% in Kampot over a full farm-year. This was achieved mainly by using farm resources better, with land use of 150% in Takeo and 122% in Kampot. Using wells and pumps for supplementary irrigation improved returns in Takeo, whereas farmers in Kampot were limited by their reliance on surface storage. Thus, a lack of tube-wells and pumps to access groundwater is the key obstacle to expansion of the double-cropping area, both within and between regions.

Introduction

RICE is not only the staple food for Cambodia but rice production also contributes a major share of the national economy (FAO/WFP, 2000). The success or failure of the rice crop has a critical effect on food security, gross domestic product, and employment of rural labour. Cambodian rice yields and production had been high until the late 1960s (Helmers 1997). Indeed, Cambodia was one of the region's rice exporters. However, because of the civil war and social and political upheavals of the 1970s and after, Cambodia not only missed out on the green revolution which benefited most other rice-producing countries in Asia, but also lost much of its existing production potential. Hence, rice production started to decline shortly after 1970 and has not yet fully recovered, even though production has slowly

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increased after the collapse of the Khmer Rouge regime in 1979 (Chandler 1993, Helmers 1997, Makara et al. 2001).

The constraints to rice production in Cambodia in the past two decades include the loss of land to landmines, lack of infrastructure (roads, irrigation), lack of research and extension, and lack of access to inputs and credit.

There are also two longer-term factors that limit Cambodian rice production (Pingali 1988, Nesbitt 1997). First, most of the rice land in Cambodia is of low productivity due to poor soil fertility and physical conditions. Second, the highly seasonal pattern of rainfall contributes to very low yields and the high risk of yield loss—given that most rice production continues to take place in rainfed lowland conditions, the rainfall pattern has traditionally restricted farmers to a single crop of rice per year in the wet season (WS).

In principle there is potential to overcome some of these constraints and improve rice production in Cambodia by expanding the cultivated area and by crop intensification. Since there is negligible potential to expand the rice area in the rainfed lowlands, crop intensification is the most suitable strategy. Rice double-cropping (two rice crops a year on the same land) has been practised by Cambodian farmers, but this requires a full irrigation supply if the additional crop is grown in the dry season (DS). Irrigation infrastructure is likely to remain limited for some time in most of the rainfed lowlands. Alternatively, in recent years it has emerged that, using a robust, short-term, introduced variety (IR66), an additional crop can be cultivated in the early wet season (EWS) with only supplementary irrigation, using underground water or surface reservoirs to reduce the risk of drought (Cox et al. 2001, Young et al. 2001). This may be both more feasible and more economically efficient, given Cambodia's current resource constraints.

The adoption of this latter form of rice double-cropping relies on two important factors, the availability of suitable modern rice varieties and supplementary irrigation. The scale of adoption not only varies from location to location but also from family to family within a small village. For example, those farmers who are able to access supplementary irrigation may cultivate a larger area than those who depend entirely on rainfall. Socio-economic factors may also influence the practice of rice double-cropping since the shift from single- to double-cropping involves significant changes in the production process: changes to the cropping calendar, increased use of cow manure and chemical fertilisers, and increased labour costs. A credit source may also be important in allowing farmers to invest in supplementary irrigation, for example, by buying a pump, installing a tube-well or excavating a pond.

This study aimed to assess the impact of the EWS-WS pattern of rice double-cropping on farm incomes and the use of farm resources, and to identify farm-level constraints to the adoption of double-cropping. It was hypothesised that double-cropping could increase farm income over a full farm-year and use farm resources more efficiently than if single-cropping was used. However it was also hypothesised that shortage of capital to install tube-wells and pumps for supplementary irrigation was the key obstacle to the adoption of double-cropping.

The study consisted of a survey of 115 rice farmers in two locations in southern Cambodia, both part of the same rainfed, lowland environment. The locations were selected because it was known that some farmers were practising EWS cropping. The first location was in Takeo Province, about 60 km south of Phnom Penh, where 54 households from three adjacent villages were surveyed. The second location was in Kampot Province, about 90 km south-west of Phnom Penh, where 61 households from one village were surveyed. Rainfall in Kampot (1800 mm) was higher than in Takeo (1250 mm), though in both locations rainfall was highly variable and drought was a serious constraint. Soils in Kampot were somewhat sandier and less fertile than in Takeo, but in both places were not very favourable for rice production. The practice of rice double-cropping occurred to some extent in both locations. The key difference between the two was access to supplementary irrigation, which was more advanced in Takeo than in Kampot. Hence, overall the Takeo site was more favourable for double-cropping than Kampot.

Survey methods

The survey was in January and February 2001. General observations were made of fields and cropping patterns in each of the four villages, and discussions were held with key informants (the village head, vice head, and some other villagers) to gain a general picture of the village. This provides us with critical information such as the number of families, population, land tenure, village size, village geography, area of rice production land, cropping pat-

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terns, land classification, and farming and non-farming activities. In each case, before the household interviews began, a talk was held with the village head to ask permission for the survey.

In Takeo Province there were 18 respondents from Tungke Village, 16 from Sla Village and 20 from Snao Village—54 respondents in all, representing a sampling fraction of about 11%. In Kampot Province all 61 respondents were from Damum Village, representing a sampling fraction of about 27%. There was no previous stratification of farmer interviewees into single-cropping and double-cropping farmers. The respondents were approached directly without being aware of their cropping practices. Hence the proportion of single-cropping respondents and double-cropping respondents differed in each location.

A questionnaire was developed with 59 mostly open-ended questions and some sub-questions. The questionnaire contained such questions as household membership, land holdings, cropping patterns, inputs and outputs for rice production, use of farming equipment, supplementary irrigation, and reasons to practise double-cropping of rice. The only preliminary question used to screen farmers was whether they grew rice. To obtain as random a sample as possible, interviews began with a few households along the main road of the village and proceeded across the village lands to both sides of the road toward the village boundaries. There may, however, have been a slight bias towards double-cropping households, as single cropping was more likely in remote, less accessible farms.

Profiles of the survey sites

Takeo Province

Three villages, Tungke, Snao and Sla, all located in Prey Kabas District, were included in the survey in Takeo Province. The soils, climate, land tenure, farming resources and farming activities of Tungke, Snao and Sla were similar.

Tungke was one of five villages in Snao Commune, Prey Kabas District, about 10 km from Highway 2, which runs south from Phnom Penh. The road linking the village to the highway was narrow, unsealed, and full of potholes. There were 176 households in Tungke with a population of 866. As in the other two villages, almost all the adult population in Tungke earned a living through farming. Rice production generated most income for most households. About 70 households (40%) practised double-cropping of rice, and the rest grew a single wet-season rice crop. The total area of the village was 304 ha, comprising 21 ha of housing land, 32 ha of upland crop land, 102 ha of upper field rice land, and 149 ha of lower field rice land. The lower land was unfavourable for rice cultivation because of flooding nearly every year, but rice was sometimes broadcast on these lands in the hope of obtaining some yield.

Snao Village, bordering Tungke Village to the east, was part of Snao Commune in Prey Kabas District. The population was 1242 in 232 households. Snao Village occupied around 500 ha with 210 ha of direct-seeding paddy land (flooded fields), 198 ha for the main rice crop, 43 ha for non-rice crops, and 31 ha of residential land. About 80% of the villagers cultivated early wet season rice in addition to the main wet season rice crop. The cultivation of non-rice crops before wet season rice was also practised in this village.

Sla Village, located to the southwest of Tungke Village, belonged to Cha Commune, also in Prey Kabas District. Sla has a smaller population and land area than Tungke and Snao with only 81 households and 417 people. Of its about 200 ha of land, 12 ha was residential, 114 ha was used for main wet season rice, and 63 ha for direct-seeding paddy fields. It did not have an area for non-rice crops because villagers mostly cultivated non-rice crops within their home yards. Since the majority of Sla villagers occupied rice fields far from home, the percentage of households practising double-cropping of rice was only 40–50%.

Kampot Province

The second location for the survey was Damum Village in Baneave Commune, Chuk District, Kampot Province. It was about 7 km from Highway 2, 90 km southwest of Phnom Penh. Kampot is one of the two coastal provinces in Cambodia. Hence rainfall is higher than in Takeo Province.

The road linking Damum Village to the highway and to the district market used to be a constraint for travelling and transporting products but had just been reconstructed by the Ministry of Rural Development. The usual type of transport—a small two-wheel trailer pulled by a motorbike and carrying 10–15 people—was affordable by the farmers in the village at 500 Riels (US$0.13) per person for a single trip to the district market.

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The population of Damum Village was 1215 in 229 households. The village occupied more than 237 ha, including 199 ha of paddy, 7 ha for non-rice crops, 23 ha of residential land, 1 ha of dikes, 7 ha of canals and 0.4 ha for roads. The land holdings of each family in the village ranged from 0.2 ha to about 3 ha but the most common holding size was smaller than 1 ha. In contrast to the three villages in the first location, houses in Damum Village were scattered over the entire village area, with farmers generally building their houses on their own paddy lands. Because of the short distance between their dwellings and paddies, the transport costs for cow manure, chemical fertilisers, and post-harvest outputs would have been lower than in the Takeo villages. Crop management may also have been better because farmers could monitor their crops every day.

Almost all the population in the village earned their living through farming, in particular rice production. Double-cropping of rice was common in this village, with one crop in the early wet season and another in the wet season. However, the early wet season one was mostly cultivated on a small plot of land. Less than 10% of the 229 families cultivated only a single rice crop. Non-rice crops, including coconut, mango, cucumber and pumpkin, were cultivated around the home yard and (for vegetable crops) in the rice fields during the dry season. Besides keeping cattle for draught power, the raising of pigs, chickens and ducks was also an important source of farm income. Palm sugar production was popular in the village since the area was rich in palm trees and fuelwood was readily gathered from the nearby hills.

Costs and returns analysis

Definition and measurement of costs and returns

Even though agricultural economists use costs-and-returns analysis as a general tool, there is no standard set of definitions used to analyse the costs and returns of agricultural production (Herdt 1978). To avoid ambiguity, therefore, the definition of each category of costs and returns and the analytical techniques used in this paper are first explained. The definitions are intended to reflect those used in other developing countries because the ways in which Cambodian farmers access land, labour and capital for rice-farming are similar to those of other semi-subsistence farming economies.

Variable costs were classified into cash expenditure, in-kind expenditure, and family-labour costs. All costs of inputs were valued at market rates, even though farmers did not spend their own money for items such as family labour, seed, and cow manure. Any expenses that the farmers paid in cash for their rice production, for example, chemical fertilisers, pesticides, fuel, irrigation costs (such as pump hire), and other hired or contract labour costs, were considered cash expenditure. In-kind expenditure referred to inputs that were available within the farm household, such as rice seed and organic fertiliser, and contract labour paid in kind. Even though villagers in both Takeo and Kampot normally cultivated rice using family labour and exchange labour, they sometimes needed to hire extra labour during peak work periods. The hired labour cost was used as the standard for valuing family-labour inputs.

Having distinguished the categories of input costs, various measures of returns were defined. Gross income (GI) was the market value of the entire output the farmers harvested, based on the price at the time of harvest or interview (soon after harvest). Gross margin (GM) was measured as GI minus cash expenditure. Farm family income (FFI) was the result of deducting from GI cash expenditure and in-kind expenditure. Return to land (RTL) was calculated by subtracting from GI all cost items, except land, using imputed prices for all non-marketed inputs.

FFI was considered the most practical situation for semi-subsistence farmers since it represented a sustainable return to the farm family's labour and land, which are committed or 'sunk' in farming. That is, FFI can all be consumed or sold, and the cropping cycle can still continue, allowance having been made for cash and in-kind costs such as seed and manure.

Results for Takeo

Early wet season (EWS) crop

Eighty per cent of respondents in Takeo cultivated EWS rice. The area of EWS rice was generally less than the total rice area owned, with an average of 0.4 ha. The largest area of EWS rice was 0.9 ha, while the smallest was 0.06 ha. The majority of double-cropping farmers (58%) cultivated the EWS crop on less than 0.5 ha.

IR66 was the only variety used during the EWS by all the double-cropping farmers in the three villages.

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Most interviewees had adopted the IR66 variety for three years, some for longer. The reasons farmers gave for selecting this variety for the EWS was that it was a photoperiod-insensitive, short-cycle rice that produced good yields and had soft eating quality. The farmers had no idea of the original source of this variety because most farmers obtained the variety through their neighbours, though a few bought it from local markets.

Underground water with tube-wells and pumps was the most popular irrigation source for EWS rice in this area. Over 70% of the double-cropping farmers owned a tube-well and pump, while a few families who could not afford this equipment on their own shared it with relatives. Some households also cultivated EWS rice using water from surface storage such as ponds. Those who did not own a tube-well or did not have a pond could share a tube-well with other farmers but needed to hire a pump or cultivate EWS rice relying entirely on rainfall.

The EWS crop produced a quite promising grain yield, with an average of almost 3 t ha^{-1}. Even though two farmers harvested less than 2 t ha^{-1}, three others produced as much as 4 t ha^{-1} (Table 1). It may not be logical to conclude that the poor yield of the first two farmers resulted from illiteracy but it was observed that it was most difficult to obtain information from these two. In general, grain yields of the EWS crop varied between 2 and 3.5 t ha^{-1}. Of the EWS rice households, 26% practised the direct seeding method but the yield showed no difference between transplanting and direct seeding.

On average, the costs of EWS rice production were around US$270 ha^{-1}. Family labour was the most costly input at around US$125 ha^{-1}, while the paid out cost for chemical fertilisers, pesticides, fuel, and other contract labour was US$65 ha^{-1}. Besides the labour costs, cow manure was a costly input if valued at market prices. More than US$80 ha^{-1} was paid for in-kind expenses, mostly for cow manure.

With a good yield, the EWS rice could generate a relatively high gross income (GI). The average GI from EWS rice was US$260 ha^{-1} (Table 2), implying an average price of around US$90 t^{-1}. Total gross income was less than this, averaging US$110, because most cultivated areas were smaller than 1 ha. In fact, 89% of double-cropping farmers earned a GI of less than US$200 from EWS rice. Thus the distribution was highly skewed to the right, reflecting the distribution of cultivated area. Farm family income (FFI), which reflects farmers' bottom line, was also positive at US$110 ha^{-1} and comparable to the WS crop (Table 2). The negative figure for RTL did not necessarily mean the farmers were making a loss, as the opportunity costs of family labour were probably overestimated.

Wet season (WS) crop

In contrast with their plantings of EWS rice, all surveyed households planted WS rice, the crop considered the most important in this farming system.

Table 1. Distribution of EWS and WS rice yield in Takeo and Kampot.

Crop yield (t ha^{-1})	Takeo				Kampot			
	EWS Crop		WS Crop		EWS Crop		WS Crop	
	Number	%	Number	%	Number	%	Number	%
<1	0	0	1	2	0	0	0	0
1–1.9	2	5	23	43	5	9	17	28
2–2.9	19	44	30	56	27	47	42	69
3–3.9	19	44	0	0	22	39	2	3
4–4.9	3	7	0	0	3	5	0	0
>5	0	0	0	0	0	0	0	0
Total	43	100	54	100	57	100	61	100
Range (t ha^{-1})	1.2–4.1		0.2–2.9		1.2–4.2		1.4–3.3	
Mean (t ha^{-1})	2.9		2.0		2.8		2.2	

One farmer in Takeo Province who obtained less than 1 t ha^{-1} of WS rice suffered from flooding
Two farmers in Takeo Province who obtained less than 2 t ha^{-1} of EWS rice also suffered from flooding

Table 2. Mean area, output and income per crop in Takeo and Kampot.

	Cultivated area (ha)	Grain output		GI		FFI		RTL	
		Total (t)	Per ha (t ha^{-1})	Total	Per ha	Total	Per ha	Total	Per ha
				US$					
TAKEO									
Single-Cropping Pattern									
WS Crop	0.7	1.5	2.0	148	200	92	117	–8	11
Double-Cropping Pattern									
EWS Crop	0.4	1.2	2.8	111	260	46	112	–5	–13
WS Crop	0.8	1.6	2.0	151	194	97	123	6	4
KAMPOT									
Single-Cropping Pattern									
WS Crop	0.8	1.7	2.3	166	225	117	151	–2	–2
Double-Cropping Pattern									
EWS Crop	0.2	0.6	2.8	49	236	30	145	–5	–25
WS Crop	0.9	2.0	2.2	186	210	134	147	–2	–2

The mean area was 0.8 ha. A few farmers cultivated WS rice on fields as small as 0.2 ha, but areas of between 0.5 and 0.7 ha were more typical, accounting for 33% of respondents. Almost a quarter (24%) of farmers used more than 1 ha for the WS crop and one household planted 2 ha.

Traditional, photoperiod-sensitive, long-duration rice varieties were most popular for cultivating in the WS. More than 10 varieties were reported by the farmers from the three villages. Even though the villages were adjacent to each other, they differed in their choice of varieties. For example, *ath chhmars* and *srau kol* were grown by most farmers in Tungke Village, *somaly* and *neang menh* in Sla Village, and *phka khney* (ginger flower) and *srau sar* (white rice) in Snao Village. Cambodian rice (CAR) varieties, selected and promoted by CIAP researchers, had also been disseminated for a couple of years among the villagers. Normally, each household selected more than one variety with different maturation periods, for two critical reasons. First, varied duration of standing water in the rice fields required different maturation periods, for example, early-maturing varieties were suitable for higher fields, while later-maturing varieties matched the lower fields. Second, varieties of different maturity helped farmers to use labour effectively, which reduced labour bottlenecks from transplanting until harvesting. Household economics was another factor in selecting varieties, for example, a better-off farmer selected varieties based on the eating quality but a poorer one cultivated varieties with high yield and a high swelling potential when cooked. Social factors also influenced varietal selections, for example, most farmers cultivated some glutinous rice for making cakes during the traditional and religious celebrations.

Even though this crop relied on rainfall, occasionally those who were able to extract underground water supplied their fields with supplementary water when a mid-season drought occurred. From direct observation and the farmers' comments, it was apparent that farmers generally continued to wait for rain until the crop was severely affected. This was because pumping costs (not only for fuel but the time and effort needed to transport the pump to the field and irrigate) were high, and there was always a possibility that it would rain the next day, wasting the irrigation. Having an inconsistent water source and lower inputs, WS rice produced an average yield of 2.0 t ha^{-1}, lower than the EWS crop (Table 1). The highest yield was 2.9 t ha^{-1}, while a few farmers harvested as little as 0.2 t ha^{-1} because of flooding. The poorest yield without suffering any major constraint was about 1 t ha^{-1}. The WS yield showed no difference between single- and double-cropping farmers.

The average cost for the WS crop was US$211 ha^{-1} for single-cropping farmers, compared with US$190 ha^{-1}for double-cropping ones. Among the cost items, family-labour inputs were the highest, at US$130 ha^{-1} for single-cropping farmers and

US$120 ha^{-1} for double-cropping farmers. Cash expenditure was similar for both groups but in-kind expenses were higher for single-croppers because the double-croppers applied less cow manure or did not apply it at all for the second crop, using the residue from the EWS crop.

The average GI of the WS crop was around US$150 or US$200 ha^{-1}, with little difference between single-cropping and double-cropping farmers (Table 2). Some 40% of farmers obtained a total GI of less than US$100, indicating a right-skewed distribution. However, with little or no cow manure applied, the FFI of double-cropping farmers was somewhat higher (US$123 ha^{-1} compared with US$117 ha^{-1}) than that of single-cropping farmers. Furthermore, the double-cropping farmers produced a positive RTL, in contrast to the RTL for their EWS rice, while the single-cropping farmers obtained negative RTL. However, as noted above, farmers would be more interested in the level of FFI.

Comparison of EWS and WS crop

Some differences between the cultivation of EWS and WS rice can be noted from the results and discussion above. EWS rice was generally cultivated on only a part of the farmers' total land area, which was fully used for WS rice. The mean area planted to the EWS crop was 0.4 ha but the mean area for WS rice was 0.8 ha. Only the modern variety IR66 was cultivated in the EWS, while more than 10 traditional varieties were grown during the WS. About 30% of the EWS rice was cultivated using the direct-seeding method. Only the transplanting technique was used during the WS.

Varieties were one influential factor contributing to the widely different yields between the two crops. The average yield of the EWS rice was 3 t ha^{-1}, while that of the WS rice was 2 t ha^{-1}. Further, the highest WS rice yield was below 3 t ha^{-1}, but almost 50% of the EWS rice yielded between 3 and 4 t ha^{-1}and a few farmers obtained above 4 t ha^{-1}. The better yields of the EWS rice resulted in a greater GI per ha than for WS rice, though the smaller cultivated area meant that total GI from EWS rice was about three quarters that from WS rice.

However, the EWS rice required high inputs compared with WS rice. The total variable costs of the EWS rice averaged US$270 ha^{-1}, compared with US$210 ha^{-1} for WS rice. The double-cropping farmers spent only US$190 ha^{-1} for WS rice because of the saving on in-kind expenditure. The cash expenditure and in-kind expenditure for EWS rice were higher than for WS rice because more chemical fertilisers, fuel for irrigation, pesticides, and cow manure were used for the first crop. Even though the family labour costs showed no difference between the two crops, in fact the cultivation of EWS rice demanded more labour per hectare. The mean labour input for EWS rice was 150 worker-days per ha compared with 123 worker-days per ha for WS rice (though the minority practising direct-seeding had a much lower input) (Table 3). The seasonal labour wage was almost the same between EWS and WS rice, though labour bottlenecks usually occurred during the main season, presumably because of the larger scale of cultivation.

Table 3. Labour use in the EWS and WS crops in Takeo and Kampot.

	EWS Crop		WS Crop	
	Average	Range	Average	Range
	Worker-days ha^{-1}			
TAKEO				
Single Cropping Pattern			126	81–154
Double-Cropping Pattern				
– Transplanting	150	88–200	123	84–159
– Direct-seeding[a]	95	55–131		
KAMPOT				
Single Cropping Pattern			182	160–224
Double-Cropping Pattern	192	114–256	174	108–240

[a] 26 per cent of double-cropping farmers in Takeo used direct-seeding for the EWS crop

Whole-year analysis

The impact of double-cropping is best seen through a whole-year analysis. The double-cropping farmers were able to increase their rice production and incomes through intensifying the use of their limited land. On average, the total rice area the double croppers owned was around 0.8 ha (compared with 0.7 ha for single-croppers) but they cultivated 1.2 ha during the year (0.4 ha in the EWS plus 0.8 ha in the WS) (Table 4). Their total grain output was almost 3.0 t compared with 1.5 t for the single-cropping farmers. Their annual GI averaged US$260, nearly two times that of single-cropping farmers (Table 4).

After cost deductions, the double-croppers achieved an FFI of US$143, substantially higher than the single-cropping farmers (US$92), indicating that the additional costs incurred provided net benefits. The distribution of FFI indicated that over 60% of double-croppers were above US$100, compared with only 10% for single-croppers (Table 5). One farmer obtained a very high FFI of US$600–700. The less relevant indicator of RTL was close to zero or negative but was still better than for single-cropping.

The yield per hectare per crop (that is, annual output divided by the sum of the areas cultivated in each season) was just slightly higher for the double-cropping farmers, reflecting the higher yield of the EWS crop (Table 4). This resulted in only a slight difference in GI, that is, US$220 ha^{-1} against US$210 ha^{-1}. Double-cropping farmers obtained a RTL per ha close to zero, while the single-croppers had a negative RTL.

In terms of output per hectare per year (that is, as total farm area, regardless of the frequency of cultivation), the above per hectare figures for the single-cropping farmers did not change, but the grain yield of double-cropping farmers jumped from 2.3 t ha^{-1} to 3.5 t ha^{-1}, reflecting the better use of available land (Table 4). The average GI increased to US$325 ha^{-1}, 55% higher than for the single-croppers. Similarly, the FFI was US$180 ha^{-1} (37% higher). This good outcome indicates that the practice of double-cropping effectively used cash, household resources, and

Table 4. Mean whole-year output and income from rice production in Takeo and Kampot.

	Area (ha)	Grain output (t)	GI	FFI	RTL
			US$		
TAKEO					
Single-Cropping Pattern					
Total		1.5	148	92	–8
Per ha cultivated	0.7	2.0	211	131	–11
Per ha owned	0.7	2.0	211	131	–11
Double-Cropping Pattern					
Total		2.8	261	143	1
Per ha cultivated	1.2	2.3	218	119	1
Per ha owned	0.8	3.5	326	179	1
KAMPOT					
Single-Cropping Pattern					
Total		1.7	166	117	–2
Per ha cultivated	0.8	2.3	208	146	–3
Per ha owned	0.8	2.3	208	146	–3
Double-Cropping Pattern					
Total		2.5	235	165	–7
Per ha cultivated	1.1	2.3	214	150	–6
Per ha owned	0.9	2.8	261	183	–8

Table 5. Distribution of whole-year farm family income (FFI) in Takeo and Kampot.

	Takeo						Kampot					
	Total		Per cultivated ha		Per ha owned		Total		Per cultivated ha		Per ha owned	
	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%
Single Cropping												
< 0	0	0	0	0	0	0	0	0	0	0	0	0
0–100	10	91	4	36	4	36	2	50	1	25	1	25
101–200	0	0	7	64	7	64	1	25	2	50	2	50
201–300	0	0	0	0	0	0	1	25	1	25	1	25
301–400	1	9	0	0	0	0	0	0	0	0	0	0
401–500	0	0	0	0	0	0	0	0	0	0	0	0
501–600	0	0	0	0	0	0	0	0	0	0	0	0
601–700	0	0	0	0	0	0	0	0	0	0	0	0
Total	11	100	11	100	11	100	4	100	4	100	4	100
Double Cropping												
< 0	1	2	1	2	1	2	0	0	0	0	0	0
0–100	14	33	18	42	4	9	12	21	5	9	4	7
101–200	17	40	23	53	21	49	31	54	45	79	31	54
201–300	9	21	1	2	11	26	8	14	6	11	20	35
301–400	2	5	0	0	5	12	2	4	1	2	2	4
401–500	0	0	0	0	0	0	3	5	0	0	0	0
501–600	0	0	0	0	0	0	1	2	0	0	0	0
601–700	0	0	0	0	1	2	0	0	0	0	0	0
Total	43	100	43	100	43	100	57	100	57	100	57	100

family labour. Although the RTL was small, it can be assumed that land was more effectively used than with the single-cropping practice since the FFI indicator represented a sustainable return on family labour and land.

Summarising the results for Takeo, it would seem that the main effect of using a modern variety to permit double-cropping was through more efficient use of available land and labour, and only secondarily through increased net returns per hectare cultivated.

Results for Kampot

EWS crop

In Damum Village in Kampot, although the incidence of double-cropping was higher (93%), the largest area of EWS rice cultivated by any one farmer was only 0.45 ha. The mean area was 0.2 ha and almost 70% of farmers cultivated less than 0.25 ha. Limited supplementary irrigation was the most important factor that discouraged the farmers from expanding the area of EWS rice.

Two modern varieties, IR42 and IR66, were cultivated during the EWS. Only one household continued to grow IR36. The percentage of interviewees cultivating IR42 was higher than the percentage cultivating IR66. However, the latter appeared to be becoming more popular since most farmers who cultivated this variety had previously grown IR42.

Rainfall was critical for the practice of EWS rice in this village. Most farmers depended on small ponds and canals. Small ponds were excavated adjacent to the farmers' houses for storing rainfall, which could be consumed by the household and used as supplementary irrigation for the EWS crop. As described above, houses were mostly built on a part of the rice field that was raised above the flood level. Fields were also irrigated from adjacent canals and ditches in which water was stored during the EWS. The canals and ditches dried out in the dry season. Few farmers cultivated EWS rice by depending entirely on erratic rainfall and not having some form of water reservoir.

The grain yield of the EWS crop varied widely, ranging from 1.2 to 4.2 t ha^{-1} (Table 1). However, the mean yield was just under 3.0 t ha^{-1}, comparable with Takeo. Table 1 indicates that in 86% of cases the yield was between 2.0 and 3.9 t ha^{-1}. Though the Kampot village was considered to have less favourable conditions, the yield figures did not show this because Kampot farmers reduced the risk of drought by cultivating only a small proportion of the area they owned—and this could be supported by the small adjacent reservoirs.

The average cost incurred for EWS rice was US$310. Once again, the highest cost item was family labour at around US$175 ha^{-1}. The other two cost items were lower—cash expenditure (US$50 ha^{-1}) and in-kind expenditure (US$40 ha^{-1}).

Valuing EWS grain at the market price, the average GI was US$235 ha^{-1}. However, no farmer had a GI above US$200 because of the small area cultivated. Some 52 households, accounting for 93%, obtained less than US$100 of GI. The total GI averaged just under US$50. These results affected the different measures of income (Table 2). The average FFI was US$145 ha^{-1}, reflecting the lower outlay on inputs (cash and in-kind) compared with Takeo. The average RTL was negative.

WS crop

Most farmers in Damum Village owned less than two hectares of land for rice; the mean area owned was 0.9 ha. In general, WS rice was cultivated on all the land the farmers owned. The average area of WS rice cultivated was 0.8 ha for single-cropping farmers and 0.9 ha for double-cropping farmers (Table 2).

A range of traditional, photoperiod-sensitive, long duration varieties were cultivated in the WS. At least 10 varieties were cultivated but the most common were *sar teap* (short white), *krarham leak sonlek* (red hide leaves), *changkaom phal* (yield bunch) and *por doung* (coconut colour). The maturation period of these varieties was not the same but they were mostly harvested from the first week of December. The cultivation of WS rice relied entirely on rainfall, hence the crop was frequently damaged by short dry periods during the WS.

The grain yield of WS rice ranged from 1.4 t ha^{-1} to 3.3 t ha^{-1}. The average yield of single- and double-cropping households was 2.3 t ha^{-1} and 2.2 t ha^{-1} respectively (Table 1). Most farmers obtained a total output below 2 t because they owned less than 1 ha. On average, the total output of the single-cropping farmers was 1.7 t and of double-cropping farmers, 2.0 t.

As with the EWS crop, the labour cost was higher than the other input categories. Labour accounted for just under US$160 ha^{-1} and was similar for single- and double-cropping farmers. The cash and in-kind costs were much lower than the labour costs and also similar for single-cropping (US$50 and US$25 ha^{-1}) and double-cropping farmers (US$45 and US$20 ha^{-1}). In-kind costs were low because farmers in this area applied less cow manure for the WS rice in spite of cultivating only one crop a year. The total variable cost for the single-cropping farmers was US$227 ha^{-1} compared with US$222 $ha^{-1}$for the double-cropping farmers.

As the yields of the two groups were similar, the GI was also quite similar, US$225 ha^{-1} and US$210 ha^{-1} if the grain was valued at the market price (Table 2). Total GI of the farmers at this site was widely distributed, ranging from below US$100 to over US$500. Just over half (54%) obtained a GI of US$100–200. The means for FFI were positive and similar between the single-cropping and double-cropping farmers (Table 2). Both groups obtained negative RTL. Notwithstanding, the positive values for FFI indicated that both groups made no loss in cultivating the WS rice.

Comparison of EWS and WS crop

Several differences between the EWS and WS crops can be noted for this location. All the interviewed households planted WS rice and almost all (93%) planted EWS rice. However, only part of the farmers' land was planted to EWS rice, normally less than 0.5 ha, while the WS rice was grown on all the land the farmers owned, mostly much more than 0.5 ha. A few modern, photoperiod-insensitive, short-cycle varieties were planted for the first crop, but around 10 traditional, photoperiod-sensitive, long-cycle varieties were cultivated for the second crop.

On a per hectare basis, the total variable costs of EWS rice were higher than for WS rice. Cash expenditure per ha for the two crops was similar because, although EWS rice required supplementary irrigation, this did not need petrol, only extra labour. EWS rice used more in-kind inputs than WS rice, mainly cow manure. The family labour cost per hectare was clearly higher for EWS rice than for WS rice since the first crop demanded more labour for transplanting and irrigation (Table 3).

Even though the minimum yield of both EWS and WS rice was similar, the maximum yield of the EWS crop was 4.2 t ha^{-1}, while for WS rice it was 3.3 t ha^{-1} (Table 1). The average yield for EWS rice was 2.8 t ha^{-1}, over 25% higher than the average of 2.2 t ha^{-1} for WS rice. The GI per hectare of EWS rice was slightly better than for WS rice, but the total GI was only around one quarter because of the small area cultivated. Most important, FFI per hectare was almost identical at US$145 ha^{-1} and US$147 ha^{-1}. The RTL was negative for both. The main difference was again in the overall level of income (rather than income per hectare), with EWS rice producing only a quarter of the corresponding income measure for WS rice (Table 2).

Whole-year analysis

A whole-year analysis allows double-cropping and single-cropping to be compared. Though the number of single-croppers in the Kampot sample was small, the close similarity between the two groups in the results for the WS crop suggests the single-croppers provide an adequate basis for comparison.

On average, the double-croppers increased their cultivated area to 1.1 ha per annum which, given an average rice farm of 0.9 ha, represents a cropping intensity of 122% (Table 2). Thus, only a small proportion of their farm was used for the additional EWS crop. The double-cropping farmers harvested a total of 2.5 t, nearly 50% more than the single-croppers. This translated into a total GI of US$235, while single-cropping farmers earned only US$165 (Table 4). After deducting input costs, the total FFI was around 40% higher for the double-cropping farmers. The high value imputed to the costs of labour and land meant negative whole-year RTL.

The average yield per hectare per crop was the same for the single- and double-cropping farmers (2.3 ha^{-1}) (Table 4). This led to similar small differences in GI and FFI per hectare. RTL was negative for both groups. However, analysing the results on the basis of the output per hectare per year, the yield from double-cropping was 2.8 t ha^{-1}, 22% higher than from single-cropping (Table 4). The GI was US$260 ha^{-1} and FFI US$185 ha^{-1}, all around 25% higher than from single-cropping. Though the RTL was negative, it can be summed up that the inputs of cash, household resources, family labour and land were more effectively used for the cultivation of two crops a year as shown by the increased annual GI and FFI per hectare. Again, the conclusion is that the improved income from double-cropping was mainly because the capacity (available land and family labour) was used more effectively, rather than because a high-yielding variety was introduced.

Comparison of double-cropping in the two locations

EWS crop

Although in Takeo Province the cultivation of EWS rice was a recent phenomenon, most farmers having first planted this crop in 1997, it was cultivated over a relatively large area (0.4 ha) compared with the second location in Kampot Province (0.2 ha), where some farmers had cultivated EWS rice for more than 10 years. Supplementary irrigation was the most important factor contributing to the different cultivated areas. Tube-wells and pumps were used to extract underground water to supply the EWS crop in Takeo, whereas the EWS crop in Kampot was cultivated relying completely on small reservoirs near the rice fields to store rainfall. Farmers in Kampot did use underground water for home consumption, using hand treadle pumps and wells, but it seemed to be unknown for the farmers to use underground water for crop irrigation. They expressed surprise and interest when asked this question in the survey.

Modern, photoperiod-insensitive, short-cycle varieties were cultivated in both locations but only IR66 was planted by the farmers in Takeo, while three different varieties, IR42, IR66 and IR36, were coexisting in Kampot. However, it seemed that IR66 would become the most popular because the farmers who cultivated IR66 had previously planted IR42. Only a few farmers in the Kampot village continued to grow IR36. It was also observed that the broadcasting method was practised by some farmers in the villages of Takeo Province but none of the interviewees in Kampot Province used this method in the EWS.

Even though there was no difference in yield between the two locations, the GI per hectare of the Takeo farmers was higher than that of the Kampot farmers because the former received a better price (Table 2). The use of underground water and the large amount of cow manure applied contributed to higher per hectare cash expenditure and in-kind expenditure in Takeo. However, Kampot farmers used more labour, leading to a higher family labour cost per hectare. The crop needed about 192 worker-days ha^{-1} in Kampot, but only 150 worker-days ha^{-1} in Takeo (Table 3). The use of contract harvesters and threshers in Takeo contributed to the lower labour costs. These differences in cost categories were largely offsetting, so that total variable costs and total costs were similar.

GI per hectare was higher in Takeo, but FFI per hectare was higher in Kampot, reflecting the different cost structures. The farmers in both regions obtained negative RTL. The figures for total GI and FFI were considerably higher in Takeo because of the larger EWS area cultivated.

WS crop

The WS crop was almost homogenous between the two locations for cultivated areas, cropping calendar, and planting methods. However, rice varieties were different between the two areas, even though they were all traditional varieties. It is common for Cambodian farmers in different regions to cultivate different rice varieties because variety selection is a form of cultural heritage spanning many generations. The traditional varieties in Cambodia show markedly diversified characters. Until 1994, CIAP was able to collect 2109 traditional varieties to evaluate their agronomic characteristics (Javier, 1997).

The combination of a slight difference in grain yield and a better grain price increased the GI in Takeo. As with the EWS crop, in-kind expenditure was higher in Takeo but family labour costs were higher in Kampot, which led to higher total variable costs and total costs. There was a difference of around 50–60 worker-days per hectare between the two locations.

Although the farmers in Kampot had higher costs than in Takeo, the second location achieved higher FFI. The other return category, RTL, was better in Takeo though all gave negative values.

Whole-year comparison

Several points of comparison can be made between the two sites for the whole-year analysis. The Takeo mean farm area was 0.8 ha and the annual cultivated area was 1.2 ha, compared with a farm area of 0.9 ha and a cultivated area of 1.1 ha in Kampot (Table 4). The higher land use in Takeo (150% compared with 122%) contributed to a better annual total output (2.8 t) and annual yield per hectare (3.5 t ha^{-1}) than the 2.5 t of total output and 2.8 t ha^{-1} per hectare in Kampot. Takeo farmers achieved higher annual GI in total and per hectare, but after including the in-kind costs Kampot farmers had higher FFI (Table 5), because farmers in Takeo used more in-kind inputs. However, farmers in both sites obtained zero or negative RTL.

Conclusion

Across the two locations, EWS rice generally produced a higher grain yield than WS rice; in each location around 30–40% higher. It is true that the EWS rice crop, using modern varieties, needed a higher investment than WS rice, for example, higher costs for supplementary irrigation, chemical fertilisers, organic fertilisers (cow manure) and wages. However, for most farmers in the four villages, and other similar villages in the rainfed lowlands, the disadvantages are currently outweighed by the advantages of the double-cropping system. Food security is a priority in Cambodian households and this encourages farmers to double-crop. The net returns per hectare from harvesting the crop were generally as good as or somewhat better than the WS crop. In particular, the positive figures for farm family income, the most important indicator, show that the EWS crop can produce a good return. Furthermore, the high expenses for EWS rice may have had a carryover impact on the second crop, given that double-cropping farmers applied little or no cow manure for WS rice.

The contribution of the EWS crop was most clearly seen in the whole-year analysis. Double-cropping farmers were able to increase their cultivated area if inputs were available, averaging 150% land utilisation in Takeo and 122% in Kampot. Even though the farmers were able to cultivate EWS rice on only a proportion of their land, the double-cropping farmers in both sites could generate considerably better returns than single-cropping farmers in the same 12-month period. Thus moving to double-cropping could increase food supply by 75% in Takeo and 22% in Kampot, and farm family income by 37% in Takeo and 25% in Kampot. Most importantly, the double-cropping practice used all resources, including cash, household resources, family labour, and land, more effectively than single-cropping. In fact, the main effect of incorporating a modern variety in the EWS was the improved use of land and labour rather than

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significantly higher per unit productivity. The rice double-cropping system was a reliable source of additional employment and income, given that off-farm job opportunities were generally out of the villages and not always available. The increase in EWS rice production would also have helped to reduce the seasonal fluctuations in rice supply and price.

Other benefits of double-cropping emerged from the survey. Adoption of EWS rice technology opened up other technological options (such as direct seeding) and market options (such as selling seed). Farmers could also derive financial benefits from growing surplus rice. After milling, rice bran could be used to raise animals such as pigs, chickens and ducks. Rice straw, which was quite costly and hard to buy, could be stored for feeding to draught animals during the periods of forage shortage. Also, the EWS rice harvest was a source of quality seed for the following dry season, as part of a larger farming system for those who wanted to triple crop or to supply neighbours who cultivated a DS crop.

The major constraint to the adoption and expansion of the EWS-WS double-cropping system was access to supplementary irrigation. The survey in Kampot showed that EWS rice can be cultivated without supplementary irrigation from groundwater. The farmers in this location grew EWS rice using only water from small-scale reservoirs such as ponds, ditches and canals. However, with these water sources, farmers were able to cultivate EWS on a very limited scale because the capacity of these storages could not meet the demands of larger fields or lengthy drought. The enlargement of reservoirs may help, but the findings from the Takeo region suggest that underground water is likely to be a better option. While the use of tube-wells and petrol pumps was profitable in Takeo, further study of the hydrological and economic impacts of tube-well development in Kampot is necessary.

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Developing sustainable land and water management for the Aral Sea Basin through an interdisciplinary approach

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Abstract

During Soviet times, vast desert areas in the Aral Sea Basin were transformed into artificially irrigated, agricultural land to grow cotton. The ensuing ecological problems strongly affect the livelihood of the local population. The agricultural production systems that are at the heart of this transformation are characterised by large monocultures and heavy inputs of fertilisers, pesticides and water. The extensive irrigation systems are expensive to maintain; up to 70% of the water is lost. The state order on crops, which is imposed via strongly centralised government structures, secures the predominance of cotton production and impedes a transition to a market economy. At present, the agricultural production is ecologically and economically unsustainable.

ZEF, with its partners in Uzbekistan, established, in March 2002, a research program to develop sustainable and efficient land and water use practices for the region. The program is based on the assumptions that applicable concepts for sustainable and efficient land and water use must be developed on the basis of sound scientific research, and that the complexity of the problems needs an interdisciplinary approach integrating natural resource management as well as economic and institutional changes. The project therefore integrates these different disciplines into a unified model that can be applied to different scenario to test the value of restructuring. This would be followed by practical testing on pilot farms.

First results include the mapping of groundwater and soil salinity, and of land use (trees and forest plantations), as a basis for later recommendations for improved, sustainable resource use. Studies on the performance of tree growth preceded a more intensive monitoring of the growth and irrigation needs of the best-performing trees on marginal land. For the first time in the region, detailed irrigation water budgets for single fields are being established and these have revealed the large contribution of ground water to the crop water needs. Initial economic assessments based on government data and field surveys of selected farms reveal the intricate structure of the agricultural production process in which the strong hierarchical, state-governed characteristic of the former Soviet system prevails. Studies of health problems related to drinking water reveal the deteriorating health care system. A study of the administrative performance of the newly formed Water User Associations and an investigation into farmers' perceptions of the needed reforms complete the studies undertaken in the first year of this project.

COMBATING desertification and providing sustainable, efficient land and water management options in the Aral Sea Basin is the goal of a project developed by the Center for Development Research (ZEF) at the University of Bonn. During Soviet times, from 1925 to 1985, the area under irrigation in the Aral Sea Basin was increased from 2.0 to 7.2 million ha to produce cotton (FAO 1997). To achieve this, much water has been withdrawn from the tributaries of the Aral Sea. The Aral Sea, once the world's fourth largest inland water body with a size of some 68,000 km^2 (Micklin & Williams 1996), has lost 80% of its

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original water volume and 60% of its surface area (Ressl 1996).

The local agricultural production systems are characterised by large monocultures and heavy inputs of fertilisers, pesticides and water, the latter being delivered by extensive irrigation systems that are expensive to maintain and from which up to 70% of the water is lost. The so-called 'state order' on crops, which is imposed via strongly centralised government structures, still secures the predominance of cotton production and impedes a transition to a market economy, which further hampers progress. At present, the agricultural production is ecologically unsustainable, and the system is also economically unstable. The inhabitants of Karakalpakstan and Khorezm, two regions on the lower reaches of the Amu Darya River (Figure 1), the largest of the Aral Sea's tributaries, suffer most from the accumulated effects of low water availability, soil degradation and salinisation, as well as from the economic and administrative orientation towards soviet-style centralised structures.

Since the independence of the Central Asian states in the early nineties, many international efforts have been directed at the complex and multinational nature of the 'Aral Sea Syndrome' (WBGU 1999); however, with little visible results. Recently, the policy aimed at regional disaster mitigation has shifted to a new paradigm. The goal now is not to save the Aral Sea at all costs—efforts to that effect could take decades and the outcome is uncertain—but to help increase the health and welfare of the people affected by the destruction of the ecosystems in the Aral Sea and in the river deltas (e.g. UNESCO 2000). Ecological negative effects include the:

- destruction of the aquatic ecosystems
- almost complete loss of natural, periodically flooded river bank forest (Tugai forests)

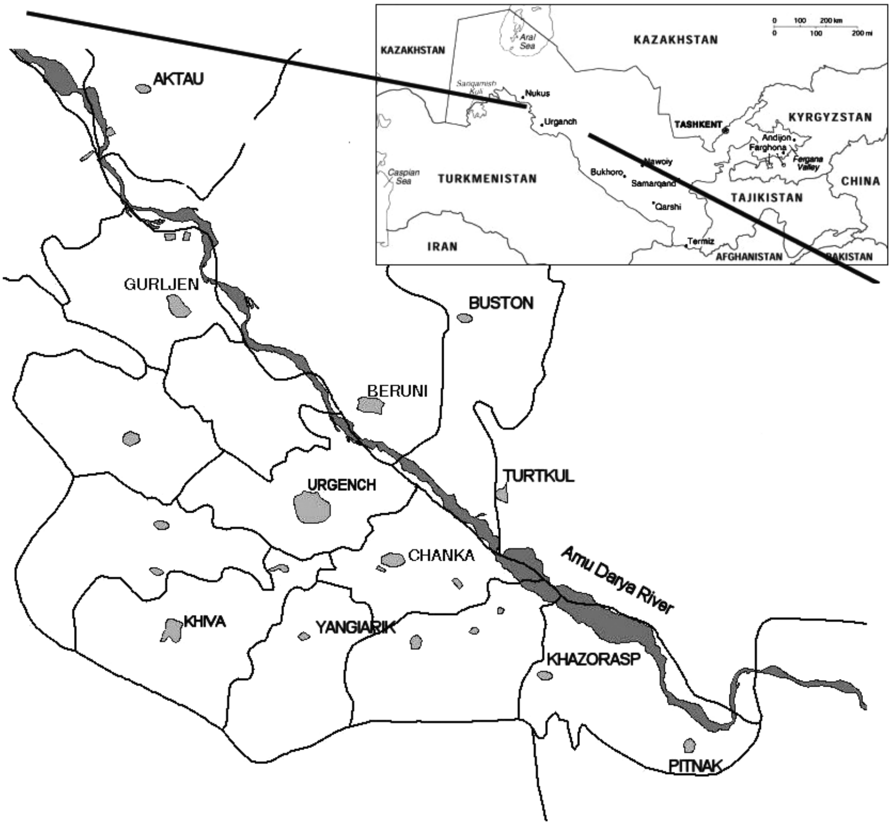

Figure 1. Map of the study region, Khorezm district, in Uzbekistan (inset).

- lack of clean drinking water
- rise in the average regional temperature from loss of water surface
- high incidence of salt/dust-laden storms arising from the now exposed Aral Sea bottom and affecting nearby regions (Micklin 1991, 1988; Micklin and Williams 1996; Létolle and Mainguet 1996; Giese 1998; UNESCO 1998, O´Hara et al. 2000; Breckle et al. 2000).

All these factors contribute to the ecological deterioration of the region and lead to poor health conditions and a high morbidity among the population living in the basin. Glantz (1998) has defined the Aral Sea problem as a typical example of a 'creeping environmental problem' (CEP). That is, a slow-onset, low-grade, long-term, cumulative environmental change, that evolves slowly—almost imperceptibly—thus making the perception and the onset of counterbalancing action especially difficult ('... the demise of the Aral Sea has become acknowledged as one of the major examples of human-induced environmental degradation in the twentieth century'). Efforts are urgently needed to stabilise the region ecologically. However, a scientific approach that looks critically at the issues and establishes sound data from which solutions can be developed is needed.

In March 2002 ZEF started a research program (ZEF 2001) that is being implemented in close cooperation with a local research institution, the State University of Urgench. Urgench is the capital of Khorezm district in Uzbekistan. Khorezm is a 630,000-hectare region of irrigated land on the lower Amu Darya (Figure 1). The program developed by ZEF is based on the hypothesis that the ecologically critical situation in the Aral Sea Basin is a result of economic policy and administrative measures and that therefore the complexity of the problem can only be addressed by a truly interdisciplinary approach.

Using natural resources effectively means applying adequate planning tools to optimise land-use policies. For agriculture, the dominant land-use type in the region, alternatives have to be found to the production system that at the moment is characterised by cotton monocultures, inefficient irrigation systems, and an almost total lack of ecological sustainability. The economic analysis of the status quo is laying the groundwork for establishing development pathways to transform the local economy into a market-oriented system. The aim is to deal with the strong 'path dependency' of the existing irrigation infrastructure and reform existing agricultural practices. Legal-institutional studies are needed to understand the functioning of the institutions and interest groups involved in the decision-making process.

The project is further based on the assumptions that:

- an application-oriented, interdisciplinary scientific investigation program is needed to provide suitable concepts for sustainable and efficient land and water use
- international cooperation can be built up only in equitable agreements and via long-term cooperation
- human capacity building, the education and training of young Uzbek scientists, eventually the future decision makers, will empower the Uzbek people to effectively and sustainably take care of the regions' problems.

The interdisciplinary approach integrates the three disciplines of natural resource management, economy and social sciences into a restructuring program aimed at optimising land and water use.

The program therefore comprises research in four thematic areas that will provide the basic data input for an integrative, interdisciplinary model (Figure 2). These areas cover:

- Natural resource management strategies (N) targeted at decision makers, in which:
  - optimal land-use patterns (including the introduction of trees and ponds as alternative land uses with ecological functions) will be determined
  - ways for an efficient, sustainable management of the two most important resources, water and land, will be elaborated
  - indicator functions for a sustainable resource use related to water quantity and quality (salinity in irrigation and drinking water), and soil quality, will be established allowing the success of the restructuring measures to be assessed
- Production systems (P) in which:
  - possibilities for diversifying crops by introducing alternative crops, cropping systems and rotations will be exploited
  - possibilities for improving fertiliser efficiency will be studied
  - irrigation efficiency on the field level will be addressed to develop recommendations targeted at farmers as the main land users

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- Economy (E) aiming at:
  - establishing development pathways for transforming the local economy from a centrally based to a market-oriented system
  - the acquisition of primary research data on farm management, market conditions, profitability of diversified crop production systems, expenditures of regulating the economy as well as costs of intergenerational distribution
  - a socio-economic assessment of losers and winners of possible reforms, all related to the question of how the land and water use can be improved
- Society and institutions (S) aimed at:
  - understanding the formal (legal) ways of resource distribution in the state institutions and the newly formed water user associations
  - increasing our understanding of the informal ways of by-passing these institutions in decision making
  - assessing environmental legislation and the legal aspects of land tenancy and land use with the aim of identifying the possibilities for legal, institutional and administrative modifications needed for land reform, market liberalisation and an effective increase in land/resource use efficiency and sustainability.

In area S, the project also addresses the question of international competition for water in Central Asia and thus provides the link between the development of water distribution on regional and supranational scales.

The project is divided into four phases (Table 1).

The first phase of the project (2001–03) has been dedicated to 'data mining', that is, assessing the vast official Uzbek data sets on land and water, many of them only available as grey literature and some unreliable or not collected according to current scientific standards. The main aim was to separate reliable existing data sets from areas where project research will be crucial to determine the parameters needed for implementing improvements in land and water use. Furthermore, all those field studies aimed at analysing the processes and interrelationships needing long-term approaches were initialised during this first project phase.

The second phase (2004–06) is dedicated mainly to deepening understanding of processes and relationships necessary to develop the first draft of a modelling tool that will mainly be used to simulate

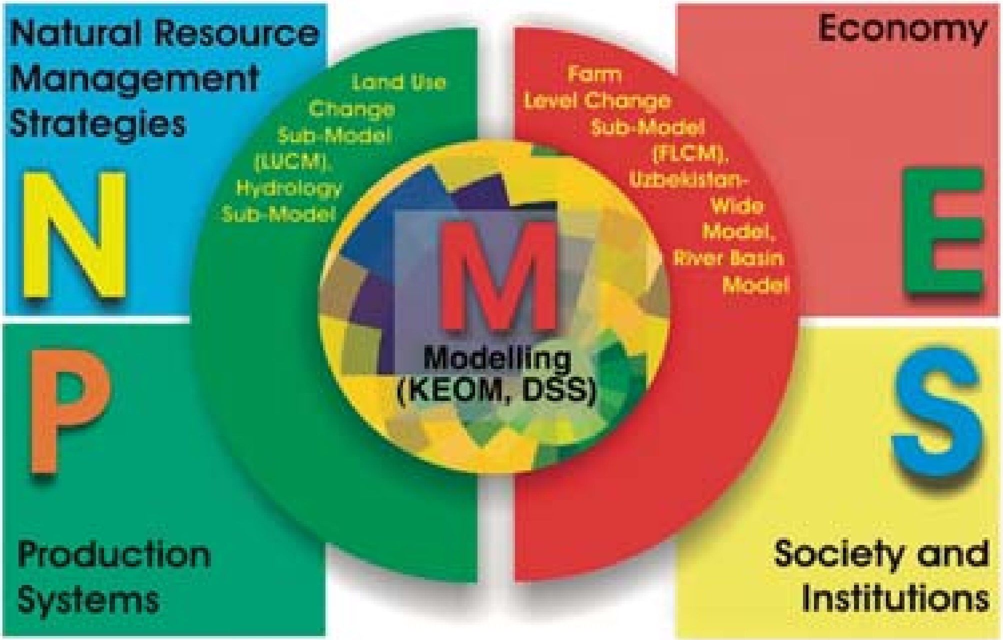

Figure 2. The four project research areas feed through sub-models into the Khorezm Ecological-Economic Optimization Model (KEOM).

various scenarios for restructuring land and water use, privatisation, and institutional reform, the 'Khorezm Ecological-Economic Optimization Model' (KEOM). Later, the KEOM will be developed into a fully operational, decision-support system to be used by local decision makers.

In a third phase (2007–10), the most suitable options arising from the KEOM simulations will be developed into a comprehensive restructuring concept, and this will be tested under real conditions in a pilot-farm scheme in close cooperation with the farmers as the main stakeholders. The proper implementation of the optimised water- and land-use schemes will require freedom from all state constraints; this is a pre-requisite for the functioning of this phase. The pilot farms will also serve demonstration purposes for 'good practices'. At the same time, the decision-support system (DSS) will be fully developed.

During the last project phase (2011–12), the concept will be implemented, eventually after final adjustments necessary to account for the experiences on the pilot farms during Phase III.

Research areas: natural resource management strategies and production systems

The ZEF concept promotes setting aside land for ecological purposes while compensating agricultural production loss through more efficient land and water use. One avenue pursued is the integration of tree plantations into the current agricultural systems. Consequently, studies on land-use systems concentrate on establishing tree plantations, of minimum-tillage and other conservation agriculture methods for annual crops tested with priority on winter wheat, but also on additional crops. We see tree plantations as an alternative land-use option for the most marginal soils (considered to account for roughly 20% of the land in Khorezm according to official soil quality or 'bonitet' maps; Table 2). Existing tree plantations and shelterbelts in Khorezm are being monitored through remote sensing, based on aerial photographs obtained from Uzbek authorities (Figure 3), to assess the extent to which shelterbelts and trees are already part of the landscape in Khorezm, and to establish relationships between trees and biophysical conditions. The first experimental plantations of 15 native and introduced tree species were established in 2002 under different irrigation regimes to screen for optimal root growth (necessary to survive under drought; cf. Figure 4), production, and performance. Based on these data (Table 3), three tree species were selected (*Populus euphratica, Elaeagnus angustifolia* and *Ulmus primula*) and planted in 2003 in a larger experimental plantation dedicated to establishing water-saving, tree-planting technologies (Khamzina 2003). To support the tree plantation studies, the susceptibility of trees to pests was mapped in a monitoring program throughout Khorezm. Considerable differences have been found in the tree species' susceptibility to the most common pests (bark and longhorn beetles; Ruzmetov 2003). For example, poplar trees (*Populus* sp.) are most susceptible to these pests, and apple (*Malus* sp.) trees least susceptible, a result that will be considered in future plantation experiments.

Another land-use option being studied is the potential for transformation of marginal land into small fish ponds for decentralised aquaculture. In the Soviet past, aquaculture in Uzbekistan was oriented towards large, collective fish farms where ponds typically occupied large areas of 70–100 ha. The idea is that fish production in smaller ponds will allow de-

Table 1. The different phases in ZEF's Khorezm project.

Phase	Years	Main activities	Status
I	2001–03	Inventory; establishment of central databases and infrastructure	Ongoing
II	2004–06	Field trials for process understanding, development of a modeling and decision support tool (KEOM) for research purposes	Beginning
III	2007–10	Testing of the concept for the restructuring of the land use on pilot farms, demonstration of 'good practice' and development of final decision support system (DSS) for extension purposes	Planned
IV	2011–12	Adaptation of concept and implementation in the region (Khorezm-wide)	Planned

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centralising the fish production, thus providing a better adaptation to the small-farm structure that will very likely be established soon by Uzbek government decrees on farm privatisation. Fish farming will make use of excess drainage water that currently often surfaces at undesired spots in the fields, and will produce fish to provide protein and additional income. Previously, imported fish feed was used for feeding, but after independence this has become too expensive for small-scale fish production. Consequently, locally available plants, remainders of field crops, manure and aquatic plants such as *Azolla* are being screened for their suitability as fish feed (Khurambaeva 2003). The first trials using various amaranth species and other locally available plants such as alfalfa have shown promising results.

Table 2. Soil fertility classification[a] of land in Khorezm, in hectares and as a percentage. (Source: Khorezm Land Planning Department). According to this data set, 19.13% of the land is rated with a bonitet <40, which is considered marginal land.

Bonitet class	Area in Khorezm (ha)	% of area
0–10	0	0.00
11–20	1 290	0.66
21–30	8 197	4.20
31–40	27 823	14.26
41–50	35 151	18.02
51–60	31 944	16.38
61–70	62 908	32.25
71–80	22 849	11.71
81–90	3 789	1.94
91–100	1 110	0.57
Total	195 061	100.00

[a] Soil fertility in Uzbekistan is defined by a number of inherent properties (agro-physical, agrochemical, capacity of biologically active layer etc.) and estimated on fertility class. The quality class (bonitet) is a comparative rating of soil quality (natural and acquired) at an average level of agricultural practices and intensification. This is expressed in terms of the extent to which land is capable of producing, with irrigation, the maximum potential yield of a crop (An environmental profile of the Republic of Uzbekistan, Chapter 4, p. 213). Soil fertility originally is defined for cotton while using a 100-point scale. For example, for cotton the value of one point equals 0.4 centners ha^{-1}. Thus, under maximum fertility (which equals 100 points) it is possible to get up to 40 centners ha^{-1} (100*0.4 = 40) of cotton while using average farm equipment and machineries and intensive farming. Based on this principle it is possible to derive the fertility of soils for other crops as well.

Aside from the studies on trees and ponds, that is, on alternative land-use systems that can be integrated into the present agricultural systems, alternatives to the crops traditionally grown in Khorezm are screened. This includes conservation agriculture approaches as alternatives to the practice of uncontrolled flood irrigation (Karimov 2003). On two long-term research fields of different soils totalling 7 ha, the first of this kind in the region, the no-tillage and bed-and-furrow practices were tested in different bed depths and in combination with mulch as a soil cover. As the no-till system was less well adapted to the local conditions, future trials will concentrate on bed-and-furrow. Also, appropriate equipment for the local situation is being developed.

With land and water as the main natural resources, an extensive measuring program has been established to determine the on-farm water use efficiency and provide basic data to model on-farm and on-field water use. This study will be the first to collect accurate measurements of water inputs and losses in and from single fields in this region. Although losses of water in the irrigation system are high (see above), it is expected that the ensuing high groundwater table will contribute substantially to the water need of the crops (yet to be verified). Models are being tested that incorporate groundwater table and water salinity and allow developing crop, water-demand based, irrigation schemes that reduce water use, directly benefit the farmers, and increase ecological sustainability.

The new concept for landscape restructuring will be based on a close monitoring of soil and water salinity leading to the prediction of salinity ‘hot spots’. The mapping of groundwater salinity (Vlek et al. in press) is a first step. The study, based on data from 1900 measuring wells sustained by the Uzbek government in Khorezm during the past decades, concluded that the high spatial heterogeneity of groundwater salinity (Figure 5) makes a differentiated, site-specific water resource management necessary. Another study (Akramkhanov 2003) links soil to groundwater salinity and to environmental parameters and will eventually lead to the development of easy-to-use soil salinity indicators that can be used by farmers without sophisticated equipment. An example shows that a neural network analysis indicated topography as one proxy indicator of soil salinity (Figure 6). If further analysis corroborates this finding, this would help farmers to decide, based on simple indicators rather than relatively complicated salinity analysis, where they should plant the different crops.

In the experimental tree plantations and conservation agriculture trials, soil ecology is being monitored to determine the actual baseline for biogenic soil functions against which to compare the development in diversity and density of soil biota under changing cropping systems and water regimes. Up to now, soil fauna has been monitored in the trials (Abdullaev, unpublished), and more specifically, termite populations were assessed as these represent a typical component of soil life (Abdullaev et al. 2002; Aitmuratov 2003).

Finally, assessing the health of the rural population, which has been exposed to environmental stress factors for several years or even decades, is a central part of the investigations. For example, the relationship between access of households to drinking water and sewage systems to the incidence of Hepatitis A and other water-borne diseases has been studied. The relationship proved to be very close (Herbst et al. 2003; Figure 7). An apparent decreasing trend in disease incidence throughout the years of the study, which is counter to all observations made in Uzbekistan, probably indicates a reduced level of reporting to government institutions in recent years. This indicates that a deterioration of the public health

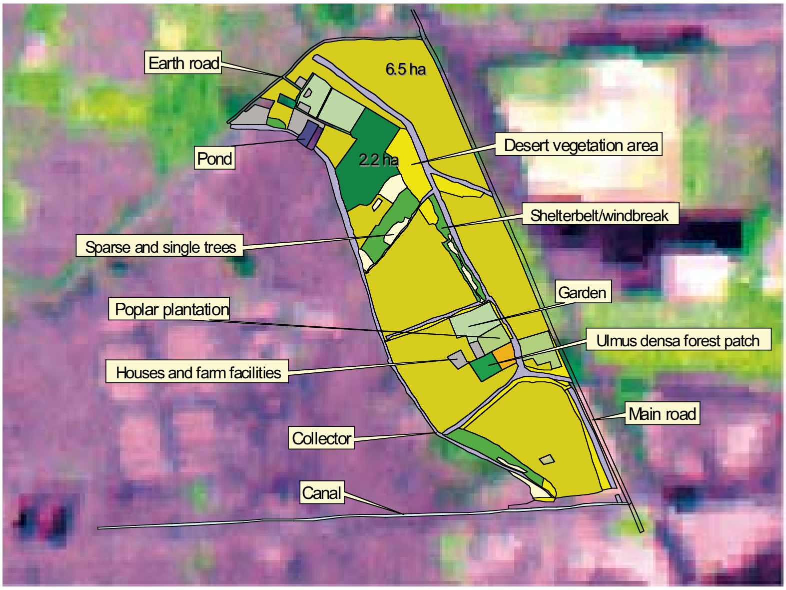


Figure 3. Test interpretation of tree and forest plantations from air photos of Karakum Plot, Khiva district, Khorezm province, Uzbekistan (Tupitsa 2003).

Table 3. Combined performance indicators for different tree species on two soil types (loamy, sandy) in Khorezm (Khamzina 2003). Below-ground score accumulates all root growth parameters (coarse and fine root biomass, coarse and fine root length, maximal depth and radius of coarse roots). Above-ground score accumulates growth in height and diameter and total above-ground biomass parameters.

Species	Below-ground score	Above-ground score
Tamarix androssowii (salt cedar)	84	35
Elaeagnus angustifolia (Russian olive)	78	32
Ulmus pumila (Siberian elm)	76	24
Populus nigra var. *pyramidalis* (black poplar)	69	24
Fraxinus pennsylvanica (swamp ash)	67	26
Populus euphratica (Euphrates poplar)	57	26
Armeniaca vulgaris (apricot)	17	4

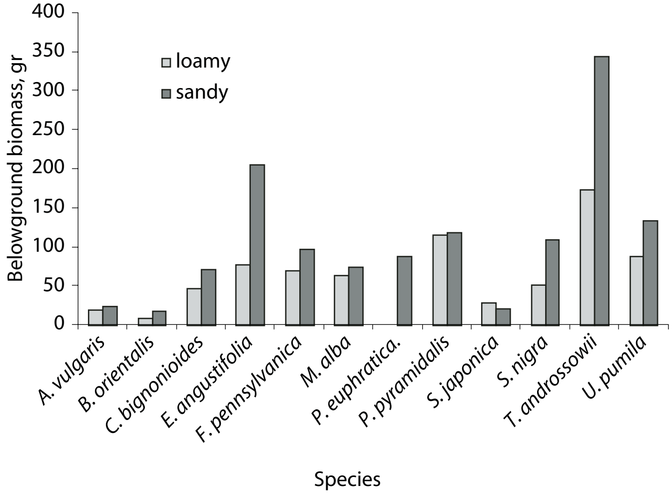


Figure 4. Below-ground biomass of the tree species on different soil types, Khiva forestry station, Khorezm (Khamzina 2003).

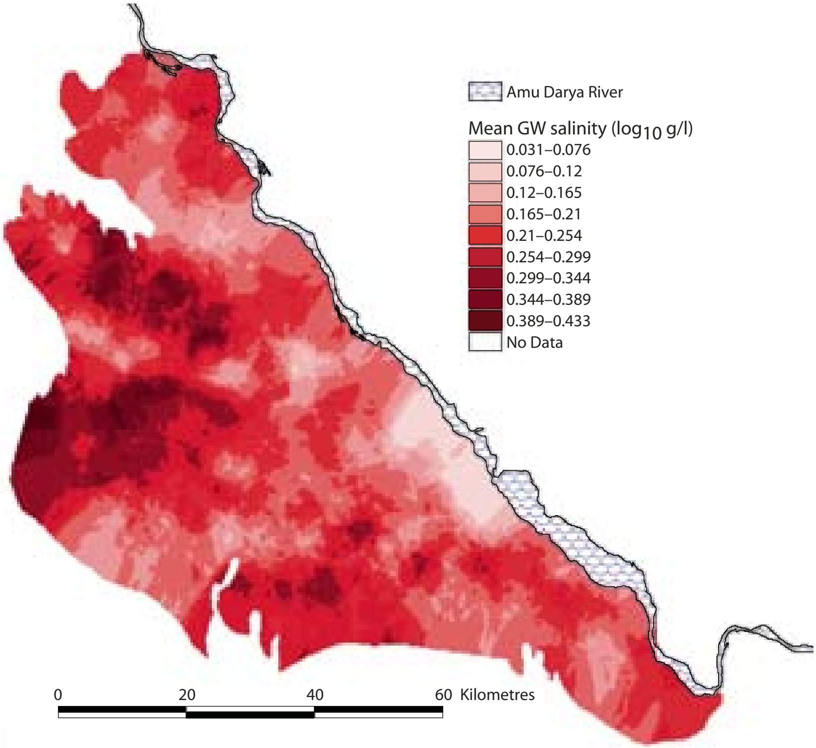


Figure 5. Spatial heterogeneity in average groundwater salinity throughout irrigated land in the Khorezm district of Uzbekistan (Vlek et al., in press).

system is taking place, which further aggravates the situation for citizens of Khorezm. Other health-related studies concentrate on diarrhoea and bacterial water quality, and on salinity-related heart and kidney diseases.

As a first step towards data integrating, a supervised, remote sensing, land-use classification for Khorezm was undertaken with 2002 Landsat satellite data, ground-truth information and data from the projects' central GIS database as inputs. This will

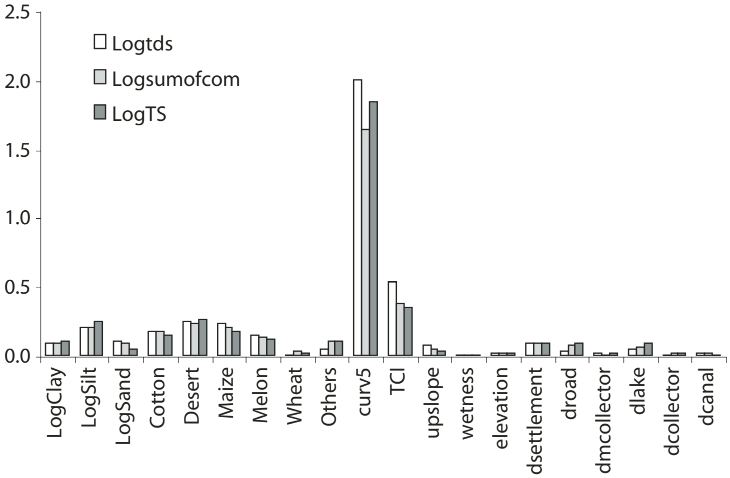
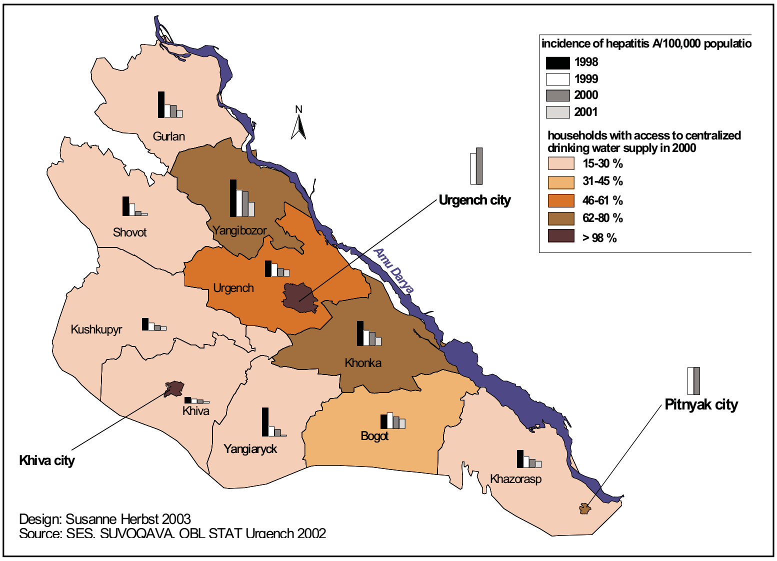


Figure 6. Spatial distribution of soil salinity: a neural network analysis for correlation of site properties with soil salinity (Akramkhanoz 2003).



Design: Susanne Herbst 2003
Source: SES. SUVOQAVA. OBL STAT Urgench 2002

Figure 7. Drinking water supply and waterborne infectious diseases in Khorezm: access to centralised drinking water supply in the districts of Khorezm (shaded) and incidence of hepatitis A (bars) in consecutive years (1998–2001) in Khorezm (Herbst 2003).

provide objective and quantitative information on location and spatial extent of different land-use types in Khorezm. Based on the site-specific conditions of major land use types and their spectral, spatial and temporal representations in corresponding Landsat satellite images, the first knowledge based classification was derived and serves as a basis for the development of a land-use monitoring system (Ruecker and Conrad 2003). The rules were then applied for land-use classification of a satellite image of the year 2001, where no training data from the same year was available (Ruecker and Schweitzer 2003). Further testing will ultimately lead to a knowledge-based land-use classification algorithm.

A time-series analysis of spatial patterns of the leaf area index (LAI) allowed seasonal vegetation dynamics of land-use types within the lower Amu Darya Basin to be identified and hypotheses on their causes and relationships with other environmental factors to be developed (e.g. different water supply and land management conditions during the season; Ruecker and Conrad 2003). This will allow monitoring and short-term forecasting of crop growth and water demand throughout Khorezm, as an input into the KEOM and the DSS, to provide farmers and water managers with quick and timely information on which they can base the land management in accordance with the actual seasonal conditions.

Research area: economy

In contrast with many other countries in the former Soviet Union, Uzbekistan has chosen a gradual, hesitant approach to reform. In the agricultural sector, the institutional legacies of the former socialist system prevail, in particular for land and water use. The delay in farm privatisation has caused little change in today’s farm structures compared to the situation before independence. The maintenance of obligatory relative land allotments (the so-called state orders) for the most important crops (cotton, wheat, and in part, rice; Table 4) prevents the decentralisation of decisions on any individual farm’s production pattern. The hesitant approach also to market liberalisation leads to strongly state-dominated domestic food wholesale and retail markets and agricultural input markets. This limits the freedom of individual farmers to respond to market signals and make their production decisions free of government interventions.

Against this background, the objectives of the economic studies in this program are to:

- analyse the economic situation of different types of farms and different agricultural production activities including the effects of government policies on farmer’s production decisions
- provide a first overview of the socio-economic situation of households in the region and the consequences of the negative environmental externalities of agricultural production on human health
- develop policy analysis tools to assess the economic effects of alternative forms of land and water use.

The Uzbek government reorganised the former collective state and collective farms into so-called ‘shirkats’. Another farm type, ‘dekhans,’ private farms that are subsistence oriented, consists of small-scale household plots or kitchen gardens of sizes restricted officially to a maximum of 0.35 ha of irrigated land (Table 5). The Uzbek government is currently (2003) considering further steps in farm restructuring that might strengthen private farm oper-

Table 4. Government purchase of main crops, in 1000 tons.

		1998	1999	2000	2001
Cotton	Purchased	217	290	199	243
	Produced	217	290	199	243
	%	100%	100%	100%	100%
Wheat	Purchased	41	45	50	43
	Produced	162	163	153	123
	%	25%	28%	33%	35%
Rice	Purchased	87	70	2	0
	Produced	161	141	38	13
	%	54%	50%	6%	2%

Source: N. Djanibekov unpublished data.

ations further; a draft legislation of the federal government proposes that all shirkats should be dissolved within the next two years and split into private farms. This would represent a more significant shift away from central planning.

At present, neither shirkats nor private farmers are free to make production decisions, as evident from survey findings (Djanibekov 2003). Although the findings show extreme variation, they indicate nevertheless that farmers have great difficulties in determining their actual costs and revenues. Calculated average gross margins for rice are much higher than for the other two major crops, cotton and wheat (Table 6). Nevertheless, the 'private' farmers have to plant a higher share of wheat and cotton to fulfil the state order. Farmers accept this order since it entitles them to obtain the inputs needed for agricultural production (water, machinery and fertilisers) and which are then used not only on the state order crops but also on other crops.

Table 5. Area share by farm types in Khorezm (Source: Khorezm Department of Statistics of Ministry of Macro-Economics and Statistics of the Republic of Uzbekistan.

	1998	1999	2000	2001
Shirkat	82%	81%	75%	70%
Farms	3%	4%	10%	14%
Household	14%	13%	13%	14%
Subsidiary farms	2%	2%	2%	2%

Source: N. Djanibekov unpublished data.

The survey indicates also that the actual production of rice might be higher than officially reported (Djanibekov 2003). Furthermore, the data suggest that potatoes might be an attractive alternative crop to cotton. However, further analysis will show how the relative profitability of different crops would be affected if the 'tranche' system of state-supplied inputs and output markets were substituted by true markets—for example, if farmers had to pay for the water delivery in the extensive irrigation systems. Also, the economic options for introducing suitable cash crops (needed inputs and outputs, and processing, storage and marketing) must be studied.

The assessment of input quantities used in agricultural production is associated with high insecurity. It is unclear how much water, labour, and other variable inputs are used per unit of land of certain crops, and it is difficult to determine their price. This is particularly true for water for which not even an implicit (i.e. shadow) price seems to exist.

On the output side, much depends on the marketing channels used to sell the products. For products subject to production targets, the prices for those quantities that have to be sold through the state channels are regulated. Normally, only small amounts of some of the strategic crops (e.g. wheat and rice) can be sold via free wholesale and retail markets where prices are higher (Table 6). Because a significant share of total national agricultural production (>60%) is produced by the dekhan farms, large proportions of the domestic production never reach the commercial markets.

The unreliability of the official farm data makes primary data collection a prerequisite for designing options for viable economic reforms. Efforts to obtain officially reliable data from shirkats proved rather unsuccessful, because the shirkat directors provided information mostly based on official accounting data. Tangible questions, for instance, on water use and allocation, often remained unanswered.

A second focus of economic research is to develop a model of the complex system of land and water allocation. Three different approaches are pursued to provide adequate cover of the different economic problems.

Table 6. Average gross margins in agricultural production in Khorezm (preliminary results from a survey of private farmers in spring 2003; values given in US Dollar ha^{-1}; including outliers).

Crop	Average	SD	Maximum	Minimum	N
Cotton	143.02	153.49	575.58	–127.91	297.67
Wheat	187.21	137.21	720.93	–141.86	252.33
Rice	616.28	525.58	3,193.02	–259.30	209.30
Potato	1,847.67	2,110.47	7,229.07	–289.53	19.77
Vegetables	936.05	874.42	3,438.37	–196.51	74.42

Source: N. Djanibekov unpublished data.

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First, the development of linear programming (LP) models will provide specific models for the various farm types and represent each of the 10 districts (rayons) of Khorezm. Water use particularly will be represented in these LP models. It will be modelled on a monthly basis to better represent the scarcity of this essential input during critical seasons.

Mueller (2003) estimated agricultural input use and production functions. Reliable information from farmers about the input of water for different crops is not available, but is essential for the modelling of alternative scenarios of water use. Mueller therefore used a Bayesian approach, the 'mixed estimation method', to approximate the required water input levels using the available prior information. While the methodology still has to be refined, first estimations yielded plausible results (Mueller 2003). In a second step input estimates will be used to calibrate preliminary production functions for different agricultural crops.

Second, data on the overall economy of Khorezm and Uzbekistan will be the empirical basis for a stylised version of an Uzbekistan-wide economic model, a so-called general equilibrium model developed by Wehrheim (2003) for Russia. It is currently being adapted for Uzbekistan such that it will represent two regions, Khorezm and the rest of Uzbekistan. It focuses on agriculture and natural resources (land and water) and represents foreign trade operations, because these are needed to assess the marketing potential of the cash crops to be introduced. The model will allow the economy-wide repercussions of alternative policies of land and water use that are currently discussed in Uzbekistan to be assessed, and will thus provide essential input to decision makers. The model is built around a complete and consistent input–output table documenting all income flows in the economy per year. Although such a table seems to be available for Uzbekistan from official sources, it is an undisclosed document, which makes it necessary to create it from secondary information.

Third, an economic river basin modelling approach will combine hydrological, soil, economic, and institutional information and will bridge the gap between the economy-wide model and the farm models. The model takes into account substantial inputs from the natural science studies, for instance hydrological and soil information. A blueprint version of a river basin model obtained from the International Food Policy Research Institute (IFPRI) has been used to start developing the theoretical version of the model.

Research area: society and institutions

Building the legal and institutional foundations for a new administrative system and creating efficient and competent institutions acting in accordance with the law are two major challenges related to the allocation of agricultural resources in Uzbekistan. The research activities concentrate on the necessary modifications of the legal framework, on the institutional organisation, on the informal organisation of decision making by-passing these institutions, and the attitude of agents involved in the implementation of sustainable, efficient agricultural or alternative systems.

One objective during Phase I was to assemble an overview of the present legal situation for resource management. A handbook is being compiled at ZEF in which the relevant legal texts for land use and the different types of land tenancy are collected, translated and analysed for structure, competencies and procedures relating to agricultural production. Also, the legislation passed since 1992 on environmental protection (more specifically the regulation of natural preserves, the protection and use of flora and fauna, forests, free air, water use, waste, the protection of agricultural plants from pests, diseases and weeds) was compiled, and other laws having an impact on environmental protection (Land Code, Administrative Liability Codes, Criminal Code and the act on self-government institutions of citizens) were summarised (Tillyaev 2003). A review of the legal possibilities of setting land aside for the establishment of forest patches or fish ponds for combined ecological and economic effects concluded that normative steps will be needed to establish privileges and subsidies that make the establishment of tree plantations a profitable and beneficial business. The study also suggests that these norms be based on existing regulations on land use.

Preliminary studies have been made of the institutional and organisational problems of water management and administration in the district departments for agriculture and water resources (Wegerich 2003a), and the informal network structures used to influence water distribution (Wegerich 2003b). These indicate that formal organisational structures between the province or district governors (Hokims) and the shirkat managers coexist with an informal network characterised by strong family or friendship ties. The informal networks seem to be used more frequently when the formal network fails or is not functional, that is, when water is short (e.g. the drought in 2002). These informal arrangements imply that the ongoing land reform could be manipulated through the network ties. Should the recently proposed water reform based on a shift from administration to hydrological boundaries be realised, the informal networks of different districts might begin to compete against each other, and the formal organisation (the water departments) could lose its influence in favour of the informal structures. The inconsistencies in the system revealed by this study make a larger, more profound analysis of these issues necessary, because a thorough understanding of decision making is needed to implement any modification effectively.

A qualitative analysis of social change due to land reform in rural Khorezm (Trevisani, unpublished) is based on the assumption that the restructuring of the agricultural sector might potentially increase poverty among some groups of the rural population. A rise in discontent has been observed in other rural regions of Uzbekistan during recent years. Decreasing living standards and increasing land and/or water shortage are increasing the pressure on the state-imposed inefficient agricultural production system.

A study of the institutional performance of the recently formed water user associations (WUAs) is reviewing the organisation, main functions and benefits of WUAs in Uzbekistan and identifying problems in the realisation of WUAs as well as obstacles to their expansion (Zavgorodnyaya 2003) (Table 7). Among the main reasons for slow implementation of WUAs are:

- the lack of water measurement facilities in the irrigation network
- the managers' lack of skill and training to independently manage the units
- the way people currently consider water to be a free resource.

The unstable financial condition of WUAs is explained not only by the lack of managerial skill, but also by the fact that the importance of fees in the beginning of the establishment of a WUA is poorly explained. One conclusion is that little importance has yet been given to introduce financial stimuli, for example fees for maintaining a functioning water delivery service.

ZEF asked an external consultant to evaluate the local farmers' priority setting towards expected changes in agricultural development, and to identify eventual barriers to technology adoption in Khorezm. Findings from group discussions with representative farmers and interviews with farm managers showed that the amount, price and quality of products are all of a lower priority to the interviewed farmers in Khorezm. In contrast, issues such as soil and water quality, financial resources and the timing of irrigation are seen as of key importance (Wall 2003). At present, farmers make few autonomous decisions, a fact that poses a key constraint to the successful transfer of technologies. In addition, considerable preconceptions of the role of farmers and decision makers are prevalent, which may also have an adverse effect. This highlights a need for increased educational efforts and stronger involvement of farmers and decision makers in research.

Table 7. Ostrom's (1999) design principles for institutions and their application to the Water User Association, Mirob, Khorezm, Uzbekistan.

Ostrom's (1999) design principles	In the eyes of the Mirob members	Interpretation of the author of the study (Zavgorodnyaya, 2002)
Clearly defined borders and participants	++ (clearly present)	+– (not clear)
Congruent rules	+ (present)	– (not present)
Arenas for collective decisions	+	+–
Control	++	++
Differentiated sanctions	++	++
Conflict resolution mechanisms	++	++
Recognised organisational law	+	–
Embedded enterprises	+	–

Source: Zavgorodnyaya 2002.

Modelling of development scenarios for Khorezm

The results of the single studies that have been presented here in brief are based on preliminary information available after only one year of activities, but represent the building blocks of a scientific, multi-disciplinary approach. The program will be able to provide sustainable land-use options only if these building blocks are fully integrated into a unified, multi-disciplinary concept for land and water use. This will be the main task during the upcoming project phases II and III.

In Phase II, the main aims of the project will be to:

- gain the necessary understanding of natural, economic, and social processes that allow alternative restructuring concepts to be proposed
- develop the ecological-economic optimisation model (KEOM) to assess the impact of various restructuring concepts on economic and ecological developments
- develop, together with the local land users and based on the KEOM, a pilot scheme for large-scale privatisation of shirkats (communal farms)
- initiate the development of a decision support system (DSS) to aid decision makers in the privatisation process and reallocation of land and water resources.

The data compiled during the field research will be integrated into various sub-models representing the thematic components of the program, and these sub-models, in turn, will integrate the central model (KEOM).

In search area N, a central task is the development of two sub-models, one for land-use change and one for hydrology. Both will integrate land and water use including alternatives for land use, crop and water management and feed these into the KEOM. Together, they represent the natural resources sub-unit of the KEOM.

Similarly, in the economic domain, three sub-models will be used to integrate the different levels of economic reform. The key to the success of restructuring will be functioning markets and privatisation of agriculture, and it will be necessary to prepare options for both farm-level restructuring and economic measures that need to be implemented on larger scales (in Khorezm, and in the whole of Uzbekistan). The three sub-models used to represent these aspects in the KEOM are the farm-level change sub-model (FLCM), which deals with farm restructuring, the Uzbekistan-wide economic model which addresses market reform, and the economic river-basin sub-model for Khorezm that links the two. Together they represent the human driver sub-unit of the KEOM.

Scenarios for different options for an optimisation of land and water use will be obtained through simulations in the ecological–economic optimisation model (KEOM), which will be a spatially distributed computer model consisting of the mentioned sub-units representing resource utilisation and natural constraints on one side, and economics and human driving forces on the other (Figure 2). The KEOM will allow assessing the impact of possible scenarios (climatic changes, policy changes, introduction of different land management, etc.) on the long-term sustainability of ecological and economic conditions of Khorezm and Uzbekistan.

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Household-level irrigation for efficient water use and poverty alleviation

Jack Keller[1] and Michael Roberts[2]

Abstract

Optimising the efficiency of irrigation water under conditions of scarcity is a common concern of farmers in arid and semi-arid regions as well as those in monsoon climates with long dry seasons. A wide technology gap exists between currently available irrigation technology and the specific water needs of the rural poor. Nevertheless, several household-level irrigation technologies have emerged that can be marketed through private-sector distribution channels at sustainable, unsubsidised prices and still be affordable to even very low-income smallholders. Simple, efficient manual pumps, appropriate drip irrigation, and plastic water storage bags are highlighted as examples of household-level irrigation technologies that meet smallholders' needs for low entry cost, rapid return on investment, high rate of return, low-cost manual operation, easy maintenance, and suitability for small landholdings. Household-level irrigation can be extremely efficient, both in water usage and in targeting economic benefits toward the rural poor. Household-level irrigation systems stand out as simple, practical, and widely applicable tools for catalysing the agricultural potential of smallholders and creating opportunities for more active and effective market participation through the production of income-generating, high-value crops. This paper also outlines a methodology for designing and implementing coordinated interventions to identify and resolve critical smallholder market constraints using household-level irrigation as a strategic entry point. To maximise the poverty alleviation impacts of irrigation, there is a strong need to focus research efforts on improving irrigation effectiveness under smallholder farming conditions.

Introduction

THIS PAPER describes the existing and potentially much expanded role of small-scale irrigation in improving water use efficiency, increasing agricultural production, and reducing poverty. It presents the field experience of several non-government development organisations and sets that experience in the context of a broad vision for harnessing water control and market participation as motor forces for poverty alleviation among large numbers of smallholders.

The majority of the world's poor live in rural areas and depend directly or indirectly on agriculture for their livelihoods. Despite trends toward urbanisation, the locus of poverty is likely to remain in rural areas for decades to come (IFAD 2001). Progress toward reducing poverty has been slow and, at the current pace, will fall far short of Millennium Development Goals including the resolution to reduce by half the proportion of people surviving on less than one dollar per day by 2015 (World Bank 2001). At the same time the average size of farms in developing countries in Asia is steadily decreasing as a result of population pressure. Population growth, urbanisation, industrialisation and environmental degradation are also intensifying competition for scarce water

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resources (Rosegrant et al. 2002). These factors point to a future, already upon us, where much of the world's food is produced by people with little capital, small land holdings, and scarce water resources.

It is in this environment that Sok and Theary, a farming couple in south-eastern Cambodia, labour to support themselves and their two children. With only a small 1500 m^2 plot of land, they were unable to meet their basic food needs by growing rice. Instead, with the help of an inexpensive foot-operated pump (treadle pump) and a pond that captures water from the monsoon rains, they have turned their small plot into a commercial garden providing cucumber and lemon grass to local markets. For the past seven years, this enterprising couple has earned enough income from vegetable production to take care of their food needs, pay for their children's education, and build a small wooden house.[1]

Similar stories of small-scale irrigation opening up new opportunities for smallholders have been repeated more than two million times now across the developing world. Access to affordable irrigation has significantly reduced poverty because it addresses critical leverage points in the livelihood strategies of the rural poor by (a) enhancing agricultural production and (b) creating opportunities for more active and effective market participation.

The type of small-scale irrigation described in this paper is a distinct category of irrigation that we have termed *household-level irrigation*. Household-level irrigation can be defined as self-contained irrigation technologies for use on small plots of land (typically 20–20,000 m^2) by small groups of people (typically a single household) without the need for collective infrastructure. These technologies are affordable to the rural poor (typically recouping investment costs within one growing season) and may be used as stand-alone tools or in combined technology packages to meet the specific water needs of individual users.

Water, the unique input

Several managed inputs are essential for profitable farming including a reliable water supply, adequate soil fertility, productive seeds, and good cultural practices. Among these inputs, the unique characteristics of water create particular challenges and opportunities for smallholders and development agencies.

Water is unique, first of all, because of the sheer mass required. Compare, for example, the amount of water, fertiliser, and seed needed to cultivate two typical crops grown in an arid area with negligible rainfall during the growing season.

To produce one kilogram of a field crop such as maize that is harvested when the kernels are dry requires:

- 700–1000 kg of water in 10 irrigation applications spaced throughout the growing season
- 50 g of fertiliser in two applications, one at the beginning and the other in the middle of the growing season
- 1–2 g of seed at the time of planting.

To produce one kilogram of a vegetable crop such as tomato that is harvested when the fruit is plump and full of moisture requires:

- 70–100 kg of water in 10 to 20 irrigation applications spaced throughout the growing season
- 5–10 g of fertilisers in three applications, one at the beginning and the other two during the growing season
- 5–10 g of tomato seedlings germinated from a few milligrams of seed six to eight weeks before they are ready for transplanting.

From the above, it is easy to visualise that water must be available close to the area to be irrigated because smallholders cannot economically convey it over long distances or pump it from deep sources. This is not the case for fertilisers and seeds, which can be transported economically over long distances. In addition, water must be applied frequently and uniformly to optimise yields and minimise water requirements. If the water is not applied uniformly and/or the period between applications is too long, the amount of water needed per kilogram of production can easily be more than tripled. The management of irrigation applications is therefore critical in arid and semi-arid areas, where water supplies are usually limited or difficult to develop, and in monsoon climates with long dry seasons.

Another unique aspect of water is its homogeneous form and widespread applicability. The composition of water is basically identical for all crops in all places (although water sources, quality, and methods of delivery will vary). This is not so for seeds and fertilisers, which must be tailored for specific crop-climate-soil conditions for optimal performance. All

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[1] This case based on a July 2003 interview by the author (M. Roberts) in Svay Rieng province, Cambodia. Names have been changed to protect confidentiality.

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crops require water in large volumes and at frequent intervals, and lack of access to and/or control over water resources are pervasive constraints facing most farmers. Consequently, advances in the effective and efficient delivery of irrigation water will generally be widely applicable. Moreover, since most farmers are smallholders whose purchasing decisions are exceptionally price-sensitive, reductions in the cost of irrigation to levels affordable to the rural poor will increase its accessibility to a much broader and poorer population.

Filling the technology gap

The development of improved water management through irrigation made a major contribution to the achievements of the Green Revolution. Between 1970 and 1990, the total irrigated area in the developing world expanded by 42% from 123 million to 175 million ha (FAOSTAT data). When combined with high-yielding seed varieties and fertilisers, increased irrigation resulted in impressive gains in world grain production. However, most irrigation investment (both public and private) was directed toward relatively large and technologically sophisticated systems in more favourable agro-ecological regions populated by more well-endowed farmers. Poorer farmers with small plots of land in marginal areas were, by and large, left on the sidelines.

Prolonged neglect of small farmers by mainstream irrigation development policy and practice has resulted in a wide gap between existing irrigation technology and the irrigation needs of smallholders. Nevertheless, innovations have emerged that provide smallholders with appropriate and affordable options for irrigated agriculture, among which are the household-level irrigation technologies described in subsequent sections of this paper.

These technologies fit within, but do not fill, the irrigation technology gap. A significant commitment of research effort and resources is needed to develop a wider range of irrigation technologies specifically suited to smallholders' unique characteristics (e.g. small landholdings, low capital availability, low risk tolerance, and relatively low opportunity cost of family labour). It is generally not sufficient to merely scale down technologies that are appropriate for larger farms; solutions must be re-engineered from the smallholder's point of view. Technology features that are important to smallholders include low cost, suitability for small fragmented land parcels, rapid return on investment, simple and inexpensive maintenance, a manual power source, and divisibility[2]. A smallholder-friendly technology will exhibit most or all of these features.

The need for increased research effort is not restricted to the development of irrigation hardware. Equally important is the development of effective and sustainable methods for delivering household-level irrigation technologies to a large and dispersed population of potential users. It is also critical to understand the broader market context within which household-level irrigation plays a catalytic role. These issues are discussed in more detail later in the paper.

The following sections describe some household-level irrigation systems currently in use or under development. The technologies cover a range of functions including water lifting (treadle pumps, rope and washer pumps), efficient water application (drip irrigation), and water storage (plastic water bags).

Treadle pumps

Treadle pumps are simple, foot-operated pumps that can lift water from shallow groundwater sources or surface water bodies. The pumps consist of two vertical cylinders fitted with pistons that are activated by an up and down stepping motion. The pistons create suction to lift water from depths of up to 7 m with a flow rate ranging from 40–80 litres per minute (Lpm) depending on the water depth and cylinder diameter. Treadle pumps can be made from a variety of materials and in a number of design variations but the basic version is fabricated from welded sheet steel with the treadles and support structure made from wood or bamboo (Figure 1). The pump has several characteristics that make it suitable for agricultural use by low-income farmers:

- It is inexpensive. In South and South-east Asia, the retail cost of a basic model ranges from US$12 to US$15 including the wood/bamboo support structure. The cost of a borehole (when necessary) varies according to local geological conditions but typically ranges from US$20 to US$80 in alluvial soils.

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[2] By divisibility we mean that the technology can be sized to fit the available land, water, capital, and labour resources of the smallholder while maintaining a similar cost per unit of irrigated area and similar returns per unit of capital invested. Divisibility also implies the ability to start small and expand incrementally over time as financial resources allow.

- The design is elegantly simple and can be manufactured by local craftsmen using readily available materials. The treadle pump can be maintained and repaired easily by the user. Parts needing periodic replacement include plastic piston seals, which are common to many popular hand pumps and readily available in local markets. Foot valves at the bottom of each cylinder are made from rubber that can be replaced using a discarded bicycle tyre inner tube.
- Water in the suction pipe is kept in motion with each up- and down-stroke resulting in a continuous water flow, high flow rate, and efficient use of energy.
- The pump is operated using the leg muscles in a natural walking motion making it possible to pump comfortably for long periods. Pumping three to four hours per day delivers enough water to irrigate about 2000 m^2 of vegetable crops each growing season.

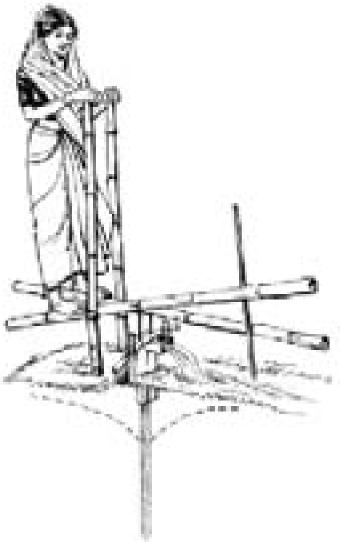

Figure 1. Treadle pump mounted on borehole.

The treadle pump was developed in Bangladesh by a non-government development organisation (NGO), Rangpur-Dinajpur Rural Services (RDRS), and popularised by another NGO, International Development Enterprises (IDE). Beginning in 1986, IDE-Bangladesh facilitated a market network of about 65 manufacturers, 700 dealers, and 5000 installers and stimulated demand for the pumps through mass media campaigns in rural areas (Hiereli 2000). About 1.5 million treadle pumps have been distributed so far through market channels in Bangladesh and another half million through similar IDE programs in other Asian countries (Table 1).

Table 1. Treadle pumps distributed in Asia through IDE programs.

Country	Year started	Total treadle pumps[a]
Bangladesh	1986	1,500,000
Nepal	1987	40,000
India	1990	440,000
Cambodia	1994	20,000
Total		2,000,000

[a] Approximate totals as of 2002 (IDE, unpublished data)

Shah et al. (2000) studied the social impact of the treadle pump in the so-called ‘poverty square’ comprising parts of eastern India, Nepal, and most of Bangladesh. The research indicated that treadle pumps enabled smallholders to intensively manage water and other inputs on ‘priority plots’ within their land holdings, which significantly increased their agricultural production and income. The average additional income generated by the treadle pump was found to be more than US$100 per year, and a significant percentage were making an extra US$500 or more per year. The extra income enabled some treadle pump owners to graduate to a higher level of mechanisation by purchasing diesel pumps for irrigation.

Not all of the two million treadle pumps in Table 1 are actively generating income for smallholders. A proportion will consist of replacement purchases for pumps that have worn out, and pumps that have been abandoned without graduating to more advanced production technology. Assuming that only 50% of treadle pumps are currently generating the average net annual income of US$100, the total contribution of treadle pump irrigation to rural economies is conservatively estimated to be US$100 million per year.

The potential for future expansion of the treadle pump technology in India and Nepal could be as large as 9–10 million households (Shah et al. 2000). Currently, IDE is also exploring potential new applications for the treadle pump in China, South-east Asia, and sub-Saharan Africa.

Rope and washer pumps

Treadle pumps are limited to pumping water from depths of up to 7 m. For lifts from greater depths, the rope and washer (R&W) pump provides an effective alternative.[3] The R&W pump has been promoted in Nicaragua since 1983 by several local and international NGOs. There are now more than 40,000 pumps installed and 10 private manufacturing enterprises, the largest of which is Bombas de Mecate SA. IDE has recently begun to transfer the R&W pump technology to Bangladesh, India, and Cambodia.

- The R&W pump consists of a rope with plastic washers fixed at 1 m intervals along its length. The rope is threaded through a vertical 34 mm PVC riser pipe and joined to form a loop that hangs from a pulley with a hand crank (Figure 2). The washer diameters are slightly smaller than the inside diameter of the riser pipe so that each washer acts as a piston, lifting a volume of water up the riser pipe as the pulley is turned.
- The R&W pump can draw water from depths of up to 70 m at flow rates ranging from 40 Lpm (at 10 m depth) to 8 Lpm (at 60 m depth). Water can be pumped from hand-dug wells or from boreholes with a diameter of at least 75 mm (allowing enough space for the riser pipe and the downward-moving half of the rope loop). It is also possible to use a sloping riser pipe to pump up hillsides, river banks, or from the edge of a pond.
- Like the treadle pump, the R&W pump design is simple, elegant, and inexpensive. In Central America, the pumps are US$45–60 (larger models intended for community use range up to US$130). In Bangladesh and Cambodia they are US$25–30.
- The pump is made from commonly available materials (steel, rope, and a modified motorcycle wheel and tire for the pulley) making it easy to manufacture locally and simple to repair and maintain. The only specially manufactured parts are the injection-moulded polyethylene washers and a glazed ceramic guide block that provides a low-friction turning point at the bottom end of the rope loop.
- Maintenance includes oiling the axle bushings every few months and adjusting the rope when it becomes loose. The rope and washers need to be replaced every six months to five years depending on use. Replacement washers therefore need to be made available through the pump supply chain.
- The flow rate of the R&W pump is lower than the treadle pump but is adequate for both domestic water use (which was the original purpose of the pump) and for small-scale irrigation. Pumping for three to four hours per day at the low-end flow rate of 8 Lpm will deliver enough water to irrigate about 500 m^2 of vegetable crops. Larger models of the R&W pump powered by pedals, animal traction, motors, and windmills have also been developed.

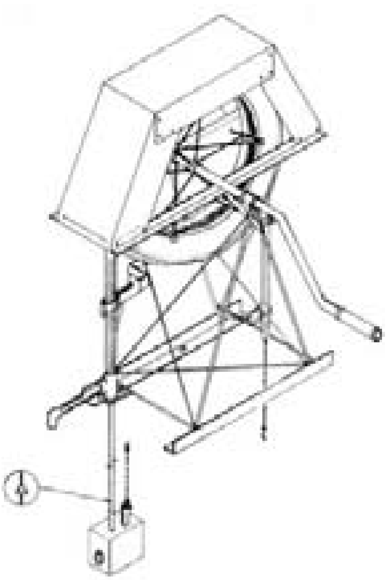

Figure 2. Rope and washer pump.

Pumping technologies such as the treadle pump and R&W pump should be used with caution in regions where arsenic concentrations in groundwater are higher than 10 ppm (the World Heath Organization's recommended limit for safe drinking water). High concentrations of arsenic in drinking water pose a serious public health hazard, the worst example being Bangladesh where up to 46 million people are exposed to potentially dangerous arsenic levels in their tube wells (Yu et al. 2003). How arsenic in irrigation water affects health is less clear. However, given the high probability that irrigation pumps will also be used for drinking water, groundwater pumping should not be promoted in arsenic-affected

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[3] Technical data on rope pumps obtained from the website www.ropepumps.org, which summarises the experience of a number of organisations active in the development and promotion of the rope and washer pump technology.

areas unless and until clear strategies for mitigating health hazards are in place.[4]

Drip irrigation

Drip irrigation provides a way to irrigate precisely, maximise uniformity and minimise water use. Drip systems deliver irrigation water directly to the plants through a system of plastic tubes and emitters with minimal distribution and evaporation losses. The area of land that can be fully irrigated from a given volume of water can be significantly increased by converting from traditional surface irrigation to drip irrigation. The agricultural production per unit of water supplied is often increased by 100 to 200% (Table 2).

Table 2. Water productivity gains from shifting to drip from conventional surface irrigation in India[a].

Crop	Change in yield (%)	Change in water use (%)	Water productivity gain (%)[b]
Banana	+52	–45	+173
Cabbage	+2	–60	+150
Cotton	+27	–3	+169
Cotton	+25	–60	+255
Grapes	+23	–48	+134
Potato	+46	~0	+46
Sugarcane	+6	–60	+163
Sugarcane	+20	–30	+70
Sugarcane	+29	–47	+91
Sugarcane	+33	–65	+205
Sweet potato	+39	–60	+243
Tomato	+5	–27	+49
Tomato	+50	–39	+145

Source: Postel et al. (2001)

[a] Results from various Indian research institutes.
[b] Measured as crop yield per unit of water supplied.

State-of-the-art commercial drip irrigation systems are well beyond the reach of the world's poorest farmers for a number of reasons: they are expensive to install, costing US\$1500–2500 per ha (US\$0.15/m^2 to US\$0.25/m^2); they are over-sized, with the smallest commercially available systems starting at about 2 ha; they operate at high pressures, typically 10 m of head; and are relatively complex to operate and maintain. In contrast, the drip systems described below are low-cost, available in small packages, operate at low pressure, and are easy to understand and maintain by small farmers. To achieve these advantages, compromises are made in operational convenience, manufacturing tolerances, and, to some extent, the uniformity of irrigation applications.

R. Chapin, of Chapin Watermatics, was among the first to recognise the need to promote a low-cost version of drip irrigation among low-income households. In 1974, at the invitation of an NGO (Catholic Relief Services), Chapin introduced small-scale drip irrigation systems in Senegal to help subsistence farmers produce vegetables where there was little or no rain. In the mid 1990s, IDE developed and began promoting a variety of drip irrigation kits that were appropriate for small land holdings. In India, for example, standard irrigation kits range from a US\$6 'bucket kit' irrigating 20 m^2 to a US\$130 'quarter-acre kit' irrigating 1000 m^2 (IDE 2003). The systems are expandable so that farmers can start small and scale-up as their financial capacity and technical skills increase.

As illustrated in Figure 3, a typical system irrigating 100 m^2 consists of a 200 L water storage tank supported 1 m above the ground. The tank feeds 16 mm outside diameter (OD) main and sub-main pipes leading to five 9 m long, 12 mm OD laterals. Water is emitted through 150 micro-tubes (1.2 mm inside diameter) cut in 0.6 m lengths and inserted at 0.6 m intervals along the laterals. Two micro-tubes are inserted at each interval, one for each of two vegetable rows that are irrigated from a single lateral. The main, sub-main, lateral lines, and micro-tubes are typically made of linear, low-density polyethylene (LLDPE) tubing.

A major price breakthrough for drip irrigation occurred in 2001 as a direct result of the ingenuity of Indian smallholders. Some innovative cotton farmers began using drip laterals made of thin-walled clear plastic tubing that was produced for packaging a confectionary treat called *Pepcee*. Instead of using emitters, the farmers punched holes in the tubing with a needle. The resulting water application was not uniform and the low-quality tubing began to disintegrate within a few weeks. The clear plastic also

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[4] A number of low-cost arsenic mitigation technologies are currently in development or are being promoted by IDE and other organisations; arsenic-removal filters, rainwater collection systems, and bacteriological water filters can all provide safe alternatives to drinking contaminated groundwater.

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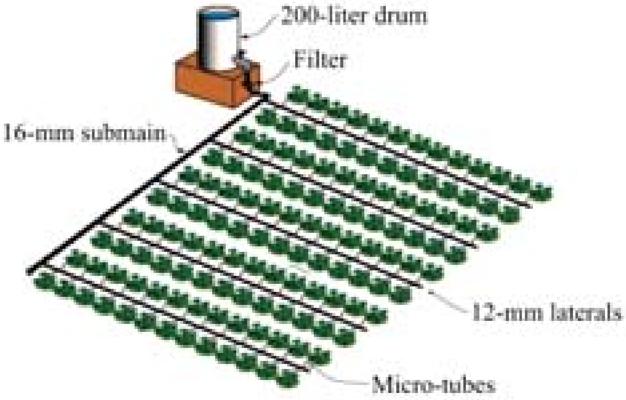

Figure 3. Schematic of a low-cost micro-tube drip irrigation system.

allowed algae to grow inside the tubes. But these systems were successful because they cost only about US\$0.01/m^2 and they lasted long enough to germinate a cotton crop six weeks before the monsoon rains began, which increased yields by 25–50%. IDE-India modified the *Pepcee* tubing to improve its strength and suitability for irrigating full-season vegetable crops. The resulting lay-flat tubing has a wall thickness of 0.125 mm and is made from a mixture of LLDPE, low density polyethylene (LDPE), and carbon-black so it is strong and resists stress cracking, ultraviolet deterioration, and internal algae build-up. Furthermore, the systems are affordable, with the laterals plus sub-main (see Figure 3) costing less than US\$0.04/m^2. Under low operating pressure heads, the discharge rates from micro-tube emitters are about ideal, clogging problems are minimal, and on relatively level, small fields the application uniformity is comparable to that achieved by conventional drip systems in developed countries. Under 2 m of pressure head, a 50 m lateral (the longest recommended length) has an emission uniformity (EU) of 76–89% for emitter spacings of 45–90 cm. At lower pressures and shorter lateral lengths, EU values as high as 96% can be achieved. This compares favourably with conventional irrigation systems, which are typically designed to produce EU values of 85% or higher (Keller and Keller 2003).

Thus, the cost of drip irrigation has been reduced by a factor of four or more, from state-of-the-art systems costing US\$0.15–0.25/m^2 to US\$0.04/m^2 for low-cost systems using thin walled, lay-flat tubing. The availability of drip irrigation systems in small affordable packages unlocks the potential benefits for literally millions of resource-poor farmers. In addition, it opens the potential benefits of irrigation even where water supplies were considered insufficient or too costly to acquire for traditional irrigation methods to be practical. To date, more than 70,000 low-cost drip irrigation systems have been distributed through market channels in India, Nepal, Vietnam, and Bangladesh. Many of these systems have been installed in the semi-arid region of the state of Maharashtra, India, where the average land holding is less than 1 ha. The following comments are based on discussions that occurred during the past year between the author (J. Keller) and over 25 purchasers of the low-cost, micro-tube drip systems promoted by IDE in India.

- Most farmers had previous experience producing vegetable crops (such as tomatoes, eggplant, okra and squash) using traditional surface irrigation supplied from hand-dug-open wells fitted with electric or diesel powered pumps. During the dry season their wells produced little water (5–20 m^3/day). The sizes of their vegetable plot ranged from roughly 200 m^2 to 2000 m^2.
- All of the farmers interviewed said the conversion to drip irrigation was very cost-effective and many of them had increased an annual net return from additional vegetable production that was several times the investment cost. Farmers reported yield increases of 50–100% and decreases in water use of 40–80% compared to their experience with traditional surface irrigation systems. The net returns from areas under double cropping were

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roughly US$0.50/m^2 greater under the drip systems than with their traditional surface irrigation systems. However, in most cases water was the limiting resource and they have been able to double or even triple the irrigated area by converting from surface to drip irrigation[5] and generate increased net returns of US$1.00/m^2 of newly irrigated land.

- From field observations and farmers' experience, the expected life span of the thin-walled, lay-flat tubing is expected to be about four growing seasons, or about two years under double cropping.
- Farmers found the drip systems to be much easier and less time consuming to operate than traditional surface systems, particularly where water supplies were limited.
- Micro-tube clogging was not a problem with any of the drip systems in Maharashtra, even though they were being supplied directly from open wells and most of them did not even have simple in-line screen filters. The few micro-tube emitters that clogged were simply replaced if flushing did not unclog them (micro-tubes cost about US$0.01 for three). A few farmers elected to simply punch holes in their thin wall drip-tape instead of using micro-tubes as emitters and they did experience problems with clogging.

Low-cost storage

Water storage is often the most expensive component of small-scale water systems for both domestic water supply and irrigation. Traditional cement jars, for instance, typically cost about US$0.02 per L of storage (US$20 per m^2), which accounts for about 70% of the total cost of a roof-top rainwater collection system. The rigid plastic 20 L buckets and 200 L tanks used for small-scale drip irrigation kits, as described above, typically cost US$0.06–0.02 per L, making up a significant proportion of the total system cost.

In India and Bangladesh, research is currently underway on flexible plastic water bags that will redefine what is meant by 'low cost' water storage. Experiments are being conducted with various plastic materials, including a two-walled design with the inner layer formed by a thin replaceable polyethylene liner which provides water-tightness. The outer layer is made from woven polyvinyl chloride (similar to the material used for many fertiliser bags) and provides support strength. For large storage volumes, support strength becomes a constraint that can be overcome by half-burying the water bag in the ground and allowing the soil to provide most of the support. The double-layer storage bags have been made in sizes up to 5 m^3 with costs as low as US$2.00 per m^3, or one tenth the cost of the least expensive cement and rigid plastic containers.

Low-cost water storage opens up new possibilities for combining inexpensive components to create useful irrigation tools for smallholders. The US$6 bucket drip kit is transformed into a US$1 drip kit by replacing the 20 L bucket with a 25 L water bag and by using lay-flat tape instead of thick-walled pipe for the two lateral lines. Such a significant drop in cost makes irrigated agriculture possible for a much poorer segment of the population.

In the mountainous areas of Guizhou province in southern China, 20 L water bags fitted with screw caps that act as a drip emitter have been used to irrigate persimmon trees and hua jiao shrubs during the critical flowering stage. Individual water bags are placed at the base of each tree and refilled every two to three days for about one week.

At the other end of the storage volume continuum, it is possible that very large storage bags will soon enable smallholders to collect and store monsoon rains to irrigate a small crop in the dry season. With careful soil-water management (including the use of plastic mulch and drip irrigation) and cultivation techniques (such as conservation of antecedent soil moisture from the wet season and late transplanting of seedlings) it is possible that 5 m^3 of water storage could irrigate a 20 m^2 garden for a 90-day period in arid regions (ET = 4 mm/day). By growing a high-value, off-season crop that fetches gross revenue of US$0.75/m^2, a smallholder could pay off the investment cost of such a system and receive a small profit in the first growing season (Table 3). The system is scalable so that larger or smaller areas could be cultivated depending on the volume of water stored.

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[5] A note of caution is in order here because by increasing the irrigated area the total water consumed by Crop ET would be proportionately increased. From a basin-wide water resource perspective this would not increase the production per unit of water consumed if the so called 'losses' from the less efficient traditional surface irrigation were being reused. The losses are only 'real losses' if the water is discharged to salt sinks or consumed by salinisation of unwanted evaporation and transpiration.

Applications such as this are on the verge of economic feasibility and are testing the boundaries of what it is possible to achieve with household-level irrigation tools. More research is needed and field tests are underway in India to determine the expected lifespan of the system components and to identify additional opportunities for water savings.

Table 3. Economic viability of dry season irrigation using water bag storage.

	First year	Subsequent years
Expenses (for a 20 m^2 garden)		
Water bag (5 m^3)	US$10.00	–
Lay-flat drip tape (20 m)	US$0.80	–
Plastic mulch sheet (20 m^3)	US$0.50	–
Seed, fertiliser, pest control	US$1.50	US$1.50
Subtotal	US$12.80	US$1.50
Income		
20 m^2 @ US$0.75/m^2	US$15.00	US$15.00
Net income	US$2.20	US$13.50

Increasing poverty reduction per drop

Optimising the efficiency of irrigation water under conditions of scarcity is a common concern of small farmers, the majority of whom live in arid and semi-arid regions or in monsoon climates with long dry seasons. It is clear that the household-level irrigation technologies described above can improve water productivity significantly. Judicious use of nearby water sources at the individual household level limits water losses during storage and distribution and drip irrigation enables smallholders to approach world-standard levels of water application efficiency. There is, however, another form of efficiency to which household-level irrigation can make a valuable contribution and that is in targeting economic benefits toward the rural poor. Household-level irrigation has the potential to increase both ‘crop per drop’ and ‘poverty reduction per drop’ in the following ways:

- Household-level irrigation systems provide an affordable entry into irrigated agriculture, giving smallholders an opportunity to increase their production and generate income by selling their surplus. There are few investment options in rural areas of developing countries that offer as much potential for as many people as irrigated agriculture (Shah et al. 2000). By combining low entry cost, high return on investment, and short payback periods the technologies meet the needs of many small farmers.
- The economic benefits resulting from the household-level irrigation technologies are biased toward the poor because the technologies themselves are self-targeting. Treadle pumps, R&W pumps, and low-cost drip, for instance, have high labour requirements relative to more expensive irrigation options such as engine pumps and state-of-the-art drip irrigation equipment. For this reason, the household-level systems are primarily attractive to the rural poor, who have small landholdings and relatively abundant family labour, but they are of little interest to more wealthy farmers with larger landholdings.
- Household-level irrigation generates both on-farm and off-farm employment, which is extremely important to the rural poor, especially the land poor. On-farm employment is increased as a result of increased production and cropping intensity. Local enterprises are engaged in the production, distribution, and installation of the irrigation equipment, creating employment in the rural non-farm sector. The broader rural economy is stimulated by financially empowered smallholders purchasing agricultural and non-agricultural goods and services from rural markets.
- Household-level irrigation also contributes to gender equity by reducing women's workloads, improving family nutrition, providing a source of independent income for women, creating opportunities for women to learn new skills, and reducing the need for family members to migrate away from the home for seasonal wage labour.

The market approach to technology dissemination

In economic terms, reduced poverty from any technological innovation is directly related to its effect on individual farmers, the number of farmers affected, and the multiplier effect in the economy. We believe that the most effective way to maximise these factors for household-level irrigation technologies is to promote and distribute it using a demand-driven, market-based approach.

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The strategy of subsidising the cost of conventional irrigation systems so farmers with small plots can afford and use them has generally proven to be unsustainable. It has not been an efficient way to address the needs of farmers of small plots, nor has it resulted in the expected improvements in irrigated agricultural performance. For economically sustainable success, the uptake of irrigation systems for use on small plots should be demand driven and without direct subsidies. Thus the systems must be financially affordable, and farmers should be willing to pay the full ongoing cost (including reasonable profit margins) associated with producing and marketing them once the market demand is well established. The ideal is for farmers to pay the full ongoing cost, but there are circumstances resulting from extreme poverty, disasters, or other social/economic/political situations for which it may be necessary to provide subsidies. But experience has generally been that system uptake and continued use are not sustained when subsidies are discontinued.

Rather than direct subsidies, we recommend providing what are, in effect, indirect subsidies to farmers by covering the costs of developing and establishing the market demand for affordable technologies that improve productivity. Funding the development of low-cost systems and establishing the demand-driven markets for them has proven to be a very cost-effective role for donors. Heierli (2000), for instance, describes the marketing approach used by IDE in the dissemination of treadle pump technology in India and Bangladesh. In general terms, the strategy is as follows:

- Identify and develop promising technologies that have the potential to improve productivity if they can be packaged in a manner that is suitable for small plots of land and affordable to the potential farmers. While the final products may appear simple, developing affordable and user-friendly products requires inventive and talented engineering.
- Market-test the promising designs. Those that are not rejected usually undergo considerable change to trim cost, increase functionality, and better address field requirements to gain farmer acceptability.
- Release commercially viable products into the market by training local manufacturers, introducing it to distributors and retailers, and conducting awareness raising campaigns in rural areas to create demand. To ensure that the product takes root and begins to grow, local markets may need a greater or lesser degree of facilitation depending on their initial size and maturity.
- The most cost-effective way to provide systems for the initial market testing and, after that, to provide products for the early stages of marketing, may be to purchase imported or locally available components that are relatively costly. The selling price of the systems can then be temporarily subsidised to more affordable levels based on the anticipated ongoing cost (including reasonable profit margins) after the market has matured.
- The design stage essentially never ends because of remaining possibilities for reducing cost and increasing functionality. However, at some point further design changes should be restricted to those that are necessary to address significant problems uncovered by users or take advantage of new insights that have the potential to significantly reduce costs and or increase functionality.

The activities described above are legitimate roles for NGOs, donors, and governments because (a) they lay the foundation for sustainable market systems that deliver positive social benefits to the rural poor, and (b) they are unlikely to happen spontaneously without outside facilitation. Pro-poor technologies are typically designed around more or less generic components without patent protection. Private-sector manufacturers (or importers and assemblers) and vendors cannot afford to invest in the necessary product and market development activities since these costs would not be recoverable after the market demand is established. If they attempt to maintain sufficient profits to recover these development costs, competitors will arrive on the scene and undercut their prices. However, this competition is actually a positive aspect of the donor-supported market creation approach. It continuously stimulates inventiveness to gain market share by increasing cost-effectiveness and functionality. Developing pro-poor technologies and market systems as a public good is an effective way for governments and donors to extend their outreach and impact.

This market-based approach to the dissemination of household-level irrigation technology is being promoted on a global level by the Smallholder Irrigation Market Initiative (SIMI), an international network of organisations working to spread smallholder irrigation technologies to the many people for whom they offer an opportunity for better livelihoods. Members of the SIMI network include the Swiss Agency for Development Cooperation (SDC), the Dutch Government, the International Water Management Institute (IWMI), the Food and Agriculture Organization (FAO/IPTRID), IDE, and other NGOs, research institutes, donors, and private companies (www.siminet.org).

Water is not enough

For smallholders to generate significant on-farm income, solving the water constraint is a necessary but insufficient condition. The true driving forces of wealth creation are market opportunities. Irrigation and other production technologies are only useful for income generation in so far as they enable smallholders to take advantage of those market opportunities. Household irrigation is a strategic entry point from which a range of market constraints can be addressed to enhance the comparative advantage of smallholders in the production of high-value crops.

The income-generating potential of household-level irrigation is directly related to the degree to which smallholders are integrated with input and output markets. Thus, household-level irrigation is most effective where pre-existing market linkages exist or where such linkages can be created. IDE has developed an approach for identifying and resolving critical smallholder market constraints. The approach, called Poverty Reduction through Irrigation and Smallholder Markets (PRISM), can be summarised in the following steps:

- Define the geographical boundaries and target population within which smallholder markets will be developed.
- Identify agricultural market opportunities that are expanding, that offer potential for significant income generation, and for which smallholders have (or can develop) a comparative advantage.
- Develop a strategy for delivering sustainable and affordable water control to smallholders as an entry point to enable smallholders to exploit the selected market opportunities.
- Identify constraints in the value chain and opportunities that smallholders may exploit in cultivating and marketing the selected crops/market opportunities.
- Develop partnerships with civil-society, research, and government organisations that are able to collaborate in facilitating market solutions to the identified value-chain constraints.
- Design interventions to assist, support, and develop small enterprises that can help remove value-chain constraints by delivering necessary products and services to smallholders effectively, efficiently, and sustainably.

When small farmers are able to access a range of complementary goods and services for the production and marketing of high-value crops, the impact is greater than the sum of the impacts that might be expected from individual interventions in isolation. Through this process, smallholders are empowered to become more effective market participants—both as consumers of agricultural goods and services and as producers of saleable crops—with the end result being increased incomes and improved livelihoods. Household-level irrigation technologies can play a central and catalytic role in this process.

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The effect of water availability on rice-based double cropping in rainfed lowlands in Cambodia

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Abstract

The success of double cropping of rice-based systems in the rainfed lowlands of Cambodia primarily depends on managing water resources effectively. Maximising the production of double cropping demands the effective use of rainfall and in some areas supplementary irrigation. In a series of experiments in Cambodia, four different locations and four different treatments were evaluated using various combinations of rice and mungbean. The major limitations identified for double-cropping systems include the lack of reliable rainfall for the early season rice, risk of soil water saturation for early season mungbean, and lack of water for establishing and then growing mungbean after the wet season rice. The current practice is to minimise the risk and maximise the yield of the wet season rice crop, and hence there is rather limited flexibility for other crops. The early season mungbean should be planted as early as possible to reduce the risk of soil water saturation, whereas the dry season mungbean should be planted as soon as possible after the harvesting of the wet season rice. Another option would be to plant the wet season rice earlier to accommodate the dry season mungbean, or later to accommodate the early season rice. Thus a systems approach is needed to maximise productivity from the limited water available and minimise the risk of crop failure in rainfed lowlands. Characterising rainfall patterns will help in evaluating the risk of different cropping systems. The availability of supplementary irrigation even for limited, strategic irrigation reduces the risk of crop loss and increases the practice of double cropping.

Introduction

RAINFED lowland rice dominates most of the rice-based cropping systems in South-east Asia, contributing to 84% of the rice area in Cambodia (Ouk et al. 2001). Rice crops may be followed by another rice crop, and in some cases three crops per year are possible where water supply is not limited. In some lowland ecosystems, where water supply is limited for the second rice crop, sufficient water may still be available to grow an upland crop. Where growing two crops in a year is possible, the early wet season (EWS), wet season (WS) and dry season (DS) cultivation should be arranged in a system that maximises yield by benefiting from the scheduling of the two crops. Short duration grain legumes such as mungbean and black gram could be successfully grown as crops before and after WS rice (Saraf et al. 1975; Saxena and Yadao 1975, 1975). Today, legumes account for about 5% of the gross national products in Cambodia (Soeun 2001).

In Cambodia, rainfed lowland rice has been effectively used for monocropping throughout the year. The major reason for monocropping rice is a lack of water and poor irrigation infrastructure. In contrast, where supplementary water is available, crops other than rice are grown to diversify the farming system to increase farmer income. Rainfed lowland rice has a

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high risk of growing a second crop in the DS after the WS crop. This increased risk is a result of the insufficient time available to grow and complete the life cycle before the soil dries before harvest. Sowing an early maturing rice variety as the first crop is one alternative in a rice–rice, double-cropping system. However, there is an increased risk that flowering will coincide with the peak rainy season and damage spikelets, thus reducing the likelihood of pollination. Moreover, early maturing varieties are more likely to be damaged by rodents. An improved understanding of the wide range of risks associated with crop scheduling would enable farmers to successfully practice a rice-based, double-cropping system on their small farms (Chea et al. 2001).

In the experiments reported here, four treatments were imposed to investigate the feasibility of growing two crops in a year and the risks associated with the timing of cropping in relation to water availability. The farmers participating in this series of experiments knew little about growing crops across three seasons and were considered poorly resourced.

The series of rice-based, double-cropping systems were investigated to:

- identify the main limits on intensifying the cropping systems in rainfed lowland environments in Cambodia, particularly water availability during the whole cropping cycle—but also soil fertility, insect damage and labour costs
- develop appropriate agronomic practices for double-cropping systems to minimise the risk of crop failure
- evaluate profitability of various rice-based cropping systems in rainfed lowland systems in Cambodia.

Materials and methods

Experimental sites

The experiments were conducted, initially in three locations, during 2001 and 2002. These locations had various levels of water availability for crop production and are located at:

- Bat Rokar-Samrong (Takeo province) identified as a favourable environment for double cropping
- Slarkou research station (Takeo province) identified as a medium risk environment for double cropping
- Baneav (Kampot province) identified as a high risk environment for double cropping.

In 2001 and 2002, all three locations were used as rainfed lowland environments with an additional site during 2002 at the Cambodian Agricultural Research and Development Institute (CARDI, Phnom Penh), which had some supplementary irrigation water. The site selection was based on water availability in rainfed lowland rice environments. The experimental area at Bat Rokar-Samrong and CARDI had supplementary irrigation water available for EWS and WS crops but not for a DS crop, while Slarkou and Baneav were rainfed lowland environments without supplementary irrigation. Several PVC tubes were installed at these locations for continuous monitoring of water levels in paddies.

The crop combinations were determined after interviews with farmers in those areas. There were four main cropping system treatments for each location.

- Treatment 1 (T1) was WS rice only, which is a common practice in rice farming systems of Cambodia's rainfed lowlands.
- Treatment 2 (T2) was a rice–rice, double-cropping system. An early maturing, photoperiod-insensitive rice variety (IR66) was sown in the EWS and a long duration photoperiod-sensitive variety (CAR4) was sown in the WS.
- Treatment 3 (T3) was a legume–rice cropping system. Mungbean (KK-II) was the legume established in the EWS and the long-duration rice variety was sown in the WS.
- Treatment 4 (T4) was a rice–legume cropping system. The rice crop was sown in the WS and a mungbean crop was established soon after the harvesting of the WS rice crop. The rice crop was transplanted while the mungbean crop was established by direct seeding.

The total area of 0.4 ha was divided to accommodate each (approximately 1000 m^2) of the four cropping system treatments in 2001 and 2002 (Figure 1). The date of sowing and harvesting of the four cropping systems are shown in Table 1.

Crop establishment for treatments

After the land was prepared (two ploughings and two harrowing), it was levelled and all treatments assigned to a separate paddy. The crop establishment methods for mungbean and rice were different. The rice crop was transplanted after seedlings were developed at a seed rate of 40 kg ha^{-1}. Mungbean was broadcast at a seed rate of 20 kg ha^{-1} (EWS and DS mungbean) followed by harrowing to incorporate seeds with soil to avoid damage by animals such as birds. In the 2002/03 DS, two mungbean varieties (VC3541B and CARDI Chey) were planted using

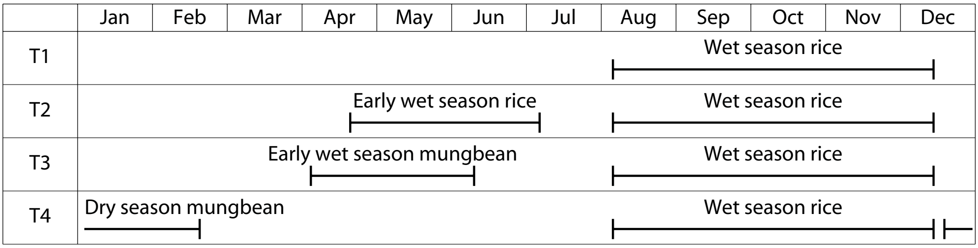

Figure 1. Approximate scheduling of four treatments used in rice-based double cropping throughout the wet and dry season.

Table 1. Sowing and harvesting dates of four treatments at Baneav, Slarkou and Bat Rokar-Samrong (Bat Rokar-S) in 2001.

		Early wet season (2001)				Wet season (2001)		Dry season (2001/02)	
		Rice (IR66)		Mungbean (KK-11)		Rice (CAR 4)		Mungbean	
Treatment	Locations	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting
T1	Baneav					16-Jul	12-Dec		
	Slarkou					25-Jul	21-Dec		
	Bat Rokar-S					12-Jul	9-Dec		
T2	Baneav	Failed	Failed			16-Jul	12-Dec		
	Slarkou	18-May	5-Sep			25-Jul	28-Dec		
	Bat Rokar-S	28-Feb	14-Jun			12-Jul	9-Dec		
T3	Baneav			4-Apr	28-May	16-Jul	12-Dec		
	Slarkou			1-May	28-Jun	25-Jul	21-Dec		
	Bat Rokar-S			8-Apr	8-Jun	12-Jul	9-Dec		
T4	Baneav					16-Jul	12-Dec	28-Dec	15-Feb
	Slarkou					25-Jul	21-Dec	2-Jan	28-Feb
	Bat Rokar-S					12-Jul	9-Dec	19-Dec	Failed

three methods of establishment just after the WS rice crop. These methods were:

- farmer practice (animal-drawn ploughing and harrowing with seed broadcast by hand and final harrowing to incorporate seeds into the soil to avoid damage by animals or birds)
- row hill method (animal-drawn ploughing with seeds placed in every third furrow)
- row drill method (no soil preparation by animal-drawn ploughing; direct seeding by hand using a stick to open the soil).

The rice seeds (IR66 or CAR4) were soaked in water for 24 hours and incubated for 24–36 hours before being sown in the nursery. Adequate fertiliser (urea) was applied to the seedbed at a rate of 100 kg N ha^{-1}. The standing water level in the nursery was about 2–5 cm, which was maintained until transplanting. Seedlings that were 25–40 days old (IR66 = 20–25 days; CAR4 = 40–45 days) were transplanted for the EWS or WS rice crop. The spacing for the rice crop was 20 X 20 cm and there were two to three seedlings per hill. Gap filling was done five to seven days after transplanting to avoid missing hills in the rice crop. Gap filling was not done for the mungbean crop.

Fertiliser application in the wet season

Before transplanting, inorganic fertilisers NPK (50–23–30 of $N–P_2O_5–K_2O$ kg ha^{-1}, respectively) were applied to each rice treatment as a basal application. The 1st and the 2nd top dressings (40 kg N ha^{-1}) were broadcast when there was enough moisture at 20 and 40 days, respectively, after rice was transplanted. For the mungbean crop, fertiliser was applied at a rate of 27–69–60 kg of $N–P_2O_5–K_2O$ kg ha^{-1} respectively.

General maintenance

Hand weeding was done in the usual way, three times for the rice crops and five for the mungbean one. One week after germination, Azodrin™ (active ingredient monocrotophos @ 600 g L^{-1}) was applied when the insect pest damage could be seen on the mungbean crop. The entire crop was protected from birds and rodents at flowering and pod or panicle bearing stages.

Data collection

In addition to measuring grain yield and biomass at harvest in both crops, a range of other characteristics of crop growth were calculated from three sample areas (40 × 40 cm). Measurements for the mungbean crops included plant density and date of flowering, total grain yield (pods were harvested three times as they matured) and total biomass.

Measurements for the rice crop included date of transplanting, flowering and harvest, total tiller number at maximum tillering, plant height at ripening stage, number of panicles per m^2 at ripening stage, total rice grain weight (in whole field), weight of straw and grain sub-sample (4 m^2).

Other observations included weekly standing and ground water depth, rainfall data, insect and other pest records and labour needs for each operation.

Results

Water availability for cropping systems at experimental sites

The rainfall pattern in 2001 and 2002 was variable at all locations during the experiments (Figure 2). In 2001, there was a high rainfall at Slarkou and Bat Rokar-Samrong compared to Baneav. The total rainfall received at Bat Rokar-Samrong and Baneav in 2002 was similar (1760 mm and 1794 mm) and well below the total rainfall received at Slarkou (2270 mm). As expected, the EWS rainfall distribution was lower at Baneav compared to the other two locations. At CARDI in 2002, the mungbean crop grown in the EWS was damaged by flash floods. The rainfall at CARDI in the 2002/03 DS was the highest among all experiment sites.

The water levels in rice fields for all locations during the experiment period in 2001 and 2002 are presented in Figure 3. The water level pattern at Bat Rokar-Samrong was similar to Slarkou in 2001 and 2002, although the variation in water levels was higher in Slarkou in 2001. All three locations had standing water for most of the WS but water levels fell 20 cm below the soil surface during November.

Crop establishment

Sowing and harvesting dates in 2001 and 2002 cropping cycles are shown in Tables 1 and 2 respectively. EWS rice establishment failed at Baneav in both years because of poor rainfall. The DS mungbean crop was established in 2001 at Bat Rokar-Samrong with the available soil water after the WS rice crop. However, since there were no other crops in the field during the DS, cattle damage caused crop failure. As a result of drought the EWS mungbean crop at CARDI in 2002 was sown in mid-July, but there was no harvest because of floods. The short duration variety, IR66, was sown late (4 October) and irrigated in the wet season at CARDI in 2002 (Table 2).

Grain yield in 2001

Early wet season rice (2001)

Despite supplementary irrigation in Bat Rokar-Samrong the grain yield was 2.5 t ha^{-1}, which was lower than Slarkou (2.9 t ha^{-1}) where the crop was grown under rainfed conditions (Table 3). At Bat Rokar-Samrong there were more tillers at 45 days after sowing (104 tillers m^{-2}) and a higher number of panicles at maturity (466 panicles m^{-2}) than at Slarkou (89 tillers, 327 panicles; Table 4).

Early wet season mungbean (2001)

At all locations in 2001 the mungbean yield was less than 0.08 t ha^{-1} (Table 3). The main reason for the low yields at Bat Rokar-Samrong was poor land preparation and water logging conditions during vegetative growth. The adjacent fields were continuously irrigated for rice crops and the sub-surface drain condition in the mungbean plot was poor. Therefore, root development was severely affected and the biomass production low. The insect pest problem was also severe in Bat Rokar-Samrong. Some pests were identified at different growth stages. Bean fly was a common pest in the young plants but the damage was not severe. The pest attack during flowering and pod setting stages was more severe. Aphids, leafhoppers, corn earworm and pod borers

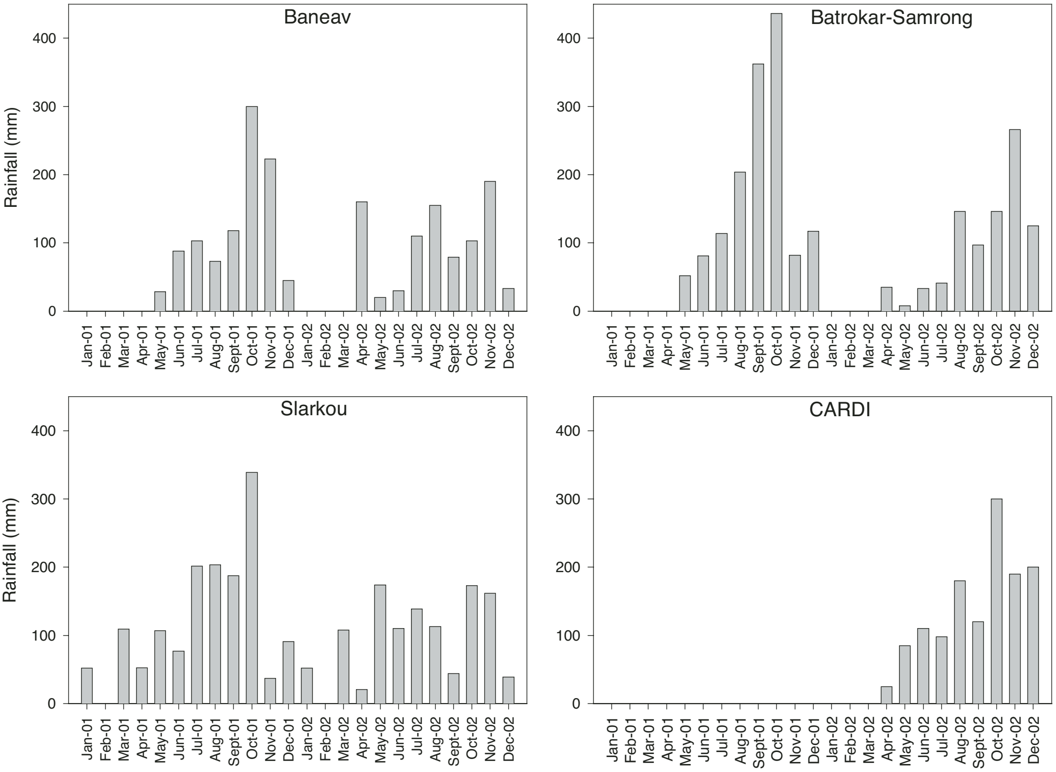

Figure 2. Monthly rainfall distribution at Baneav, Bat Rokar-Samrong, Slarkou and CARDI in 2001 and 2002.

were common in the Bat Rokar-Samrong area in which farmers did not use any pesticide.

Disease and pest problems contributed to reduced yields at Slarkou. The pod borer damage was confirmed as a serious pest for mungbean in this area. It was estimated that yield was reduced by 30% as a result of pest damage. Rain during the crop maturation time contributed to a further yield reduction. The mungbean crop was harvested two to three times as it matured.

At Baneav, there was low rainfall during the EWS. Although Baneav received low rainfall during germination, the grain yield was higher than that of the other two locations (Table 3). During vegetative growth at Baneav, extremely high soil temperature contributed to reduced soil moisture.

Wet season rice (2001)

The WS rice crop was successful at three locations (Table 3). The mean rice yield after the EWS mungbean crop (T3) was 2.44 t ha^{-1}, which is similar to that of the other three treatments (2.63 t ha^{-1}). The mean yield for the WS rice followed by the EWS rice at Bat Rokar-Samrong and Slarkou was 2.7 t ha^{-1}. Generally the yields were higher in the Bat Rokar-Samrong area where crops were grown under supplementary irrigation. There was no water shortage at any of the locations in the WS. On average, across the four treatments in the WS, Batrokar-Samrong had more tillers (342 tillers m^{-2}) and panicles (318 panicles m^{-2}) than in the Baneav (260, 183) and Slarkou (310, 204; Table 4).

Dry season mungbean (2001/02)

The DS mungbean crop was successfully established at Slarkou and Baneav. There was adequate moisture available for the early maturing mungbean crop at these two locations. The pod borers damaged the mungbean crop at Slarkou and the yield was 0.07 t ha^{-1} (Table 3).

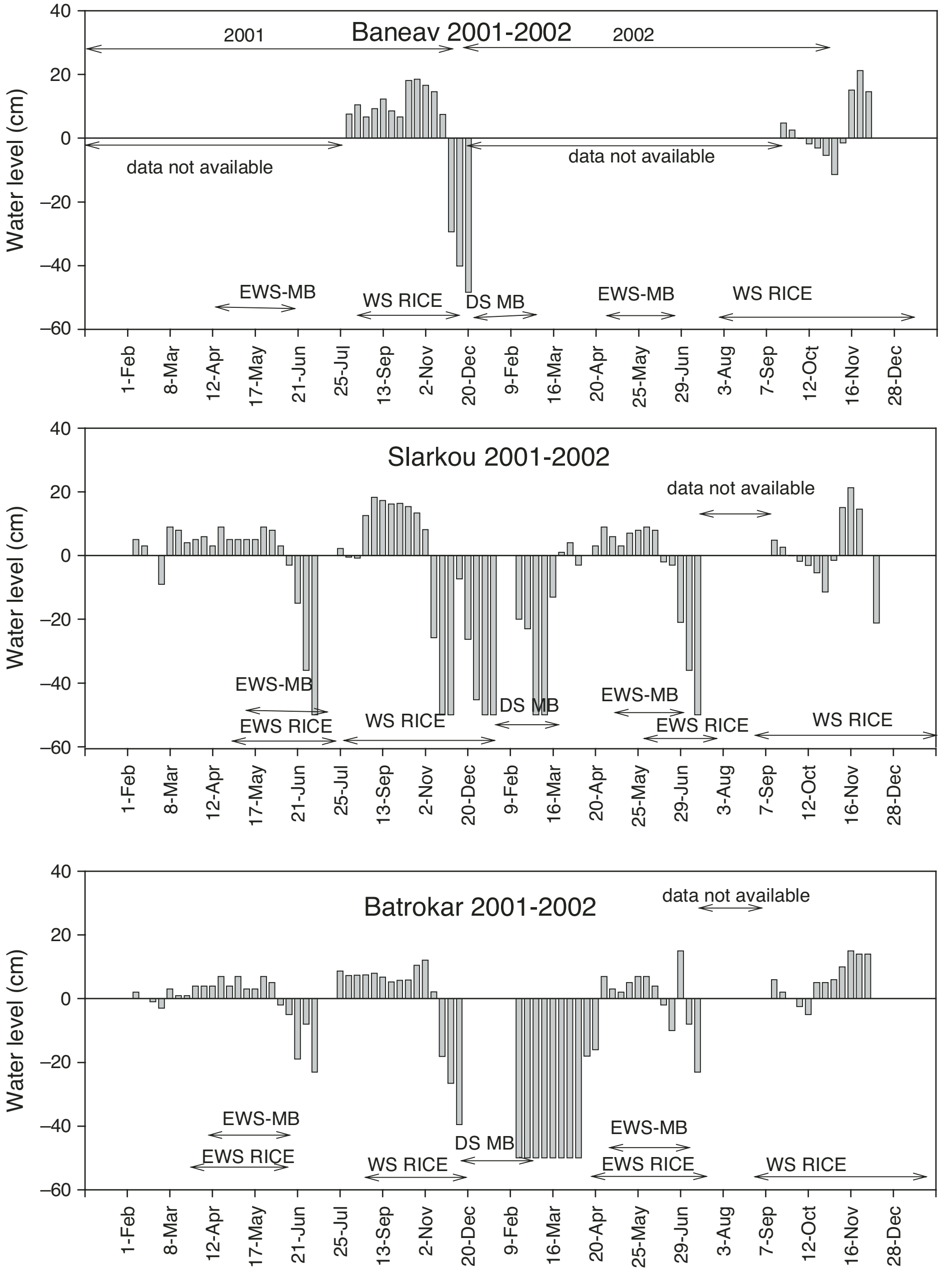

Figure 3. Water levels in EWS and WS rice crops and DS mungbean crops at Bat Rokar-Samrong, Baneav and Slarkou in 2001 and 2002. Arrows indicate the growing period (EWS = early wet season; WS = wet season; DS = dry season) for different crops (MB = mungbean).

Table 2. Sowing and harvesting dates of four cropping systems experiments at Baneav, Slarkou, Bat Rokar-Samrong (Bat Rokar-S) and CARDI in 2002.

		Early wet season (2002)				Wet season (2002)		Dry season (2002/03)	
		Rice (IR66)		Mungbean (KK-11)		Rice (CAR 4)		Mungbean	
Treatment	Locations	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting
T1	Baneav					22-Jul	24-Jan		
	Slarkou					25-Jul	3-Feb		
	Bat Rokar-S					3-Aug	25-Jan		
	CARDI					4-Oct	1-Feb		
T2	Baneav	Failed	Failed			22-Jul	24-Jan		
	Slarkou	12-May	27-Aug			25-Jul	3-Feb		
	Bat Rokar-S	23-Mar	17-Jul			3-Aug	25-Jan		
	CARDI	21-Jun	25-Oct			4-Oct	1-Feb		
T3	Baneav			2-May	22-Jun	22-Jul	24-Jan		
	Slarkou			16-May	16-Jul	25-Jul	3-Feb		
	Bat Rokar-S			2-May	6-Jul	3-Aug	25-Jan		
	CARDI			14-Jul	Failed	4-Oct	1-Feb		
T4	Baneav					22-Jul	24-Jan	30-Dec-02	
	Slarkou					25-Jul	3-Feb	30-Jan-03	
	Bat Rokar-S					3-Aug	25-Jan	-	
	CARDI					4-Oct	1-Feb	14-Feb-03	

Table 3. Grain yield (GY) and total dry matter (TDM) of rice and mungbean crops with four treatments in three locations in 2001.

		Early wet season (2001)				Wet season (2001)		Dry season (2001/02)	
		Rice (IR66)		Mungbean (KK-11)		Rice (CAR 4)		Mungbean (KK-11)	
Treatment	Locations	GY ($t\ ha^{-1}$)	TDM ($t\ ha^{-1}$)	GY ($t\ ha^{-1}$)	TDM ($t\ ha^{-1}$)	GY ($t\ ha^{-1}$)	TDM ($t\ ha^{-1}$)	GY ($t\ ha^{-1}$)	TDM ($t\ ha^{-1}$)
T1	Baneav					2.32	5.63		
	Slarkou					2.15	5.43		
	Bat Rokar-S					2.86	6.35		
T2	Baneav	Failed	Failed			2.61	6.27		
	Slarkou	2.91	6.43			2.73	6.13		
	Bat Rokar-S	2.50	5.92			2.62	5.82		
T3	Baneav			0.07	0.68	2.23	5.42		
	Slarkou			0.05	0.31	2.37	5.92		
	Bat Rokar-S			0.02	0.60	2.72	6.13		
T4	Baneav					2.67	5.93	0.12	0.72
	Slarkou					2.81	6.13	0.07	0.62
	Bat Rokar-S					2.90	6.56	Failed	Failed

Table 4. Days from sowing to maturity, tiller number, plant height and panicle number of the early wet season rice in Treatment 2 and wet season rice in all treatments in 2001 at three locations.

Location	Treatment	Maturity (days)	Tiller number (per m^2)	Plant height (cm)	Panicle number (per m^2)
			2001 early wet season (IR66)		
Baneav	T2	–	–	–	–
Slarkou	T2	103	89	89	327
Bat Rokar-S	T2	105	104	89	467
			2001 wet season rice (CAR4)		
Baneav	T1	153	244	149	188
	T2	153	271	143	169
	T3	153	292	151	190
	T4	153	233	143	183
Slarkou	T1	152	306	105	188
	T2	152	292	118	204
	T3	152	342	117	244
	T4	152	300	117	181
Bat Rokar-S	T1	160	340	128	323
	T2	160	329	145	365
	T3	160	352	135	304
	T4	160	350	131	281

Grain yield in 2002

Early wet season rice (2002)

The second cycle of the EWS rice crop was established in four locations in 2002 and the grain yield of each crop is presented in Table 5. The highest grain yield (3.5 t ha^{-1}) was obtained at CARDI where standing water was present throughout the duration of crop growth (Figure 4). The EWS rice crop matured 107–113 days after sowing. The grain yield at Bat Rokar-Samrong was slightly higher than Slarkou where the crop was grown under rainfed conditions. However, as observed in 2001, tillering at 45 days after sowing was higher at Bat Rokar-Samrong (489 tillers m^{-2}) than at CARDI (412 tillers m^{-2}) and Slarkou (370 tillers m^{-2}; Table 6). The highest number of panicles at harvest was recorded at CARDI (418 panicles m^{-2}). There were no pests or diseases reported in these three locations.

Early wet season mungbean (2002)

The EWS mungbean crop was successfully sown and harvested at all locations except CARDI (Table 5). The EWS mungbean yield was higher at the three locations than in 2001. The main reason for the higher yields in the EWS at Bat Rokar-Samrong and Baneav was improved crop establishment. At Slarkou during flowering, pests and diseases damaged pods. At CARDI, emergence was reduced by water stress and failure occurred because of a flash flood in Phnom Penh in mid-August 2002. The insect and pest problem was severe in both Bat Rokar-Samrong and Slarkou. At Bat Rokar-Samrong, some pests were identified at different growth stages. Bean fly was a common pest in the young plants and the damage was more severe than in 2001. The pest attack during flowering and pod-setting stages was more severe. Aphids, leafhoppers, corn earworm and pod borers were common in this area where no pesticide was used. Diseases and pest problems at Slarkou caused the low yield as was also observed in 2001. The pod borer was a serious pest for mungbean in this area. About 40% of pods were estimated to be lost due to pest damage at Slarkou. Heavy rain (~170 mm in May) at Slarkou coincided with maturity and may have caused further yield loss. As a result of heavy rains the crop was harvested only two times at maturity.

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Table 5. Grain yield (GY) and total dry matter (TDM) of rice and mungbean grown in four treatments at four locations in 2002 early wet season and wet season.

		Early wet season (2002)				Wet season (2002)	
		Rice (IR66)		Mungbean (KK-11)		Rice (CAR 4)	
Treatment	Locations	GY (t ha^{-1})	TDM (t ha^{-1})	GY (t ha^{-1})	TDM (t ha^{-1})	GY (t ha^{-1})	TDM (t ha^{-1})
T1	Baneav					4.70	10.45
	Slarkou					2.29	6.12
	Bat Rokar-S					3.75	6.04
	CARDI					2.29	-
T2	Baneav	Failed	Failed			4.45	10.13
	Slarkou	2.50	6.61			2.59	5.68
	Bat Rokar-S	2.91	6.06			4.27	6.96
	CARDI	3.54	8.66			2.58	-
T3	Baneav			0.28	0.40	4.50	11.55
	Slarkou			0.08	0.37	2.52	5.25
	Bat Rokar-S			0.11	0.62	3.93	7.84
	CARDI			Failed	Failed	2.51	-
T4	Baneav					4.66	11.05
	Slarkou					3.17	7.58
	Bat Rokar-S					4.66	8.22
	CARDI					3.10	-

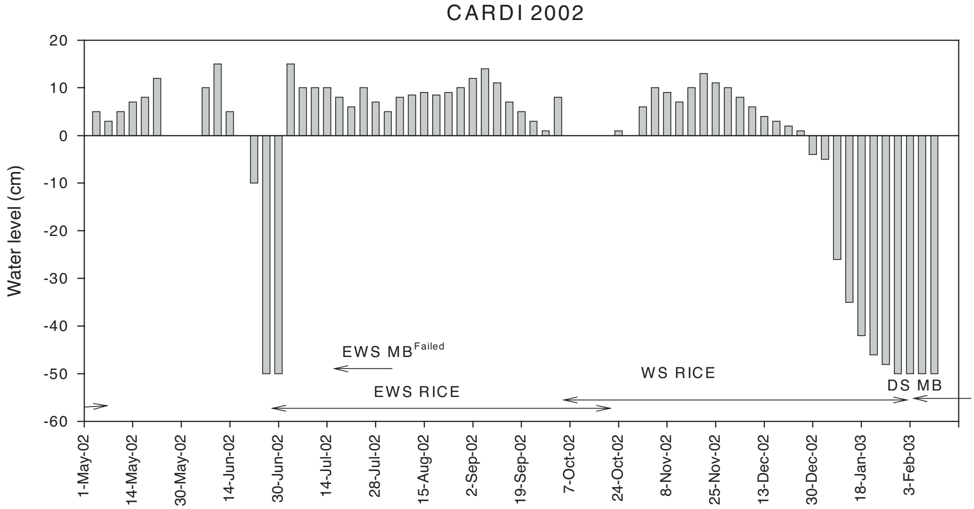

Figure 4. Water levels during early wet season (EWS) rice, wet season (WS) rice and dry season (DS) experiments at CARDI 2002. Arrows indicate the duration of the rice and mungbean (MB) crop.

Table 6. Days from sowing to maturity, tiller number, plant height and panicle number of early wet season rice in Treatment 2 and wet season rice in all treatments in 2002 at four locations.

Location	Treatment	Maturity (days)	Tiller number (per m^2)	Plant height (cm)	Panicle number (per m^2)
			2002 early wet season (IR66)		
Baneav	T2	-	-	-	-
Slarkou	T2	107	371	89	296
Bat Rokar-S	T2	113	490	71	371
CARDI	T2	110	413	95	419
			2002 wet season rice (CAR4[a])		
Baneav	T1	150	238	157	250
	T2	150	258	151	246
	T3	150	223	151	200
	T4	150	283	155	263
Slarkou	T1	150	219	123	200
	T2	150	246	126	229
	T3	150	285	124	269
	T4	150	340	131	206
Bat Rokar-S	T1	149	365	139	225
	T2	149	460	148	321
	T3	149	450	156	269
	T4	149	431	149	223
CARDI[a]	T1	113	317	80	198
	T2	115	256	69	179
	T3	113	404	81	233
	T4	113	294	75	263

[a] IR66 was used at CARDI

At Baneav, there was low rainfall during the EWS. The crop growth and grain yield was higher (0.28 t ha^{-1}) than at the other two locations. During the vegetative period of the mungbean crop at Baneav, soil temperature was high contributing to a reduction in soil moisture.

Wet season rice crop (2002)

The WS rice crop was successfully harvested at the four locations (Table 5) with no water shortage for the rice crop at any. The yield ranged from 2.3 t ha^{-1} (T1-Slarkou) to 4.7 t ha^{-1} (T4- Bat Rokar-Samrong and Baneav). The average grain yields of WS rice crops across four locations in T1 (3.3 t ha^{-1}), T2 (3.5 t ha^{-1}) and T3 (3.4 t ha^{-1}) were similar. However, yield was higher in T4 (4.2 t ha^{-1}) indicating that there was a positive effect of DS mungbean cropping for the following WS rice crop. In contrast, the EWS rice crop did not appear to have adversely affected rice yield in the WS crops. The yield of IR66 rice at CARDI was higher for the EWS crop than that for the WS, which was sown late (October). At Bat Rokar-Samrong the rice yield was lower in the EWS (2.9 t ha^{-1}) compared to the WS (4.27 t ha^{-1}). In Slarkou the yields were similar (~2.5 t ha^{-1}) which is more similar to the yield patterns measured at all locations in 2001.

Dry season mungbean (2002/03)

During the DS, two mungbean varieties were tested with three establishment methods. The DS mungbean crop was successfully established at CARDI and Slarkou. There was no mungbean crop established at Baneav in 2002/03 DS as the soil was too dry for sowing. There was no ground water at 50 cm depth at both CARDI and Slarkou fields. However, the soil moisture was adequate for a successful establishment of a mungbean crop. There were no differences between two varieties and three methods of sowing for emergence at Slarkou. At CARDI the emergence was about 70% whereas it was 83% at Slarkou. Both mungbean varieties flowered 43 days after sowing and harvesting commenced 62 days after sowing. The mungbean crop was harvested two to three times. The mean mungbean yield at CARDI was about four times higher using the usual farmer establishment (0.10 t ha^{-1}) and row hill methods (0.09 t ha^{-1}) rather than the row drill method (0.02 t ha^{-1}; Table 7). The low yields associated with the row drill method reflect poor land preparation resulting in poor establishment. However, at Slarkou, the three establishment methods produced a similar mean yield across both cultivars of 0.023–0.026 t ha^{-1}. Generally the yields of CARDI Chey variety matched or were higher than KK-II at all locations.

Discussion

This study investigated the main limiting factors for adopting rice-based double-cropping systems in Cambodia. Supplementary irrigation was highlighted as the major requirement in moving from single cropping to double-cropping systems in Cambodia (Chea et al. these proceedings). The results from the study presented in this paper also indicate that water availability is the key to successful double cropping in Cambodia. In this study water availability included the deficit and excess of water during the growth of one or more crops. Similar constraints have been reported for rice–legume cropping systems in India (Satyanarayana et al. 2001), Mayanmar (Han et al. 2001), Thailand (Palboonrath et al. 2001) and Sri Lanka (Dharnasena et al. 2001).

Wet season irrigated environment

In 2001 and 2002, only two crops were grown in two seasons (EWS and WS crops) at Bat Rokar-Samrong. The third DS mungbean crop failed in this location due to cattle damage and drought during crop growth. Grazing after WS rice is a common practice in this area. In isolation, the farmer could not protect mungbean from the cattle. The EWS rice crop was established at the end of February and harvested at the middle of June. Subsequently, the WS rice crop was sown in the middle of July and harvested in December. The EWS mungbean crop was affected by water logging conditions during the flowering stage. It was found that with early land preparation and improved water management, a successful mungbean crop could be grown in Bat Rokar-Samrong. These changes will reduce the problem of excess moisture for fine and dry seedbed preparation allowing drainage for mungbean. These practices involve increased labour and inputs, which many farmers in this area cannot afford. However, as there were irrigation systems available for rice cultivations

Table 7. Grain yield (t ha^{-1}) of two mungbean cultivars grown with three methods of establishment during the dry season at CARDI and Slarkou in 2002.

Location	Treatment	Grain yield (t ha^{-1})		Mean of treatment
		CARDI Chey	K II	
CARDI	Farmer practice[a]	0.122	0.081	0.102
	Row hill method[b]	0.081	0.092	0.086
	Row drill method[c]	0.023	0.022	0.023
Slarkou	Farmer practice[a]	0.032	0.019	0.026
	Row hill method[b]	0.028	0.018	0.023
	Row drill method[c]	0.025	0.026	0.025

[a] Animal-drawn ploughing and harrowing with seed broadcast by hand and final harrowing to incorporate seeds into the soil

[b] Animal-drawn ploughing with seeds placed in every third furrow

[c] No soil preparation by animal-drawn ploughing; direct seeding by hand using a stick to open the soil

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in the EWS and WS, farmers could earn more income by growing a rice crop than a mungbean crop. The rice–rice double-cropping system at Bat Rokar-Samrong produced a substantially higher yield and income for the farmer (pers. comm.) than the other three cropping systems. A DS mungbean crop could be grown after WS rice (T4) in Bat Rokar-Samrong if farmers improve measures to protect crops from pests and cattle.

There is no risk of double cropping in Bat Rokar-Samrong as supplementary irrigation is available during the EWS and WS. However, a short duration crop is suitable for the DS because there is no irrigation water available and soil moisture is declining rapidly.

Experiments at CARDI were only conducted in 2002, where some irrigation water was available for the EWS and WS crops. However, water availability depends on the rainfall in Phnom Penh. The EWS mungbean crop failed because of limited water at sowing and flash floods at the late growth stage. The EWS rice crop was successful even with the delayed sowing in late June. However, this resulted in late harvesting and hence late planting of the WS rice in October. It was decided to grow IR66 (a photoperiod-insensitive, short-maturation variety) as it was too late for the photoperiod-sensitive, long-maturation cultivars CAR4. IR66 produced a yield of 3.1 t ha^{-1}, but with irrigation water. EWS rice could have been planted earlier whenever water became available. However, flash floods could still occur at that time in this area and would increase lodging and subsequent yield reduction.

Favourable environment

At Slarkou Agricultural Research Station, crops were successfully established in three seasons. The EWS mungbean crop was established in early to mid-May and harvested in late June to mid-July. There is some flexibility for sowing time in May and harvesting in June–July. The EWS rice crop can be sown in mid-May and harvested in August. The WS rice was sown on July and harvested on December. The DS mungbean crop was sown during early January and harvested at the end of February.

Four cropping system experiments were successful at Slarkou despite the fact that some pests and disease problems were severe. However, rice–rice double cropping was more effective than the other three systems. When there was insufficient water for EWS rice cultivation, farmers could grow a legume crop to reduce the risk of losing income in a season. As an alternative cropping system, the DS legume crop could be combined with rice–rice double cropping to increase farm productivity. The chance of growing mungbeans successfully would increase if WS rice could be harvested earlier and mungbean planted when there is some residual water available in the field.

There are some risks in establishing a rice crop in the EWS at Slarkou. Pest problems are severe in this area as most of the farmers are growing cash crops at this time. However, it would be possible to start land preparation after rain at this time. There is no risk of establishing a legume crop in the EWS. However, intermittent rain during the later part of the EWS could increase the risk of yield loss in the legume crop due to excessive moisture. Therefore earlier sowing of EWS mungbean is advisable.

Marginal environment

At Baneav, crops were established in three seasons with no EWS rice crop. The EWS rice (IR66) crop failed in both years because there was insufficient water for crop establishment. The EWS mungbean was established early in April and harvested at the end of May. The mungbean crop at Baneav had higher yields than the other three locations. However, the day temperature was high reducing growth duration for the EWS mungbean crop at Baneav. The WS rice crop in Baneav was sown in the middle of July and harvested in the middle of December. The yield of WS rice crops was similar at this location in the four cropping systems. There was no water limitation during the WS. The DS mungbean was established at the end of December and harvested at the middle of February in 2001. However, in 2002, the soil moisture was insufficient to start land preparation at this location for a DS legume.

There is a high risk for an EWS rice crop in Baneav as the rainfall is inadequate for crop establishment in this area. However, the soil moisture during the EWS is adequate for an EWS mungbean crop. Similarly, growing DS mungbean has some risk in this area. The main risk for rice–rice double cropping in marginal areas in Cambodia is the inadequate and late rainfall during the EWS. This dry period affected the land preparation and seedbed establishment at Baneav. However, it might be possible to establish EWS rice in Baneav by sowing later after the rainfall. There are still some risks of delayed sowing in EWS, because it will affect the timing of WS crop establishment. It may be that short duration WS rice crops may be grown if the combined yield of EWS and WS rice exceeds the yield of long duration rice in WS. Alternatively, the direct seeding technology would be a better way to establish an EWS rice crop. This will allow early sowing in EWS and hence the long-duration rice could be grown in the WS. The legume–rice cropping system showed a low risk at Baneav as mungbean could grow well under the available soil moisture during the EWS. However, intermittent rain could cause some damage by increasing waterlogging conditions in the field. Improved knowledge of water management (drainage improvement) is needed to overcome such problems. The cropping system of WS rice–DS mungbean cropping system showed some risk in 2002. The success of a DS legume crop depends on the amount of rainfall received during the WS. Crop establishment methods are needed that conserve soil moisture for a DS legume crop in Baneav. No-tillage or minimum tillage are some of the options to be further investigated.

Water as a major factor determining cropping systems

There is a reduced risk in adopting three cropping systems in higher rainfall areas such as Slarkou. However, unpredictable rainfall during reproductive phases of legume crops can severely reduce yield. There are risks associated with growing EWS rice in the years when rainfall is delayed. To overcome this constraint of inadequate rainfall, direct seeding rice is a more flexible method than transplanting.

The risk for adopting three cropping systems is minimal in areas such as CARDI and Bat Rokar-Samrong where supplementary irrigation is available. However, unpredictable rainfall and flash flooding can severely damage legume crops during their growth and reproductive phases. The DS mungbean crop failed at Bat Rokar-Samrong in 2001 because of social constraints such as cattle rearing during the DS. If crops can be protected from cattle damage by fencing or other means, farmers could grow a successful legume crop using the stored soil moisture.

Insect and pest problems also reduced mungbean yields at Slarkou and Baneav. Pest populations and their control during the EWS and DS need to be investigated to improve yields in these areas.

Generally, from these four rice-based cropping systems, rice–rice double cropping produced a higher yield than the other three treatments. Where there is inadequate water for EWS rice, legume–rice rotation is one way to raise a farmer's productivity with a reduced risk of failure. Farmers identified mungbean as one alternative legume crop for this rotation.

Growing a legume before rice is preferred rather than the reverse, because a legume after rice would increase problems associated with damage from drought, insects, pests and cattle. During 2001 and 2002, the residual effect of mungbean on the grain yield of WS rice was low. However, the residuals of the legume crop could contribute to improved soil fertility. The additional benefits of legumes to the double-cropping systems in Cambodia such as contributing to soil nutrition need to be investigated further. This increased knowledge is a vital step in examining the effect of EWS and DS crops on the yield of the WS rice crop in Cambodia.

Introducing different varieties of rice and legumes are an important part of improving cropping systems throughout Cambodia. Early maturing legume and rice varieties are available in Cambodia (Javier, 1997) and need to be examined. Continued testing of varieties in a range of locations will help improve the adaptation of these cropping systems. Further experiments have been designed for the 2002/03 cropping seasons to identify the optimal sowing time to minimise the risk of crop failure. However, devising a rice-based double-cropping system for Cambodia will need to build further on the economic research by Chea et al. (2003). The development of a successful system must incorporate a range of factors including rainfall patterns, supplementary irrigation, soil nutrition, pest management, variety selection, variety–environment interaction, sowing method and economic return.

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Mekong River water: will river flows meet future agriculture needs in the Lower Mekong Basin?

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Abstract

More than 41% of the land area of the Lower Mekong Basin (LMB) is used for agricultural production and the area under cultivation is steadily expanding to produce more food for the burgeoning populations of Laos, Thailand, Cambodia and Viet Nam. Agriculture is also responsible for 80–90% of water abstractions from the Mekong River, most of which is for crop cultivation with smaller amounts being consumed by the increasing number of fish/shrimp farms and animals.

Limited access to water is a major constraint to increasing crop production in the LMB and irrigation schemes continue to be installed or improved in each of the four countries. The Mekong Delta in Viet Nam already faces water availability problems and seawater incursions during the critical months of February–May. This situation will be exacerbated even further as upstream abstractions increase. Fertile soils and a high level of renewable water resources indicate the potential for irrigation development is high in Laos and to a lesser extent in Cambodia. Use of existing schemes in North-east Thailand may also increase. New farming systems proposed by the Vietnamese Government for each of the ecological zones in the Mekong Delta may reduce the amount of water consumed by rice but increase the level of abstractions for upland crops, perennials and fish/shrimp ponds during the critical period. Each country, therefore, needs to carefully plan its current water consumption regimes. Negotiations are currently underway between the four LMB countries to ensure an equitable distribution for future development.

Introduction

THE LOWER MEKONG BASIN (LMB) is comprised of the watersheds of most provinces in the Lao PDR (hereafter referred to as Laos) (90% of country), that is:

- three provinces in the Central Highlands and a major proportion of the Mekong river delta region of Viet Nam (20% of country)
- most of Cambodia (86% of country)
- the north-east plus a part of Northern Thailand (36% of country) (Figure 1).

Parts of Myanmar and of the Yunnan province of China are included in the Upper Mekong Basin. About 18% of the total 475,000 million m^3 of water that flows annually down the Mekong river originates in the Upper Basin. The largest proportion of total flow is contributed by left-bank tributaries in Laos (Halcrow 2003). Thirty-five per cent of the total flow of the river is from watersheds in Laos, 18% from ones in Thailand, 18% from ones in Cambodia and 11% from ones in Viet Nam (MRC 2002a, 2003).

Mekong river water is used for irrigation, hydropower generation, domestic and industrial purposes. Much of the water emerging from hydropower stations is also re-used downstream. Irrigated agriculture is responsible for 80–90% of water abstractions from the basin (FAO from MRC 2002b), coming directly from the river, flooded ponds and lakes, diversion of

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water from local streams and from ground-water sources. Agriculture provides livelihoods for 75% of the residents of the LMB. This population grew by nearly 45% between 1980 and 2000 and is projected to increase another 25% over the next 20 years, placing increasing pressure on the land for extra production.

Current agricultural water demand in the LMB is estimated to be less than 4% of total annual flow. Therefore, there is theoretically no shortage of water in the Mekong river to service current agriculture needs. However, flow in the Mekong is strongly seasonal. Highest flows occur during the wet season, in August–September, when crops receive most of their water needs directly from rainfall. The lowest flow months of February to May, with less than 10% of total annual flows, coincide with the dry season when agricultural demand is highest. The very strong seasonal variation in water availability is reflected in Figure 2, which shows average monthly flows in the Mekong River at Mukdahan (Thailand), Pakse (Lao PDR) and Kratie (Cambodia) during the period 1985–2000. It is likely that shortages will occur, especially in the Mekong Delta, during the months of February to May when water flows in the Mekong river are at their lowest. The Mekong riparian counties need to plan carefully to avoid future water shortages during critical flow periods. Efficient water use planning is being assisted by the Mekong River Commission.

This paper will project future water demands by estimating the area of land that can be irrigated, the type of farming systems suited to each ecosystem, their water consumption patterns and by evaluating the potential water sources that can be exploited. Government policies affecting future use of Mekong River water will then be discussed.

Current irrigated area and potential for expansion

Although the total catchment area in the LMB is around 61 million ha, much of the land in the Central Highlands of Viet Nam, many of the provinces in Laos and parts of Thailand and Cambodia are steep, with high or moderate levels of degradation potential and should remain uncleared or be managed carefully. Some of this area is presently used for grazing and growing upland crops including industrial trees. About 41% of the LMB is used for agriculture and other economic activities.

Just under half (49%) of the total LMB land area is classified as gentle slopes and flat areas that are potentially suitable for lowland agriculture, including irrigation (Class 5 lands in the MRC Watershed Classification, MRC 2001—see Figure 1). Seventy percent of this area is in North-east Thailand and Cambodia. The percentages of the area's watersheds classified as suitable for lowland agriculture are 72% for Cambodia, 13% for Laos, 65% for Thailand, 11% for the central highlands of Viet Nam and 99% for the Mekong Delta. Despite this, the area being used for irrigation remains small (Table 1), at only 13–14% across the LMB for both the dry and wet seasons. Much of this is partial irrigation. Consequently, it would appear that there is considerable potential to expand the irrigation area in the LMB leading to increased abstractions of water from the Mekong River to cater for the expansion.

Unfortunately, many of the soils of the LMB are acidic, have low levels of organic matter, low cation exchange capacities (CECs), fix phosphorus and can possess toxic levels of aluminium under aerobic conditions. These characteristics are expressed particularly strongly in the acrisols, the most common soil in the flatter areas of the LMB (Table 2—MRC 2002c). They generally possess 'low natural fertility' (Linquist and Sengxua 2001) and are often 'difficult to manage' (White et al. 1997). One author (Euroconsult 1998) described the soils of North-east Thailand as being 'rated among the poorest in S and SE Asia'.

Large areas of land are therefore unlikely to provide good economic returns for cultivating upland crops or perennials without substantial modifications to the soil. Such modifications would include increasing soil pH, increasing cation exchange capacity and improving soil fertility. Some of these problems can be overcome when the soils become anaerobic after being flooded for long periods. Low yielding rice crops can then be grown using traditional methods. Rice yields are increased significantly by applying inorganic fertilisers. These practices drove the expansion of dry season rice production in the LMB from 272,000 ha in 1970 to 4 million ha in 2000, mainly in Viet Nam. A slower expansion rate is expected in Laos and Cambodia, but there is still considerable potential for increased irrigation within the LMB.

Typical cropping systems in the LMB

Because of the extensive waterlogging and inundation during the wet season, most of the soils in the rainfed lowlands of Laos, North-east Thailand and

Cambodia, and in the irrigated Mekong Delta in Viet Nam, are more suited to growing rice than other crops. After a period of rainfall, the watertable rises towards (waterlogging) and often above (inundation) the soil surface. Also, the predominant sandy loams form a hard plough pan or seal at the surface preventing water penetration. This results in temporary waterlogging after initial rainfall or irrigation. Upland crops do not grow well in these soils. For this reason, cropping systems in the LMB are almost exclusively centred around the cultivation of rice, which is the staple food for most of the population. Consumption ranges from 100–170 kg/person/year for LMB countries and is likely to remain high for many years to come. Food security is of paramount interest and farmers are more interested in producing sufficient rice to feed themselves and families before considering selling surplus farm production. Resource-poor farmers operate on low cash flows and carefully weigh the risks of adopting more expensive farming practices that may possess higher returns but carry greater risk of failure. Surplus rice grain can be stored and eaten if the price drops excessively. Rice consumption remains strong even when annual incomes are high. Average consumption in Japan for example still exceeds 60 kg/head/year even though GNP per capita is high.

Rainfed rice predominates farming in Laos (25% of it is upland rice), central highlands of Viet Nam, north-east and part of north Thailand and Cambodia, while fully or partially irrigated rice is grown year round in parts of the Mekong Delta of Viet Nam

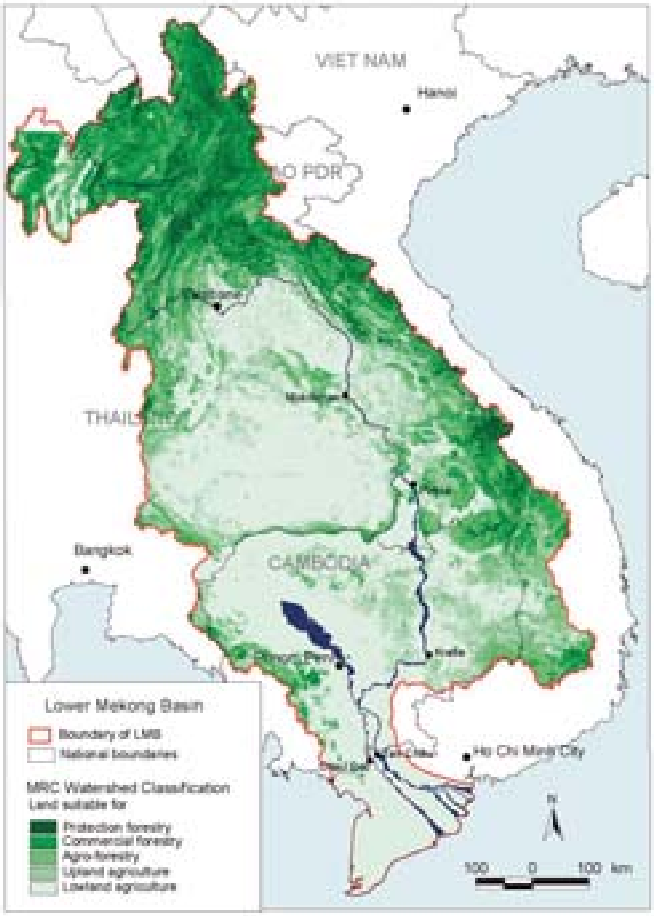
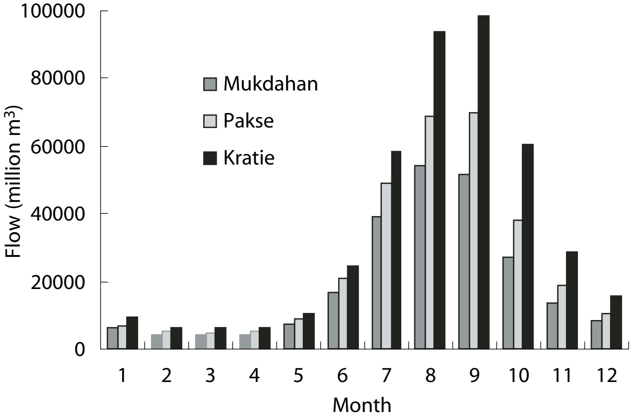


Figure 1. Lower Mekong Basin.



Source: MRC hydrological database

Figure 2. Average total monthly flow at Mukdahan, Pakse and Kratie, (1985–2000).

Table 1. Use of gentle slopes and flat land (Class 5, MRC watershed classification) for irrigation in dry and wet seasons.

Country	Area of Class 5 land (000' ha)	Area dry season irrigation (000' ha in year 2000)	Current utilization (%)	Current use in wet season, for partial irrigation (%)
Laos	2,700	92	3	17
Viet Nam CH	400	37	10	30
Viet Nam MD	3,300	3402[a]	100	22
Thailand	12,200	107	1	12
Cambodia	11,200	255	2	11
TOTAL	29,800	3,893	13	14

[a] Includes double cropping in dry season.

Table 2. Soil types in gentle slopes and flat land of the LMB (Class 5, MRC watershed classification).

	Thailand		Laos		Cambodia		Viet Nam—CH		Viet Nam—D	
	Area (mill ha)	Area%	Area (mill ha)	Area%	Area (mill ha)	Area%	Area (mill ha)	Area%	Area (mill ha)	Area%
Acrisols	8.7	71	1.4	50	6.6	59	0.2	68	0.1	2
Cambisols	0.1	0	0.9	32	1.3	11	0.0	5	0.2	5
Gleysols	0.6	5	0.2	1	1.3	12	0.0	2	2.5	75
Fluvisols	0.3	2	0.0	1	0.1	1	0.0	9	0.4	13
Leptosols	0.0	0	0.2	2	0.2	2	0.0	1	0.0	0
Ferralsols	0.1	0	0.0	1	0.2	2	0.0	11	0.0	0
Other soils	2.5	22	0.3	13	1.5	13	0.0	4	0.2	5
TOTAL	12.18	100	2.7	100	11.3	100	0.4	100	3.4	100

Source: MRC (2001), MRC (2002c)

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(Table 3). The area of land dedicated to growing upland crops (Table 3a and Table 3b) is much smaller in total than that planted to rice and fluctuates in area from year to year. Fruit and industrial crop production is expanding rapidly from a low base (Table 3b, MAC (2000), MRC–Halcrow (2003a), LNSC (2001), MAFF (2000), VSY (2002)).

Table 3a. Cropping areas in LMB (000' ha).

	Year	Rice	Maize	Cassava	Sugarcane	Other upland crops
Thailand	1999					
Wet season		4,647	383	619	480	120
Dry season		80	20			22
Viet Nam Delta	2000					
Wet season		759	19	153	76	9
Dry season		3402				
Viet Nam CH	2000					
Wet season		107	87	38	25	
Dry season		37				
Cambodia	2000					
Wet Season		1,647	54	13	5	79
Dry season[a]		255	3	2	2	8
Laos	2000					
Wet season		720	49	19	8	22
Dry season		92				

[a] Includes fully irrigated rice and recession rice with supplementary irrigation

Table 3b. Cropping areas in LMB (000' ha).

	Year	Fruit trees	Coffee	Vegetables
Thailand	1995	381	na	39
Viet Nam MD	2000	300 (e)	na	?
Viet Nam CH	2000	?	300 (e)	?
Cambodia	2000	164	little	32
Laos	2000	?	42	40 (e)

na = not grown; e = estimate; MD = Mekong Delta;
CH = Central Highlands
Note: Agricultural statistics are generally reported by province, and are quoted here for regions that approximate the areas of the country falling inside the LMB, as follows:
Cambodia—whole country
Laos—whole country
Viet Nam Delta—includes Long An (larger area than Mekong Delta as defined by MRC)
Viet Nam CH—Central Highlands region (4 provinces)
Thailand—Northeast region, plus Chiang Rai and Phayao.

Rainfed rice is generally sown at the beginning of the wet season (May–June) and harvested from October through to the following January, depending on the maturity of the cultivated variety (Figure 3). These crops may be direct seeded or transplanted. Double cropping in the wet season is now possible with recently introduced faster maturing high yielding varieties (HYVs). This practice is more common in Cambodia than in other countries and is gaining popularity in areas where there is sufficient rainfall to plant a HYV early in the wet season and harvest it in time to transplant a second traditional, photoperiod-sensitive variety. Some early wet season crops may receive supplemental irrigation.

The total area of land cultivated to rice in the LMB during the wet season is about 8 million ha with about 14% of it receiving supplemental irrigation (Table 1). Included in this estimate are the nurseries in Northeast Thailand, Laos, Cambodia and the central highlands of Viet Nam receiving extra water before transplanting in June, July or August. On the Mekong Delta, two dry season crops (April–August and November–March) are regularly cultivated in flood-prone areas, although rice is grown in some fashion all year round where water is accessible and flooding not a problem (Figure 4). Traditional rainfed rice varieties are now rarely planted in the Vietnamese part of the Mekong Delta, although they are still found in the Cambodian delta regions.

Other rainfed crops include maize, sugarcane, mungbean, sesame, cassava, soybeans, peanuts and kenaf. Maize is often grown on more fertile soil along river banks and higher rainfall areas. It is planted early in the wet season and harvested just before floods later in the year, usually in August or September. Sugarcane is also planted after the monsoonal rains start in May and is harvested from November through to the following April. Mungbeans and sesame are sown with the opening rains, and harvested before transplanting rice in July–August. Soybeans are sown later in the wet season (sometimes after mungbeans) in the uplands of Cambodia, Thailand and to a lesser extent, the central highlands of Viet Nam and Laos. Cassava is planted in well drained soils in April–May and harvested in December–January. Cultivation of all upland and perennial crops is limited to topographies that do not regularly flood. Only mungbeans and possibly peanuts receive supplemental irrigation during the wet season. A total of 129 thousand ha of these two crops were grown in the LMB during 1999–2000, with no more than 30,000 ha receiving supplemental irrigation

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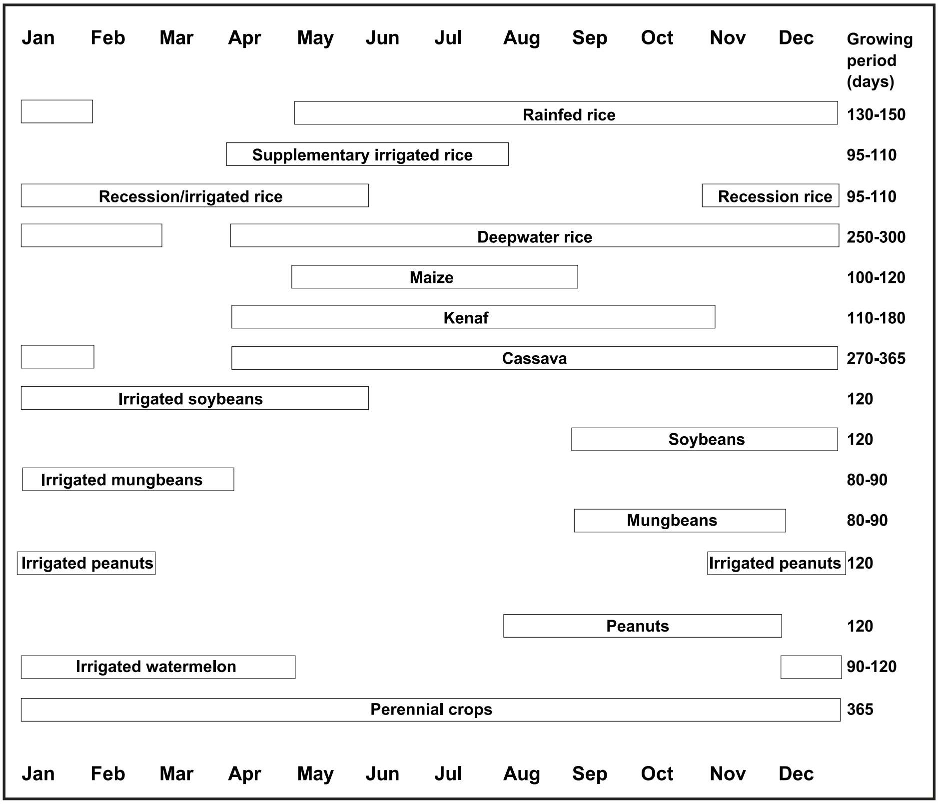

Figure 3. Generalised cropping pattern for Laos, Thailand and Cambodia.

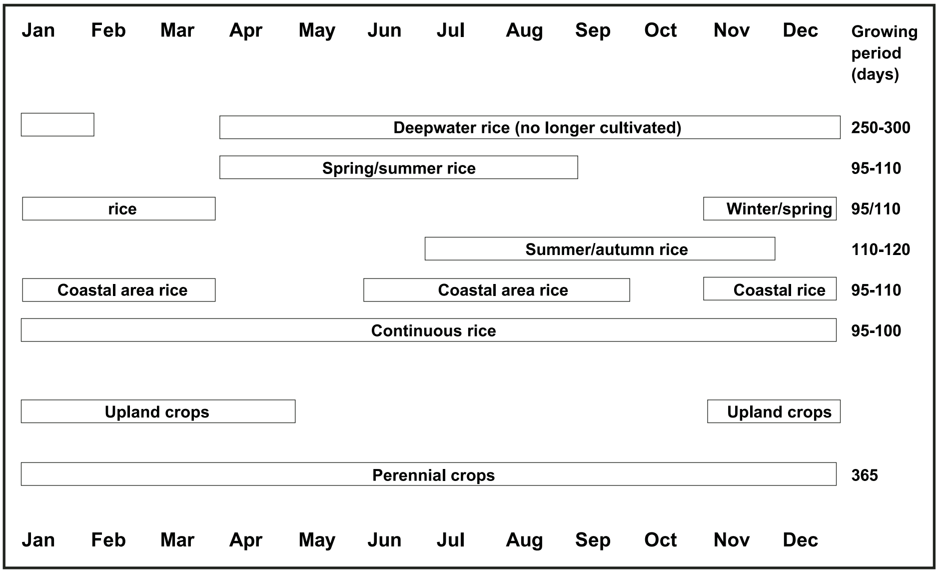

Figure 4. Generalised cropping pattern for Mekong Delta.

Fully irrigated rice is cultivated extensively in the Mekong Delta (1.5–2 million ha) but little fully irrigated rice is grown elsewhere in the region. Eighty thousand ha of dry season rice was grown in Thailand in 1999, 37,000 ha in the central highlands of Viet Nam and 92,000 ha in Laos in 2000 (Table 3a). These areas are presumed to receive all of their water requirements from irrigation. Only about 55,000 ha of the 255,000 ha of dry season rice grown in Cambodia is considered fully irrigated. The remainder is recession rice (i.e. rice planted as flood waters recede) receiving a range of irrigation supplements.

Upland crops grown in the dry season include maize, mungbeans, sesame and sugarcane. Areas under irrigation are small and not listed separately in all LMB countries' agricultural statistics. The small areas of upland crops noted to be grown in Cambodia during the dry season (Table 3) are often sown on residual soil moisture or cultivated early in the wet season, receiving little if any irrigation water.

Significant areas are planted with perennials, including coffee and fruit trees, and vegetables, in each of the LMB countries. Coffee areas in Viet Nam, for example, increased from 119,000 ha in 1990 to over 561,000 ha in 2000. Much of this was in the central highlands with 130,000 ha in one watershed in Dak Lak province alone (Giang et al. 2000).

About 60% of Vietnamese coffee originates from an estimated 300,000 ha of trees in the central highlands (www.financialexpress.com/fe/daily). There were also 42,000 ha of coffee reported in Laos in 1999 (LNSC 2001). Coffee plantations in eastern Cambodia were established during the 1990s but the total area is not known (perhaps 5000 ha). Coffee is generally grown on fertile, porous soils and supplemental irrigation from ground-water sources is needed during the dry season.

Fruit trees were grown on 381,000 ha of North-east Thailand in 1995, but the area may have expanded further since then (MAC 2000). In the Mekong Delta, the area under fruit trees is known to have increased from 175,000 ha in 1995 to nearly 300,000 ha in 2002. This area is expected to increase to over 500,000 ha in the near future as markets are established for the produce. OPCV (2002) quotes the area of fruit in Cambodia as being 164,000 ha. The central highlands of Viet Nam and Laos may produce an extra 100,000 ha of fruit, increasing the total area of fruit in the LMB to about 950,000 ha. The area of vegetables in the Mekong Delta is not reported, but the Delta is an important region for vegetable production both for local consumption and for Ho Chi Minh City and Phnom Penh. Total vegetable production in the LMB was at least 120,000 ha in 2000 (Table 3b).

Animal production

The number of large animals in the LMB has increased markedly during recent years (MacLean 1998, FAO 2003). Buffalo numbers in Thailand and the Mekong Delta in Viet Nam have diminished slightly as farmers shift from using animal-drawn implements to machinery for crop cultivation. This decline has been offset by more cattle and pigs across the basin (Table 4).

Increasing large animal numbers is a reflection of improved crop production and of the general welfare of farmers. Higher rice grain yields for example, have led to increases in the amount of stubble available for grazing both cattle and buffaloes. Such dry season grazing areas are particularly prevalent in Thailand, Cambodia and Laos. However, pigs are fed with rice bran, a by-product of milling. Increased grain production results in the support of more pigs, chickens and ducks.

Table 4. Number of large animals in LMB in 2000 (millions).

	Cattle	Buffaloes	Pigs
Laos	1.1	1.2	1.8
Thailand	2.7	3.2	1.2
Cambodia	2.9	1.9	1.9
Viet Nam MD	0.2	0.6	2.9
Viet Nam CH	0.5	0.6	1.2
Total	7.4	7.5	9

Animal sales are a major source of income for subsistence farmers and are seen as 'banks' for accumulation of wealth. Chickens are generally a source of protein for farmers, although the number of intensive chicken farms in the LMB over the past decade has expanded. There are about 24 million cattle, buffaloes and pigs in the LMB, each consuming about 50 L of water per day.

Fish and shrimp production

Fish caught from rice paddies are a major source of protein for farming populations in Laos, Cambodia and North-east Thailand (Gregory 1997), significantly surpassing chicken and other dietary meat sources (CIAP 1998). Paddy fish supplies are enhanced in deeper fields in Cambodia and North-east Thailand with the introduction of exotic herbivorous fish species. Small areas of fresh water aquaculture fish farms are also installed in Laos, North-east Thailand and Cambodia.

Fishery products provide half the protein for the Vietnamese population, about 15% of which comes from inland fisheries in the Mekong Delta (Xuan and Matsui 1998). In 1994, aquaculture production occupied 231,000 ha, of which fish occupied one-third and shrimp two-thirds. By 2000 the area under fisheries had increased to 445,000 ha (VSY 2002), despite productivity dropping as a result of pollution (Do Van Xe, pers. comm.). MRC–JICA (2003a) suggest that the area under fish ponds on the Mekong Delta in 2001 was 511,760 ha, 392,200 ha of which was for shrimp culture and 119,560 ha for fresh water fish.

Irrigation water

Surface water

More than 19,000 irrigation schemes had been installed in Laos by 2000 servicing an area of 295,000 ha in the wet season and 197,000 ha in the dry (Nippon Koei 2001). Most schemes are of the traditional weir type in the mountainous northern and central regions while pump irrigation is concentrated in the south. Overall, more than half of the irrigated area is pump irrigated (DOI 2001). Government figures indicate that about 92,000 ha of rice was harvested from the dry season irrigated area in 2000. Not all schemes are fully used because of high operational costs and low returns (Nippon Koei Co Ltd 2001). Consequently, the area under irrigation is not likely to expand rapidly in the near future without heavy government subsidisation.

In North-east Thailand, more than 750,000 ha of land has infrastructure installed for irrigation (WUP-JICA 2002). About 32% of the area has large-scale irrigation schemes, 19% medium, 27% small-scale and 22% pumping schemes. These schemes are primarily used for providing supplementary irrigation to wet season crops. In the dry season, either insufficient water is available for crop cultivation or it is uneconomical to grow crops on the infertile soils. In 1998, Euroconsult (1998) considered that the cropping intensity during the dry season was only 10–15% of the irrigation area in the Lam Praplerng and Lam Pao schemes. Fewer than 50% of farmers planted any crop at all because high labour costs or a complete lack of available labour made cultivation impossible. Of the remaining 50%, few cropped the whole farm, with most planting high-value crops like chilli and watermelon on small areas. Thai Royal Irrigation Department (RID) figures for 2001 indicate that 116,492 ha (16%) of the area under RID irrigation schemes was planted. In 2002 this figure was reduced to 94,789 ha (13%). Sixty-four thousand hectares were planted to rice, 17,470 to upland crops, 5294 to vegetables, 2065 to sugar, 342 to fruit trees, 666 to other trees and 4334 ha dedicated to fish ponds (RID crop figures). In the portion of northern Thailand within the LMB, about 13,500 ha of rice is irrigated on small schemes.

The Thai Royal Irrigation Department plans on continuing to construct irrigation infrastructure in North-east Thailand in 2003/4. These schemes are mainly in the Mun and Chi catchments. Economic considerations are not perceived to be a constraint to their installation as it is government policy to provide as many opportunities as possible for the population of North-east Thailand to remain residents of the North-east.

Cambodia has 946 operating irrigation systems in the whole country which can service 256,120 ha of the 2 million ha wet season cultivated area. In the dry season, rice is grown on 255,000 ha and 143,490 ha of this can receive irrigation water from irrigation schemes. Hence, only 12% of the wet season rice is irrigable, the remainder being rainfed. Only about 55,000 ha of the dry season crop is fully irrigated, the remainder being recession rice receiving supplementary irrigation from manually operated and diesel-driven pumps. Few of the irrigation schemes are capable of irrigating all year round. Most dry season rice is cultivated on land flooded during the wet season. Crops are transplanted as the floods recede in a similar manner to recession rice. They are then either gravity fed from upstream dams or water is pumped from irrigation canals. The latter is a common method south of Phnom Penh where most land is only 5–7 meters above sea level and high lift pumps are unnecessary. Fully irrigated crops receive about 10,000 m^3/ha. Some irrigation engineers in Cambodia (J. Himmel, pers. comm.) estimate that recession rice receives about 4000 m^3/ha of irrigated water.

The number of surface water irrigation schemes in the central highlands of Viet Nam is small compared with other parts of Viet Nam. Schemes are found

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along the river and on valley floors irrigating about 50,400 ha of rice in all of the central highlands in 2001 (VSY 2002). This compares with the 300,000 ha of coffee irrigated from ground water sources.

JICA (2003) estimated that about 1.5 million ha of agricultural land was irrigated in the Mekong Delta of Viet Nam during 2001. Estimates are that about 300,000 ha grow three crops of rice per year, 1,080,000 ha are double cropped and 200,000 ha are cultivated to upland crops (Tanh, pers. comm.) Water is extracted from 2500 km of natural rivers and creeks and 3000 km of canals (Binh 2002). Some of this water is directed into acid sulphate soils in the plain of reeds and Long Xuyen–Ha Tien quadrangle causing problems with severely acidic water being flushed along the same canals into more productive areas at the onset of monsoon rains.

Pump costs are high towards the north of the delta where flooded water levels may need to be reduced to cultivate two crops of rice during the dry season. In the fresh water alluvial zone it is possible to crop two to three crops per year using high tides to irrigate paddy fields and low tides for their drainage. The use of tides for crop irrigation is more difficult along the coastal region and the Ca Mau peninsula. These areas are becoming increasingly used for fish farming. Salt water incursion is a serious problem in parts of the Mekong Delta during the months of January–May when river flow rates are at their minimum.

Ground water

Pattanee et al. (2002) estimated that 75% of domestic water in Thailand is obtained from ground-water resources serving 35 million people in villages and urban areas. The only region in Thailand irrigating crops from ground water is in the north of the country. Ground-water studies suggest freshwater can be found among the numerous saline aquifers in North-east Thailand, but there is not the volume for wide-scale irrigated agriculture (RID, pers. comm.).

Good freshwater aquifers are located along the mountainous region of Laos and some of these are used to water the 42,000 ha of coffee in the area (Bounliep Chounthavong, pers. comm.). A little extra water is used for domestic consumption.

Ground water sources are often overextended in the support of coffee production in the central highlands of Viet Nam. In 1998, for example, almost 60,000 hectares of a total 140,000 hectares under cultivation was badly affected by drought (http://www.undp.org.vn/dmu/events/Events-1998/980000-a/en/980406-a.htm). Regardless, of problems, the area under coffee has increased dramatically over recent years in response to population resettlement programs. There are currently about 300,000 ha of coffee grown in the central highlands.

Recharge of aquifers is generally slow and farmers are known to dig horizontally from the base of wells to extract more water. Although ground-water levels are known to rise and fall with the season, water tables are declining over time (Dr Trinh Truong Giang, pers. comm.). Water in these areas is applied to coffee over the dry season at about 50 mm each nine days (SRMP 1999). This rate is equal to 65 cm (6500 m^3) per ha. Ground water is also used for domestic purposes.

The Mekong Delta possesses six aquifers with depths ranging from 15–75 m and 275–400 m. Water reserves are considered to be large (Haskoning 2000) but exploitation needs careful siting and drilling because much of the water is either brackish or saline and recharge characteristics are poorly understood. Water in the lower aquifers is 20,000–30,000 years old and not recharged from local rainfall, causing concern for its misuse. Some bores to the medium depth aquifers were artesian or sub-artesian sources 10–20 years ago but are already suffering from overuse with water levels dropping rapidly. In part of the delta, shallow ground-water aquifers have been exhausted. Water levels are thought to have declined, both through abstractions and by the extensive surface drainage system constructed during the 1990s.

The only major areas on the Mekong Delta consuming ground water for agricultural production are between and along the Bassac and Mekong rivers. Although the draw-down is significant during the dry season, the shallow aquifers are recharged by floods during the wet season and directly from the river in the dry.

Extensive shallow ground-water reserves are known to exist around the Tonle Sap lake and beside the Bassac and Mekong Rivers in Cambodia. Water levels in shallow wells and tubewells follow the river height for distances up to 30 km each side of the Bassac river (CIAP 1999) indicating the aquifers are constantly being recharged. Farmers in the provinces of Kandal, Takeo, Svey Rieng and Prey Veng have taken advantage of these reserves by installing cheap shallow tubewells to irrigate 1–2 ha of dry season crop. Unfortunately the recharge rate is slow and in some intensively irrigated areas farmers run short of water during peak periods. Dry season rice production in

Prey Veng, and Takeo, using ground water during 2001, covered an area of 5000–10,000 ha (CARDI, pers. comm.), up from zero in 1995. JICA (1999) estimated wells in the quaternary aquifers of Svey Rieng, Prey Veng and southern Kandal can yield 500–800 m^3 per day without causing adverse effects on the entire ground-water basin. Such pump rates would irrigate 4–6 ha of rice per well. The potential for irrigation from ground water from these aquifers is therefore quite high if properly regulated to ensure minimal draw-down. There is insufficient recharge capacity in the aquifers for large-scale irrigation projects.

Arsenic levels are known to be high in ground water extracted from shallow aquifers in low lying areas of Bangladesh and other parts of the world, and high arsenic levels have been reported in shallow wells along the Mekong floodplain in Cambodia and Viet Nam. In Bangladesh, there is some evidence of increasing arsenic concentration in soils as a result of ground-water irrigation. Arsenic is fixed under oxidising conditions, so is not freely available in most surface soils, but rice paddy soils are anoxic, and rice typically has higher arsenic concentrations than other crops. Arsenic in rice and other crops is mainly present in organic forms with low toxicity, and in general it is not likely that ground-water irrigation will result in significant arsenic contamination. However, it would be advisable to monitor arsenic levels in wells on the Mekong floodplain used for irrigation (D. Fredericks, UNICEF, pers. comm.).

Crop water requirements and water consumption by animals and fisheries

Total water consumption in any cropped area can be calculated using the FAO model (http://www.fao.org/ag/agl/aglw/cropwat.stm) with rainfall, evaporation, soil type, loss of water from canals and other structures, crop type, stage of crop growth, area of each crop, planting time, irrigation method, crop duration, and a range of other factors, being taken into consideration.

Rice cultivation is the largest consumer of irrigation water in the LMB. NEDECO (1991) calculated water requirements on the Mekong Delta in February averaged 0.8 L/sec/ha for rice (2000 m^3/ha/month), 1500 m^3/ha/month for upland crops and 1000 m^3/ha/month for perennial crops. These rates are included in Figure 5 to examine water requirements of the major cropping systems used in the Mekong Delta. Other rates reported in the literature for LMB countries include 10,000 m^3 per irrigated rice crop (Cambodia), 12,000 m^3 per irrigated rice crop (Thailand), 1 L/sec/ha (8,294 m^3 for 120 day rice crop) (Mekong Delta) and 19,600 m^3/year/ha (Mekong Delta). In the April, 2003 (Vol 2 No 1) issue of *Rice Today*, The International Rice Research Institute (IRRI) advertised that traditional irrigation techniques in Asia consume 5 m^3 of water to grow 1 kg of rice. Dry land crops produce the same amount of grain for 1 m^3 and irrigated rice in Australia and the United States consume about 1.2 m^3/kg. If it is assumed that 10,000 m^3 of water was used to produce one hectare of dry season rice in the LMB during 2000, average rice grain production used 2.5, 3.0, 3.3 and 2.0 m^3 of water to produce 1 kg of grain for Laos, Thailand, Cambodia and the Mekong Delta in Viet Nam respectively.

Upland crops, including vegetables and perennials, consume less water than rice. Commonly used crop factors are as follows: rice, 1.15; bananas, 0.9; maize, 0.75; groundnuts, 0.7; citrus, 0.65; melons, 0.65; vegetables, 0.65 and soybeans, 0.65. Therefore, for water conservation it would appear advantageous for farmers to grow more upland crops and less rice. Cultivation of these crops is restricted to either the higher, more fertile, well drained soil types during the wet season or must be irrigated during the dry season. Many rice paddies levelled to maximise the production of rice grain may need considerable earthworks in the form of raised beds or field gradients to cultivate such crops.

Irrigated perennial crops include fruit trees, bananas and sugarcane in the lowlands and coffee and pepper in the mountainous regions. Fruit trees are occasionally irrigated using a permanently flooded ditch and dyke system which is very expensive in terms of water consumption, irrigated by canals and ditches (intermediate water use), by pump and hose (low water use) or via trickle irrigation techniques (very efficient water use). NEDECO (1991) allowed 3628 m^3/ha for perennial cultivation in the Mekong Delta over the four month critical period between February and May. In addition to direct abstractions from canals, the trees take up water from the shallow aquifers. As the perennial cropping intensity increases on the land suitable for upland and perennial crops, more irrigation may be needed as the water table is lowered below the deep rooted trees.

In the mountainous regions of Laos and Viet Nam, natural unirrigated forest is being replaced by cultivated coffee and pepper. Both cultivated crops need to be well watered during the months of January to March to induce flowering. Rates of 6500 m^3 per ha/year are abstracted from ground-water sources in the central highlands of Viet Nam (SRMP 1999). Similar abstractions are expected from Lao and Cambodian coffee plantations.

Water consumption by animals is estimated at 50 L/day per head of cattle, buffalo and pigs. Poultry and ducks consume less. The estimated 24 million large animals in the LMB each consume 1.5 m^3 per month (36 million m^3/month for total herd). Over the four-month, critical period (equal to one rice crop) consumption by animals is equal to 14,400 ha of fully irrigated rice at 10,000 m^3/ha.

Small areas of fresh water fish farms are installed in Laos, North-east Thailand and Cambodia. However, the major aquaculture consumers of Mekong river water are the fish and shrimp farms on the Mekong Delta. Fresh water fish ponds are topped up to replace lateral and evaporative losses. Pond water is also changed before installing new fish batches. JICA, (2003) estimated consumption of irrigation water in the Mekong Delta fish ponds was at 34,000 m^3/ha across the 119,560 ha pond area in 2001. Fresh water is used in coastal shrimp culture ponds to top up water levels to prevent excessive build up of salt in the ponds. Addition of fresh water is also reported to reduce diseases (H. Guttman, pers. comm.). JICA (2003) estimated the area of coastal shrimp culture in the Mekong Delta during 2001 was 392,200 ha and each hectare consumed 4,600 m^3 of fresh water per year. Some effluent from these ponds is discharged into irrigation canals causing problems when the water is re-used by neighbouring enterprises (H. Guttman, pers. comm.). Evaporation losses from open ponds are high.

Overall water consumption in the LMB

Fifty-nine percent of the LMB watershed area remains uncleared and natural forest may still be the largest consumer of water in the basin. The forest receives all of its required water from annual rainfall and by tapping residual soil moisture, and water from shallow aquifers during the dry season. If the land is denuded of forest and cultivated with annuals, overall water consumption decreases but there will also be a change in seasonal flows into the mainstream and possible long-term, climate-change effects. Only small areas of perennial crops are grown in the LMB compared with annuals (Table 3), although fruit tree areas have not been properly documented because of the small number of trees on each property. A high proportion of the fruit trees are not directly irrigated but draw on water from the shallow aquifers which are continuously recharged from the river system (CIAP 1999, JICA 1999).

Abstractions from the Mekong river in the LMB are not limiting during the wet season when flow levels are high. However, there may be constraints on water use during the dry season, especially in regional drought years. The critical period for irrigation supply is the four months from February to May. Flow records for the Mekong River for the period 1985–2000 indicate that total flows in this period generally constitute only 7–10% of total annual flow (MRC hydrological database—see Figure 2). MRC–JICA (2003b) estimated that total inflows to the Mekong Delta for these four months (calculated from combined flows at Tan Chau and Chau Doc in the period 1980–2001) are less than 42,000 million m^3 in 50% of years, and less than 28,000 million m^3 in 10% of years.

An estimate of water consumption by agricultural activities during the critical months of February to May for the LMB is presented in Table 5. Crop areas are based on those documented in Table 3. To complete the table it was assumed that all fully irrigated dry season rice used water at a rate of 2000 m^3/month and that crops were not fully cultivated each month (Figure 5). It is also assumed that fruit trees consume sufficient water to affect river water levels. Different water-use rates were assigned to other crops, animals and fishing activities (Table 6). Total consumption for the LMB for the four months of February–March is estimated at around 17,300 million m^3. Some of this water is not taken directly from the river—for example, coffee in the Central Highlands is irrigated mainly from ground water; and fruit trees in North-east Thailand are rarely irrigated.

Comparing the estimates for agricultural consumption with estimates of total available flows indicates that even in ‘average’ years (one year in two), agricultural consumption is equivalent to up to one-third of total available Mekong flows in the driest months. In very dry years (one year in 10), agricultural consumption is equivalent to about a half of total flows from February to May.

Figures presented in Table 5 are a simplified estimate of water consumption to make comparisons across the LMB and may not accurately reflect consumption as indicated by the figures provided by the

Viet Nam Sub Institute of Water Resources Planning (SIWRP) for the Mekong Delta region of Viet Nam (Table 5). SIWRP estimated consumption for the Mekong Delta in the first 10 days of February 1998 as around 73 million m^3 per day (782.17 m^3/sec for agriculture, 2.25 m^3/sec for animal production, 24.69 m^3/sec for fisheries, 14.56 m^3/sec for forestry, 13.51 m^3/sec from canals, and 5.16 m^3/sec from waste land). More detailed measurements need to be made for each activity to refine the calculations.

However, the indicative areas presented in Table 1 and consumption rates in Table 5 plus the cropping patterns presented in Figures 3, 4 and 5 demonstrate that there is considerable latitude for maximising the effectiveness of abstractions from the Mekong river for agricultural production. It is also interesting to note that, using the assumptions in Tables 5 and 6, agricultural activities in the Mekong Delta of Viet Nam consumed twice as much water over the four-month period than in the other four watersheds combined.

Irrigation water consumption reduction strategies

Strategies for limiting the consumption of water used for agricultural purposes in the LMB include timing of cropping systems to avoid high water consumption during the critically low water flow months and reducing the amount of water each crop uses.

The lowest abstraction rates from the Mekong river occur when rainfed crops are cultivated and not irrigated. Most rainfed upland crops are grown in well-drained areas that are susceptible to neither flooding nor waterlogging. Rainfed rice may be cultivated in areas susceptible to waterlogging and some low level flooding. These crops (see Figure 3) are harvested before the critical months of February–May. Water consumption by rainfed crops can be decreased by improving their water-use efficiency (efficiency of the crop to use water in producing total dry matter), increasing the varietal harvest index (percentage of dry matter harvested as grain) and reducing the amount of transpired water (by selecting improved varieties). Ensuring the crops are properly fertilised will assist this process. Soils can also be improved for the longer term. For example, some farmers in North-east Thailand can afford to place bentonite in slots at a depth of 60 cm to improve fertiliser and water availability for sugar cane production (E. Floether, pers. comm). Land levelling reduces water losses and increases yields for rainfed rice (CIAP 1999) and installing raised beds reduces waterlogging and inundation for upland crops (CIAP 1997). Other practices that decrease overall water use include the reduction of maturation period of HYV rice varieties through direct seeding (CARDI 2000), employment of minimum tillage methods to retain soil moisture and synchronous planting to reduce pest damage to plants. Mechanisation speeds up the timeliness of these activities.

Effective water conservation techniques that can be employed during the wet season to reduce water losses include the installation of efficient water distribution systems, soil compaction of canals and fields to reduce percolation, land levelling, direct seeding, soil fertility improvement and the use of shorter duration varieties.

Supplemental watering of rainfed crops through partial irrigation usually results in abstractions during the high river flow period. Local ‘mini droughts’ of a month or so are generally not reflected in the Mekong river height. In some cases, fields in Laos, Thailand and Cambodia may suffer flooding at one end of the field and be drought affected at the other. Re-distributing this water will not affect the overall accessibility of river water at critical periods. Supplemental irrigation during the wet season is especially effective with potentially high yielding crops.

Recession rice is planted into flooded soil and may or may not receive supplemental irrigation. Crops in Cambodia are sown as early as November and subsequently harvested in February. Later sown crops are harvested during the critical period and definitely need to be irrigated for reasonable yields. The cultivation of shorter duration rices during this period may avoid the need to irrigate later than February. Techniques that allow the crops to be planted in deep flood water at the beginning of the season will also extend the irrigation free period. Upland crops needing less water cannot replace recession rice unless the fields are drained beforehand. LMB soils, generally do not have residual soil moisture properties suitable for growing unirrigated crops if the crop cycle begins with dry soil surfaces.

The planting of the winter–spring (W/S) rice crops on the Mekong Delta as early as possible also takes advantage of flooded soil conditions. Some farmers sow directly into 20–50 cm of flood water when turbidity drops sufficiently for sunlight to penetrate to the seed. These crops are irrigated from the high Mekong river water levels in October through to

December while still reaping the benefits of high energy levels for maturation in January–February. Some paddies may need to be pumped to lower water levels at the end of the flood season before they can be planted with rice. Pumping increases crop costs. Early dry season crops are most likely to reach their potential because they mature into the period that receives the highest energy from sunlight. Crops can also take advantage of new silt deposits from the wet season floods. Levelled fields and properly fertilised, direct seeded, early maturing crops should maximise the potential yield from each unit of water.

Delaying the cultivation of the second crop (summer–autumn) will reduce water consumption at the beginning of the season and use rainfall later in the year. Delaying planting may result in late season flooding of some second crops. It is difficult to replace rice with upland crops for later plantings

Table 5. Water consumption (million m^3/month) during critical period, 2000.

	Crop area 000' ha	Month				
		Feb	Mar	Apr	May	
Mekong Delta						
Winter/spring rice	1237	2394	994	0	0	
Spring Summer rice	1500	0	0	622	1286	
3 rice crops/annum	300	192	212	205	212	
Upland crops and vegetables	50	75	80	80	80	
Fruit trees	300	290	321	311	321	
Fresh water fish	100	556	616	596	616	
Shrimp production	345	250	277	268	277	
TOTAL	3832	3758	2501	2083	2792	
VN SIWRP[a] estimate		2990	2486	1669	1695	
Central Highlands, Viet Nam						
Irrigated rice	37	72	82	80	0	
Coffee	300	290	321	311	321	
Cambodia						
Fully irrigated rice	55	106	118	114	118	
Recession rice	200	194	107	0	0	
Upland crops and vegetables	40	41	37	39	37	
Fruit trees	164	159	176	170	176	
Thailand						
Irrigated rice	107	208	230	222	0	
Upland crops and vegetables	61	63	57	59	57	
Fruit trees	381	369	408	395	408	
Laos						
Irrigated rice	92	47	43	44	0	
Upland crops and vegetables	43	42	46	45	46	
Coffee	42	41	45	44	45	
TOTAL	1522	1632	1670	1522	1208	
LMB large animals	24 million	34	37	36	37	
GRAND TOTAL IN LMB		5423	4208	3641	4038	= 17310

[a] SIWRP = Viet Nam Sub-Institute for Water Resources Planning

because of waterlogging and flooding problems at the end (July–September) of the season. The crop duration and water use efficiency may be reduced by growing faster maturing, improved varieties. Percolation losses can also be limited through the selection of impervious soils for cultivation and by compacting soils to reduce losses.

Short (105–115 days) and very short (95–104 day) duration rice varieties are grown where it is possible to grow three crops of rice in one year (or five crops in two years). At these sites, the total growing season is not reduced by periods of deep flood and the soils are sufficiently fertile to continuously crop. In some locations, upland crops may replace one of the rice crops, thereby reducing water usage. Suitable sites need to properly drained and some land forming may also be necessary to achieve good yields.

High crop factors (1.15 for rice and 0.7 for many upland crops) will result in a large volume of water being consumed when any crop is cultivated and irrigated between February and May. The possibility of water shortages in the Mekong Delta are currently offset by the promise of high yields due to the high energy levels radiating on the crops. In future though, large water savings will occur if areas currently growing three crops per annum reduce their cropping intensity.

As mentioned above, upland crops do not tolerate waterlogged soils or inundation. Their cultivation is therefore restricted to the dry season and/or to well drained soils. Planting of any fully irrigated upland crop should be avoided when water shortages are predicted. If grown at all, fast maturing crops can be planted early and harvested before February. Perennial crops also use a considerable amount of water year round for survival and growth. As indicated in Table 6, any further expansion in the area of fruit trees or coffee will place greater pressure on diminishing water levels during the dry season.

The rate at which fresh water is used in fish and shrimp ponds is debatable and needs to be properly measured. However, evaporation losses from shrimp ponds cannot be replenished with sea water if salt concentration is a problem. Fresh water additions to ponds should therefore at least equal the difference between Class A pan evaporation rates of 75 cm and precipitation (25 cm) over the four month critical period (a Class A pan is a standardised US Weather Bureau evaporation pan.). In addition, fresh water ponds need to be filled and occasionally flushed. Aquaculture is a high consumer of water and expanding areas of ponds in the LMB, especially on the Mekong Delta will result in a high demand on Mekong river water. Water losses from the ponds can be minimised by ensuring percolation losses from the ponds are low and through the employment of evaporation loss reduction techniques.

Water quality in the Mekong River is not a serious issue for agriculture except in some areas draining acid sulphate soils and fish ponds, and where there is sea water encroachment in the Mekong Delta. Most farmers welcome higher sediment loads in their irrigation water. Such levels rise with forest clearing and fall below newly constructed dams.

Government policies and the potential for agricultural development in LMB watersheds

Governments of each of the four countries making up the LMB have vastly different approaches to the development of their respective Mekong watersheds. Their policies directly affect farmers' livelihoods and

Table. 6 Assumptions for calculating water use in Table 5.

Activity	Water flow (L/sec/ha)	Water req. (m^3/ha/month)	Crop irrigation life (months)	Critical period consumption (m^3/ha)
Irrigated rice	0.8	2074	3.5	7258
Upland crops	0.6	1555	4	6221
Fruit trees	0.4	1037	4	4147
Coffee	0.4	1100	4	4400
Recession rice	0.4	1037	3	3110
Fresh water fish	2.3	6000	4	24000
Shrimp production	0.3	800	4	3200
Animal production	13.9L/sec	1.5m^3/head/month	4	144 mill m^3 total

often reduce the risk farmers face from drought, waterlogging and inundation.

Laos

Lao Government policy for national development is based on the 5th five-year Socio-economic Development Plan for 2001–2005. National agricultural development priorities include:

- ensuring food security
- stabilising/reducing the area of shifting cultivation
- commodity production support
- irrigation development
- agriculture and forestry research
- human resources development (Nippon Koei Co 2001).

Development of the lowlands is primarily through improving and diversifying farming techniques while the uplands will follow community-based management practices. Data presented in Table 1 indicate Laos has over 2.7 million ha of potentially flat (Class 5) land which has not been developed for agricultural purposes. More than one-third of the flatter land (Table 2) is composed of reasonably fertile soils (cambisol and fluvisols) that would be more economical to irrigate than acrisols if water was available. As 35% of the Mekong water originates from Laos, there is considerable potential for such projects to be implemented along river tributaries. Abstractions would increase accordingly. The implications for water availability and seasonal flows after clearing the forest need further study.

Thailand

Thai Government policies delivered to the National Assembly on 26 February, 2001 emphasise the support it will give to farmers to reform their debt structures, promote the practice of mixed agriculture and optimise the use of idle land. For domestic markets, the government has undertaken to promote a ‘one village, one product’ philosophy, support improved marketing systems, strengthen cooperatives and improve its contribution to agricultural research. It is also envisaged that competitiveness in the international markets will be improved by increasing investment in agro-processing and upgrading quality standards. Government departments continue to promote development in the North-east of Thailand to ensure its population has opportunities for advancement. Infrastructure investment continues.

Most of the Class 5 areas in North-east of Thailand are already developed for agriculture which is presently based on risk averse, low input, low yield technology having evolved in response to erratic rainfall and infertile soils. Agro-processing is mainly associated with post-harvest processing such as sugar mills, rice mills, cassava processing plants, vegetable oil extraction and a few canning plants. Although irrigation offers potential for intensive cropping, so far, few crops other than rice have been found with market prospects and returns to justify farmers investment in irrigation. Rising production costs and static or falling farm prices are expected to ‘squeeze’ farmers further (Euroconsult 1998). Most observers conclude that, for the foreseeable future, agriculture in the North-east will consist of:

- wet season rainfed and irrigated rice in the most productive lower paddy fields
- dry season rice on better soils in some irrigation schemes that have sufficient water
- sugarcane production in the higher rainfall areas and on the better soils and on some irrigation schemes within transport range of sugar mills
- maize production on better soils in higher rainfall areas, for example, Loie
- intensive fruit and vegetable production under irrigation
- extensive cattle production on areas formerly planted with cassava and other rainfed crops
- intensive cattle, pigs and poultry feeding enterprises
- tree crops such as rubber, cashew, mango, eucalypts, bamboo, neem, and teak in areas formerly used for cassava and other rainfed crops
- irrigation schemes will make more efficient use of water in the dry season with higher value crops.

Cambodia

The Cambodian Government aims to transform agriculture into a driving force to achieve higher economic growth for the national economy and reduce the incidence of rural poverty (OPCV 2002). Major objectives of a public investment plan are to:

- maintain a liberal market orientated trade environment
- deregulate the exportation of agricultural products by removing unnecessary internal regulatory constraints and introducing effective licensing and registration
- develop agricultural standards by encouraging investment in appropriate infrastructure and

facilities for post harvest handling, storage and processing
- establish appropriate commercial laws and institutional arrangements for efficient and cost effective market transactions.

The government will continue to invest in research and extension services to enhance the development of technologies and their transfer to farmers. Strengthening of infrastructure plays a major role in Government policy. In the current five-year plan, emphasis is on the construction of a road network into rural areas. These roads have opened up farming land in many parts of Cambodia and settlement of tracts of land in the east of the country will rapidly follow. Future national focus is on installing irrigation facilities to reduce the effects of drought and flood. To do this, suitable sites need to be located and approved. Economically viable sites have been difficult to find in the past because of the flat nature of Cambodia and the poor soils. However, almost 8 million ha of irrigable land is underused for agriculture. Most (59%) of the area is on poor acrisol soils diminishing the economic viability of developing this land for irrigated agriculture. The remaining soils may be located in areas suited to irrigation if water is available. A majority of undeveloped land is to the East of Cambodia which is poorly serviced by rivers, but now that the area is being opened up for development, further investigations of their commercial viability may be warranted.

Viet Nam

Viet Nam's agricultural policy has strongly influenced the shape of agriculture in both the central highlands and on the Mekong Delta. In the central highlands, heavy investment in the uplands has witnessed much immigration to the central highland provinces resulting in a rapid expansion in the agricultural area. More recently annual crops have been replaced by perennial coffee and pepper (Giang et al. 2000).

Heavy government investment in the construction of canals and dykes in the Mekong Delta to control flooding and for irrigation has been curtailed. No new canals are being constructed, but improvements are being made to existing structures. Farmers are being encouraged by government policy to diversify their farming systems to stabilise farm income. The Mekong Delta has been divided into a number of zones based on production costs and financial returns to facilitate planning. Different systems are then promoted in each zone. For example, farmers are not encouraged to grow rice in the south-west corner of the delta where the benefit–cost ratios for rice are low. They are encouraged to convert their farms into shrimp production. The government would like to see a reduction of 200,000 ha in the area used for rice and an increase in the cultivation of other crops. It helps improve the quality of crops by subsidising seed production programs for rice, vegetables and upland crops. The government also provides a floor price for paddy to help the poorer farmers.

Rice production is being encouraged in the centre of the delta where there is fertile soil and yields can average 6t/ha in the dry season and 4t/ha in the wet season. Adjacent to this zone, new settlements have been established on landfill provided by the government to allow residents to remain near their farms during the wet season when the area is normally abandoned because of annual floods. Government officials envisage farmers will now invest in cages to raise fish during the flood season rather than leave the province to find work elsewhere. Acid sulphate affected areas will continue to be used for melaleuca forests or for growing green pineapples.

Other Government policies that help farmers include low taxes on agricultural produce, the provision of funding for agricultural research and extension, education for rural children and subsidies on infrastructure construction.

The Mekong Delta has considerable potential for increasing agricultural productivity with continued Government and private investment. It is envisaged that the delta will remain a rice based agriculture system with an increased level of aquaculture and fruit tree production (Dr Do Van Xe, pers. comm.). It is projected that animal production will increase as export based pork and chicken enterprises expand in number. Grain from upland crops are needed to supply animal feed requirements.

Trans-boundary issues affecting irrigation development

The waters of the Mekong are a resource shared between the six countries of the Mekong Basin, and effects of water resource developments may extend beyond national borders to downstream countries. In the case of irrigation there are three main potential trans-boundary issues of:

- decreased flows due to increased extractions from the river or its tributaries, resulting in water shortages for irrigation, and intrusion of salt water into the Mekong Delta

- increased flows available for irrigation due to construction of reservoirs (for hydropower or irrigation) which retain flood flows and redistribute them in the dry season
- changes in water quality (e.g. due to increased use of agricultural chemicals in upstream areas; or decreased sediment loads due to storages trapping sediment).
- The Mekong Delta is particularly vulnerable to decreases in flow, since it already has extensive dry season irrigation. In addition to the needs for irrigation water directly, some farming systems in the Delta are dependent on high river flows:
- preventing intrusion of sea-water;
- flushing acid-sulphate leachates from soils;
- allowing irrigation of paddies using tides to raise water levels.

A large expansion in the irrigated areas could adversely affect river levels in the Mekong Delta. MRC–JICA (2003b) report that water shortages already occur locally in the Delta during the mid-dry season (early March to May), because the water demand for irrigation in the Delta coincides with the minimum Mekong flows. In addition, about 1.7 million ha of the Delta lands are affected by salt-water intrusion, which affects domestic water supply and irrigation. Salinity intrusion impacts are complex, depending on both hydro-meteorological conditions, and water abstraction from the river.

A cascade of hydro-power dams has been proposed for the Upper Mekong in Yunnan, including two with large storage volumes: Xiowan (total storage 15,000 million m^3) and Nuozhadu (total storage 25,000 million m^3) (Hori 2000). These dams have the capacity to significantly increase dry season flows. Several dams are also proposed for Mekong tributaries in the LMB and, if constructed, will further influence the potential for downstream dry season irrigation. Preliminary results from MRC hydrological models indicate that construction of five of the proposed large hydropower dams on tributaries in Laos could increase average annual minimum flows in the Mekong at Kratie by over 10% (MRC–Halcrow 2003b). Increased dry season flows could provide opportunities for irrigation development, but since some Mekong fish species breed during the low flows of the dry season, increasing flows could damage fish stocks. The increased dry season flows come as a result of wet season flow reductions, which, while they may be welcomed by some because of the reduction in flooding, may also reduce the fish catch which appears to be related to the extent of the wet season flood (MRC 2003).

The 1995 Mekong Agreement between Cambodia, Lao PDR, Thailand and Viet Nam explicitly recognised the interdependence of the riparian countries, and committed the four countries of the LMB to cooperate in the 'sustainable development, use, management and conservation of the water and related resources of the Mekong River Basin'. As part of the agreement, the countries will negotiate rules to maintain an acceptable flow regime in the mainstream during both wet and dry seasons; and rules for water quality. An acceptable flow regime must be defined both in the context of development needs of different sectors, which may conflict, and flows needed to protect the environment and maintain ecological balance.

The rules for maintaining acceptable minimum dry season flows in the mainstream will effectively set limits for expanding dry season irrigation, by limiting withdrawals from the river. Negotiations to define acceptable minimum flows are underway, and the target is to agree on preliminary rules by the end of 2004. The negotiations are supported by the construction of hydrological models to predict the impact of possible development options on downstream flows; and by a program to assess environmental flow requirements. Rules for maintaining water quality will be negotiated by 2005.

In addition to a regulatory approach, the countries have agreed to work together to identify promising development strategies and projects that will benefit all four countries, under the Basin Development Plan (BDP).

Conclusions

Mekong River flows currently service the irrigated agricultural needs of the LMB countries and there is huge potential for an increase in the rate of water abstractions during the wet season. All LMB governments include in their policies, expansion of, or improvements to, irrigation facilities. However, in 50% of years, consumption for agriculture is already equivalent to 40% of total dry season flows (February–May). Increased abstractions will adversely affect the dry season water balance which is expected to soon become critical. The situation is fragile in the Mekong Delta during the dry season as saline water encroaches further up the rivers and canals each year.

Salinity control barriers are being installed to prevent this. Issues holding back an expansion in the area under irrigation include the low farm-gate value of agricultural produce, a prevalence of poor soils and, in some areas, a lack of infrastructure. Diversification into activities that consume less water are constrained by poor soils and poor water control during the wet season. Diversification into irrigated upland crops and perennials will increase abstractions during the dry season.

Rice cultivation dominates agriculture in the LMB for physical, biological, social and economic reasons. The crop, however, does consume much water, and the area under cultivation will need to be reduced when irrigation water shortages become more serious. Average consumption across the LMB is close to 2.7 m^3/kg of grain whereas soybeans use 56% of this. Constraints to overcome before suitable areas can be cultivated to non-rice crops include the low prices for other crops, poor storage facilities and quality control, poor marketing, pests, water quality and water stresses, a lack of labour and capital, poor plant nutrition and farmers lack of technical knowledge. Farmers are also reasonably risk averse when replacing their guaranteed family food source with a cash crop.

Agriculture in North-east Thailand is projected to, in the foreseeable future, consist mainly of low-input, low-risk, wet-season, rainfed and irrigated rice production in the lowlands. Sugar cane, maize and fruit production and tree crops will occupy higher, less flood-prone areas along with extensive cattle production. Water use is not projected to increase greatly until soil-improvement techniques are extended or food commodity prices rise.

Lao agriculture is less developed than in Thailand and there is room for expansion in rainfed and irrigated agriculture in the large areas of flat and gently sloping hills. Thirty-five percent of the total Mekong river flow originates from Laos and there are more than 850,000 ha of potentially good soils on flatter land that may be irrigated. The remaining 1.37 million ha of less fertile acrisols may also be developed for less intensive agricultural activities.

Cambodia has 8 million ha of flat land currently not being used for agriculture. Abstractions from the Mekong river will increase when this land is developed further, especially if the country continues to construct roads and provide other infrastructure to isolated areas. Although 59% of the Class 5 land in Cambodia is composed of infertile acrisols, there is still considerable potential for production increases on these and other soil types.

The aquifer system in the central highlands of Viet Nam appears to be overextended and new sources of water may be needed to support an expanding coffee industry. The area of potentially irrigable flat land is quite small and is composed of mainly infertile soil types. Room for expansion in the level of water abstractions from the Mekong river therefore appears to be quite small.

Farming system proposals for different eco-regions of the delta will reduce the area of rice grown, but there is potential for abstractions increasing during the dry season if farmers significantly expand the area under upland crops, perennials and fish ponds.

Farmers in the LMB remain poor due to the low prices received for the major agricultural commodities. Rationalisation of the industry to achieve greater economies of scale is unlikely to occur in the foreseeable future because of the basic subsistence nature of most farms. Already, farmers receive cash supplements from off-farm activities to support their incomes. Farmers are therefore unlikely to pay for irrigation water. On-farm overuse or misuse of water may, however, be reduced by promoting water saving techniques and introducing crops with higher water use efficiencies. This needs to be accompanied by a reduction in the risk farmers face in the adoption of new crops and practices.

The Mekong Agreement provides a framework for the LMB countries to work together for sustainable development of the river and its resources, including irrigation development. This includes both a regulatory approach, by establishing rules for water utilisation and maintenance of flows, and cooperation for mutual development through joint water resources projects and programs.

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Land and water resources

Benjavan Rerkasem[1]

Abstract

Among the world's developing regions, Asia holds the dubious distinction of having the most serious problems with its water and land resources. Compared with Africa and Latin America, Asia has a lot less arable land per capita. A much larger proportion of its agricultural land is being seriously degraded and its forests are disappearing at the fastest rates. This paper takes stock of land and water resources of Asian countries, focusing on issues related to their efficient and equitable use and future sustainability. Land, as considered here, encompasses the soil and all of the natural resources of indigenous plants, animals and microorganisms, of which Asia is particularly well endowed. The region's rich biotic resource has been most effectively exploited to provide for local livelihood, from fishery to rice production and gathering of minor forest products. Local management has contributed to conservation in some places, but in many others local biodiversity is now under threat—traditional rice varieties have been disappearing from farmers' fields, and fishery resources are rapidly becoming depleted. Local conflicts over water have begun to flare up between upstream and downstream users, with potential for major regional ones over the major rivers such as the Mekong, as well as across sectors, including industrial and domestic use and agriculture. Lessons, experiences and understanding from other parts of the world should be fully exploited to help Asia sustainably manage its water and land resources efficiently and equitably. However, local research and development capacity will be essential to solve problems that are unique to the region.

Introduction

ASIA is particularly well endowed with natural resources, but sharing among its large population brings the land and water available per capita to the lowest among the continents. Limited resources, however, are not necessarily always a constraint to productivity growth, as has been shown repeatedly through history particularly in Asia. The region's land and water resources have been most effectively exploited, but there are also threats to future quantity and quality of the natural resources. Scarcity has already led to local conflicts, but, increasingly, resource use will be influenced by demand from outside as well as inside agriculture. The management of natural resources will have to take into account decisions made and actions taken beyond national boundaries, from sharing of the Mekong to the introduction of genetically modified rice.

Land resources

The term 'land resource' used in this paper refers to all natural resources on agricultural and forested land, including the soil and biotic resources of plants, animals and microorganisms contained in them.

Land availability

A high population density and relatively low proportion of land suitable for agriculture has combined to make pressure on the land higher in Asia than on any of the continents. Population growth since 1960 has resulted in the area of arable land per capita dropping

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to less than 0.1 ha by 1990 in China, Japan, South Korea, Vietnam and Bangladesh (Table 1). According to one estimate, based on the United Nations' medium projection of population growth, most countries in Asia will average less than 0.1 ha per head by 2025. However, land availability is not always a constraint to agricultural productivity. On the contrary, Japan led the way with land saving technology with the world's first semi-dwarf rice and wheat from the early 1900s. Technology and necessary institutional reform have enabled Asia's most populous countries, from Bangladesh, to China, India, Indonesia, the Philippines and Vietnam, to not only feed their growing population but, for some of them, to even become food exporters. It was not a coincidence that the green revolution took off mostly in land-scarce Asia.

Table 1. Arable land area (ha) per capita, in Asian countries.

	Year		
	1961	1990	2025 (est.)
East Asia			
China	0.16	0.08	0.06
Japan	0.06	0.04	0.04
South Korea	0.08	0.05	0.04
South-east Asia			
Cambodia	0.43	0.35	0.16
Indonesia	0.18	0.12	0.08
Lao PDR	0.38	0.20	0.09
Malaysia	0.49	0.27	0.15
Myanmar	0.47	0.27	0.13
Philippines	0.24	0.13	0.08
Thailand	0.43	0.41	0.31
Vietnam	0.17	0.10	0.05
South Asia			
Afghanistan	0.71	0.54	0.18
Bangladesh	0.17	0.09	0.05
India	0.36	0.20	0.12
Nepal	0.19	0.14	0.07
Pakistan	0.34	0.17	0.07
Sri Lanka	0.16	0.11	0.08

Estimation is based on the UN's medium population growth projection.
Source: Engleman and Leroy (1995)

Land degradation

A distressing picture is painted by land degradation estimates for Asia. Of its 747 million ha of crop land, 59% is said to be affected by water erosion, 30% by wind erosion, 10% by chemical erosion and 1% by physical degradation (FAO, 1995). The World Map of the Status of Human-Induced Soil Degradation, widely cited by the United Nations Environment Programme (UNEP), United Nations Development Programme (UNDP), World Resources Institute (WRI) and others put 200 million ha of crop land and 200 million ha of range land in Asia as degraded (Oldeman et al. 1990). A more recent estimate of human-induced degradation put 350 million ha damaged by the loss of topsoil, 180 million ha by fertility decline, and 44 million ha by salinisation (UNEP, 1997). Most recently, an ADB report (ADB, 1997) has been summarised (Craswell, 1998): 'the Asian Development Bank estimates that during the past 30 years one third of the agricultural land in Asia has been degraded'. Some serious land degradation has also been reported at the national level. For example, India is said to be losing some 25 billion tons of its topsoil in the runoff every year (Repetto, 1994). Discrepancies among the different estimates have raised the question about their accuracy, as did some authors (Alexandratos, 1995; Crosson, 1995). Nevertheless, even the lowest estimates are a cause for concern. Authors also generally agree that the cost for restoring degraded land would be massive.

The concern about land degradation is largely associated with agricultural productivity. In spite of the above gloomy estimates of severe land degradation, average yields of rice, wheat and maize in Asia have shown steady linear growth ($R^2 = 0.96–0.98$) for almost 40 years (Kaosa-ard and Rerkasem, 2000). The authors suggested that implications for productivity become much clearer when degradation on the more productive croplands are considered separately from those less productive. Growth in agricultural production in Asia since 1960 came largely from irrigated land and rainfed areas with good soil and reliable rainfall. Significant decline in soil fertility and available nutrients have been reported from closely monitored intensive cropping systems such as rice–rice and rice–wheat (e.g. Cassman et al. 1997; Chand and Haque, 1997). However, the effect of land degradation on crop yield in these more productive lands has yet to be demonstrated.

Much of the land degradation in Asia is in less well-endowed areas, which contribute proportionately less to national and region-wide total production. For example, upland and unfavourable rainfed lowland rice together account for only 18% of Asia's annual rice harvest although they take up 42% of planted area. Degraded land in the less favourable environment, however, is usually home to some of the region's poorest people. This includes:

- erosion-prone uplands and highlands from the Himalayan foothills of Nepal to mountainous regions of Indonesia and the Philippines
- salt-affected areas of India, Pakistan and Central Asia
- dry lands of China's eastern provinces and of Central Asia and the Loess Plateau in China.

Any yield loss due to land degradation in such places would have a direct and drastic impact on local livelihood.

Sustainable growth in crop production on previously degraded land is not impossible (TAC, 1997). Such development, however, requires a set of technological and institutional innovations very different from those that drove the green revolution. This usually takes the form of diversification into more productive cropping systems. The higher return to land and labour has enabled farmers to use less land for cropping, so allowing forests to regenerate. Thus, in northern Thailand, we have seen former opium growing villages recover from the brink of collapse in the 1970s to become prosperous and regain much of their former forest cover (Rerkasem et al. 2002). The phenomenon is spreading fast in other parts of Thailand, south-western China and Vietnam, stimulated by improved communication and transportation within each country and across the borders.

Managing soil fertility

The management success of some of Asia's problem soils is exemplified by the phenomenal yield increases on acid sulphate soils in the deepwater rice area north of Bangkok. From barely half a ton per ha about 30 years ago, good farmers in the area now average 3-4 t/ha/crop. A crop cutting survey in 2002 found fields of Prachinburi 1, an improved deepwater rice variety from the Prachinburi Rice Research Centre of the Thai Rice Research Institute, yielding up to 6 t/ha (S. Jamjod, unpublished). Judicious management of nitrogen and phosphorus fertiliser and occasional truckloads of liming materials, usually marl, are the keys to this achievement. Similar cases of success may be found in other countries, but unfortunately, not all of the soils in the region are so well managed.

About two-thirds of the agricultural land in China and almost half of the districts in India are affected by phosphorus deficiency (Stone, 1986; Desai and Ghandi, 1989). In China, it has been estimated that a yield increase of 18%, almost the same as the gains made by their famous hybrid rice technology, could be obtained by improving nutrient management (Lin and Shen, 1994). On-farm studies have shown that Asian rice farmers do not often apply even nitrogen, phosphorus and potassium fertilisers in amounts that correspond with the soil's capacity to meet the demand of the rice crop (Cassman et al. 1997). In addition to nitrogen, other nutrient elements that have been found to limit crop yield in various locations in Asia include phosphorus, potassium, sulphur, boron, manganese, copper and zinc.

While fertilisers are underused in many parts of Asia, over-fertilisation occurs in intensive vegetable production (Morris, 1997; Phupaibul et al. 2002) and high valued fruit orchards (S. Poovarodom, pers. comm.). In addition to being unnecessarily costly and therefore an inefficient form of production, this has ecological and health consequences. Where good soils commonly contain about 15 parts per million or ppm of phosphorus, extremely high levels of over 1000 ppm have been found under vegetables and fruit trees in many locations in Asia. Too much phosphorus has already brought on zinc deficiency in valuable orchards of durian and citrus in Thailand. Applying too much nitrogen and potassium is not only wasteful, but also adversely affects the environment. The excessive nitrogen and potassium are quickly washed away in the monsoon, but the process creates two other problems. First, the soil quickly becomes acidified, with pH 4 now common especially in orchards on lighter soils, and this causes other nutritional problems. Second, the unused nitrogen ends up as nitrate in underground water and streams. A survey of 3000 dug wells in Indian villages showed that about 20% of them contained nitrate levels above the WHO limit (Handa, 1983).

The boosting of rice yield in acid sulphate soil cited above exemplifies how following fertiliser and soil management recommendations can be highly effective in improving crop productivity when they are specifically tailored to overcome local constraints. Most fertiliser recommendations in Asia are,

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however, rarely as responsive to local needs and the effects of cropping intensification. Modern plant nutrition offers many tools for fertiliser management. Far from lacking technical capacity, many of the region's analytical facilities are exceptionally well equipped from decades of development assistance, but are largely underused. Without logistical support, from sampling procedures to timely interpretation and delivery of results, the services provided are of little use to farmers, farm advisors and fertiliser sales personnel. Furthermore, results of plant and soil analysis from many laboratories are rendered meaningless in the absence of stringent quality control of the analytical procedure. The cost effectiveness of the use of chemical soil and plant analysis as a tool in fertiliser management has been demonstrated with rubber and oil palm plantations in Malaysia and Indonesia. There are also indications that the practice is spreading to high valued orchards (e.g. see Poovarodom et al. 2003). The challenge remains with the management of problem soils in environments that are less favourable economically as well as physically.

One challenge is the prevalence of Asia's acidic upland soils. In addition to being largely infertile, they are also highly erosive. In South-east Asia alone, they account for 40% of the region's total land area, covering almost 200 million ha. In Laos, the proportion is two-thirds (Garrity and Augustin, 1995). Productive and sustainable crop production on such soils has been shown to be quite possible in many parts of the world. For example, much of Brazil's wheat is grown on acid soils, up to 95 percent in the state of Rio Grande do Sul (www.worldbank.org/html/cgiar/press/wheat3.html (Internet page currently unavailable)). The breeding of improved wheat varieties that are also tolerant to soil acidity and aluminium toxicity (Hede et al. 2001) is an important contribution from the International Maize and Wheat Improvement Center (CIMMYT), in collaboration with the Brazilian government. However, acid tolerant crop varieties only partially solve the problem. Throughout South America, acid tolerant crop varieties have been successfully used in conjunction with acid tolerant legume cover crops in combination with a no-tillage practice that together protect the soil surface and draw nitrogen from the atmosphere. A recent review has outlined how this has been achieved, highlighting effective collaboration between CIMMYT, national programs and farmers (Schiøler, 2002). To transfer such success to the acid upland soils of northern Thailand or Laos the program would have to be adapted to local conditions. In the meantime, there are already local traditional cropping systems that have been producing upland rice yields of 3.5–4.0 t/ha, on soils with 2 ppm of available phosphorus and a pH of 4 under upland conditions for over 100 years (Yimyam et al. 2003).

The other soil management problem in Asia is salinisation. Much of Asia's salt-affected land is at risk of further degradation from the two related processes of:

- the use of salt-laden irrigation water
- disposal of the extra salt.

Pakistan's irrigation system, for example, adds 60–65 million t of salt to the underground water supply annually (Qureshi and Barrett-Lennard, 1998). This is made up of 35–40 million t from saline canal water and 20 million t from the application of 'fresh' or better quality underground water to salt-affected land. To manage such an area an integrated approach is needed that should include introducing salt-tolerant crops, drawing down the watertable by planting deep rooted trees and the planting of halophytes such as salt bushes (Qureshi and Barrett-Lennard, 1998).

Biotic resources

Almost 60% of the world's animal and plant species are found in the six Asian countries of China, India, Indonesia, Malaysia, Philippines and Vietnam (Paine et al. 1997). In spite of its high population density and relatively little remaining forest cover, China ranks first in the northern hemisphere, and 8th in the world, in terms of biodiversity. It is endowed with 32,800 plant and 104,500 animal species (Yin Runsheng, 1997). Indonesia, with 1.7% of the world's land, contains 17% of all known species, which is more than for the whole of Africa (State Ministry of Environment and KONPHALINDO, 1995). Many are concerned about the quantitative aspect of this biodiversity, that is, the rate of species extinction, and the disappearance of well known species such as the Bengal tiger, Ayeyarwaddy dolphin, Mekong giant catfish, Siam crocodile and the Sumatra rhino. Much less frequently mentioned, however, is the fact that the region's rich biotic resources also provide one of its major sources of livelihood.

Asia is also the centre of diversity for many of the world's major crop species including banana, citrus, eggplant, ginger, mango, orchid, sugarcane and

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timber ones, as well as those of the all-important rice. The wealth of fish species of the Mekong River system alone provides an estimated income of US$1.2 billion per year to the basin's 55 million inhabitants (http://www.iucn.org). Promises and problems from the use of Asia's biotic resources are highlighted in the region's two primary staple foods, rice and fish, followed by some aspects of shifting cultivation, one of the region's traditional use of cultivated, semi-cultivated and wild species.

Fish and fishery

At the turn of the millennium, Asia accounted for more than half of the world fishery production (ICLARM, 1999). Total production of fish and shellfish has been increasing, at 4–5% per year, much faster than production growth in food crops (www.fao.org). Much of this growth is driven by aquaculture production, which has been growing at more than 10% per year. The growth has contributed towards improved nutrition as well as employment. For example, per capita consumption of aquatic product in China has increased from 2.7 to 7.3 kg in the period between 1952 and 1992, in spite of the doubling of the population to 1.2 billion (Wang, 1996, cited in Williams and Bimboa, 1998). According to the FAO, fishery employed some 25 million people in Asia (FAO, 1998). Occasional and seasonal inland fishing make significant contribution towards the livelihood of many more. There are also job opportunities in related services and transportation, and, especially for women, in aquaculture, retailing and processing.

Exceptional rewards have been reaped from judicious investment in fishery research and development. Productivity of the Nile tilapia, currently Asia's most important cultured fish, has been greatly enhanced by genetic improvement achieved by the International Centre for Living Aquatic Resources Management (ICLARM), which has made it hardier, faster growing and cheaper to produce than the wild forms. One of Asia's success stories in biotechnology research and development is a diagnostic method for viral pathogens of shrimps using a DNA probe. This has been credited with saving the country's shrimp farming more than US$1 billion since 1996. (Tanticharoen, 2000). In spite of its growing importance, fishery has received limited public support for research compared with that for crops and livestock (Williams, 1996). Conservation and sustainable management of wild fish populations and their habitats are now beginning to receive support. For example, the Mekong Wetland Biodiversity Project in Cambodia, Laos, Thailand and Vietnam, managed by the International Union for Conservation of Nature and Natural Resources (IUCN) and Mekong River Commission (MRC), expects funding of US$30 million over five years, from the Global Environment Facility (GEF), the Netherlands Government, IUCN, MRC, UNDP, and national contributions (www.iucn.org/themes/wani/).

Another major project spearheaded by ICLARM and funded by the Swedish International Development Cooperation aims to strengthen legal and institutional frameworks for wetlands management and conservation (Torell et al. 2001). Much more research is needed to improve fish culture, to lessen its environmental impact and to increase productivity. Some valuable lessons may be learned from more developed fisheries. For example, new feeding technology has brought nitrogen loading of the water down to 30 kg per 1000 kg of Norwegian salmon produced, one-sixth the rate of waste released in 1972 (Economist, 2003). The amount of feed used to grow the same amount of fish has also been greatly reduced, now being 44% less than what it was in 1972. Vaccines have reduced the use of antibiotics in Norwegian aquaculture to 0.5% of the amount used 10 years ago. Such improvements can only happen if funds are available for research and development. One major feed supplier to salmon farming in Europe, the EWOS group, has reportedly been spending more than US$16m a year on improving nutrition, feed development and fish health. The profit motive may help drive private investment in research to increase productivity.

Rigorous enforcement of environmental regulations will be necessary to minimise impacts of intensive fish culture. Another great potential lies in flood plain fishery, long associated with Asia's great rivers and its rice crop. Although historically a capture fishery only, it is now beginning to be managed. For example, to increase the number of fish captured as floods recede, deepwater rice farmers in the lower Chao Phya Plain of Thailand have begun to augment natural deep depressions in their rice fields with excavations made with heavy machinery. Some have found this to be so lucrative they have given up rice growing altogether. Understanding of various aspects of management and the whole flood-plain ecosystem by farmers should enable greater benefits to be reaped in a sustainable way with minimum impact on the environment.

Rice and its wild relatives

Compared with fish, rice in Asia has gone much further along the path of domestication. The green revolution is the living proof of the phenomenal success in the management and use of Asia's foremost biotic resource, the *Oryza* gene pool. Semi-dwarf wheat and rice were first invented in Japan (Dalrymple, 1978) as a land-saving technology (Hayami and Ruttan, 1985). The innovation was taken to the US after World War II, and later transferred to CIMMYT and IRRI, where it gave rise to the green revolution in rice and wheat. High yielding varieties of rice continue to be developed, exploiting not only local rice germ plasm but also genes from its wild relatives (e.g. see Vaughan and Morishima, 2003). Local capacity in rice research has improved significantly since the 1960s. National efforts have been greatly strengthened by international support and assistance, particularly from the International Rice Research Institute (IRRI), and programs of bilateral assistance such as with the Australian Centre for International Agricultural Research (ACIAR). However, some important questions remain on how to manage genetic diversity in the *Oryza* gene pool[1]. These are related to two issues, conservation of genetic diversity in Asia's rice fields and invasion of wild rice.

In situ conservation of diversity in local rice germ plasm

In most Asian countries local rice varieties in irrigated and favourable rainfed lowlands have been largely replaced by relatively few, improved, high-yielding varieties (HYVs)—in China and north Vietnam by hybrid rice (Kaosa-ard and Rerkasem, 2000) and, for example in Thailand, market-preferred local varieties (OAE, 1998). Asia's last remaining local rice germ plasm still preserved in situ may be found in its less favourable environments such as flood-prone areas and mountainous regions, especially in Cambodia, Laos, Myanmar and Thailand. The mountainous region of mainland South-east Asia, which extends from the Himalayan foothills through south-western China to northern Laos and Vietnam, roughly describes the centre of diversity for O. sativa. In China, where national statistics indicate complete replacement of local varieties by modern hybrids and HYVs, some 70 varieties of upland rice were still found growing in 48 villages of the Jinuo Township in Xishuangbanna prefecture of Yunnan province in the late 1990s (Fu and Chen, 1999). In Laos, where adoption of improved varieties has made significant progress in the Mekong provinces since 1999 (Lao-IRRI, 2001), local varieties still dominate in the mountainous northern provinces. For example, in Houaphanh province in the north, local varieties still accounted for 94% of the rice area in 1999 (Central Agricultural Office, 2000).

Understanding the roles that these traditional rice varieties play in the livelihood of local people on the one hand and how local management affects diversity on the other will be crucial to in situ preservation of this important biotic resource. In the flood prone region on acid sulphate soil of the Central Plain of the Chao Phya in Thailand, a survey in 2000 found 31 local rice varieties in 242 fields covering 1138 ha (Sommut, 2003). This diversity is believed to be crucial in meeting flood conditions that may vary from year to year as well as from place to place in the time of its arrival as well as water depth and duration. Farmers are said to readily recognise important agronomic characteristics such as submergence tolerance, elongation ability and adaptation to specific location and flood regime (Sommut, 2003). Diversity is a common feature of upland rice in shifting cultivation in the mountains of mainland South-east Asia. However, rice production systems even in these areas are rapidly changing. For example, many farmers in deep water areas in the flood plains of the Chao Phya in Thailand and the Mekong in Cambodia no longer grow rice when the water is deepest in the wet season. A crop is sown when the flood recedes, with or without supplementary irrigation. In the mountains, farmers with access to markets have adopted more intensive cropping systems with fruits and vegetables, which give a higher return than upland rice. However, upland rice is still grown, especially as it is now generally recognised that the yield may be doubled or tripled in rotation with heavily fertilised and clean weeded vegetables (Rerkasem et al. 2002). Upland rice varieties that are able to respond to improved conditions are now much sought after by farmers.

Genetic diversity of cultivated species such as rice is much more than just the number of named varie-

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[1] This research and others on local Thai rice at Chiang Mai University discussed in this paper are supported by the Collaborative Crop Research Program of the McKnight Foundation, the Biodiversity and Biotechnology Interface Program of the USAID and Thailand Research Fund.

ties, even when weighted by the area or frequency grown. Insight into the structure of diversity, and how farmers' management affects it, is important to the conservation and utilisation of local germplasms. A popular wetland variety from Samneua district of Houaphanh province of Laos known locally as Kain-oyleung was examined for variation in 23 characteristics of IRRI's Standard Evaluation System for Rice (SESR) (Mounmeuangxam, 2003). The general appearance of the rice was largely uniform with small round grain (3.5 x 6.3 cm) of 25 mg each and a plant height of about 120 cm. However, variations within and between farmers' seedlots were found in many of the characters including awning (length and colour as well as presence or absence) and pigmentation of the ligule, lemma, palea, apiculus and seedcoat. The same study found even greater diversity in upland rice. Such within and between seedlots variations have also been found in popular local varieties from northern Thailand (S. Meesin, unpublished). For example, some 40 different versions have been identified in Muey Nong, a local variety valued for its resistance to gall midge, a serious insect pest. Research at Chiang Mai University now begins to find potentially useful characteristics in these local varieties, such as acid tolerance (N. Pattarakul, unpublished) and high grain-iron concentration (Prom-u-thai and Rerkasem, 2001). Preliminary studies have suggested that these potentially useful traits may also be present in varying frequencies in different seedlots. Therefore, it may be important that this is taken into account when evaluating useful traits of local germ plasm. Genetic variation will also be influenced by farmers' attempts to improve their seed stock by panicle selection, a practice common among those growing traditional varieties.

Invasion of wild rice

Throughout monsoonal Asia, wild rice has always grown close to crop rice and is an important source of genetic diversity for crop rice. Some wild rice from Thailand has been found to be abundant in endophytic nitrogen fixing bacteria (C. Koomnok, unpublished). Many have expressed concerns about the disappearance of wild rice from the rice ecosystems (e.g. Morishima et al. 1980; Chitrakorn, 1995). However, wild rice populations are still common in major rice growing regions in Thailand, Laos and Cambodia (B. Rerkasem, unpublished). Wild rice species may be found in man-made habitats including irrigation canals, waterways, farm ditches, roadside ditches and abandoned rice fields, as well as in their natural habitats of annual and perennial wetlands. In Thailand, wild rice rarely occurs in rice fields of the north and north-east. However, invasive wild rice (Figure 1) has been found in several provinces of the Central Plain (Figure 2). The invasion was associated with wet-seeded, irrigated, multiple cropped HYVs as well as dry-seeded, single crop rainfed and deepwater rice, growing either traditional or improved varieties.

Figure 1. Invasive wild rice (top right with awn) in a rice field (crop rice panicles lower left) in the Central Plain of Thailand. (Photo by Chanya Maneechote).

A survey of the dry season crop of 2002/03 in two villages in Kanchanaburi in Thailand found invasion in more than 90% of the fields (A. Unthong, A. Paokrueng and M. Kaosa-ard, unpublished). About half of the fields were rated as having an infestation above 40% (infestation defined as % of panicles identified as wild rice by the presence of awn or shattering of the entire panicle by the time of rice crop maturity). Rice yield decreased linearly with increasing infestation, to about half maximum yield with 40% infestation (Figure 3). Infestation of individual fields has been observed to increase extremely rapidly, going from mild (5–15%) to severe (>60%) within 2–3 crops in this rice–rice area in Kanchanaburi (C. Maneechote, pers. comm.). The infested area also appeared to be expanding, for example, southwards from Kanchanaburi into Ratchaburi, by 2003. In some areas, including Kanchanaburi, the invasion is easily recognised in wild rice plants that were 20–30 cm taller especially after panicle emergence and awned spikelets. In other areas, the invasive wild rice has mimicked the crop

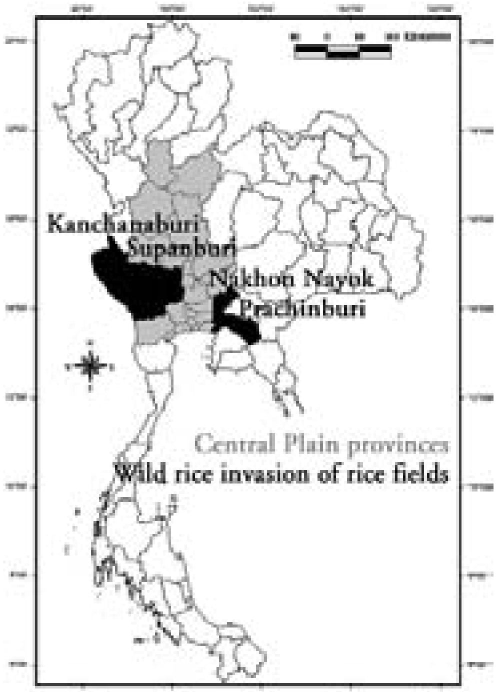

Figure 2. Provinces with major wild rice invasion in the Central Plain of Thailand.

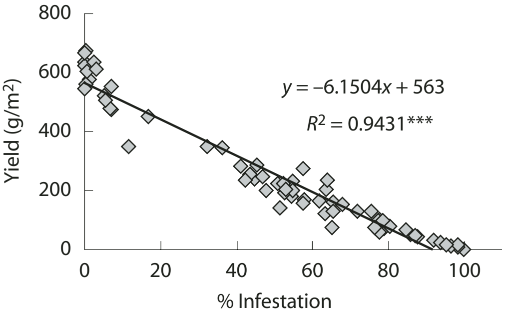

Figure 3. Yield decline in farmers' rice crop (cv. Supanburi 1, an HYV) with increasing infestation of wild rice (infestation defined as % of total panicles identified as wild rice by presence of awn or shattering of the entire panicle by the time of rice crop maturity) in two villages in Kanchanaburi province, dry season 1002/03. (*** $P < 0.001$)
Source: S. Jamjod and C. Maneechote, unpublished.

rice so perfectly the invasion seemed to have crept upon the farmers unawares. After appearing quite productive early in the season, the crop could not be harvested because the spikelets suddenly became khao deed (jumping away rice), that is, panicles shattered severely and the awnless spikelets scattered before they could be harvested. The typical wild rice characteristics of pigmented pericarp or crumbly endosperm confirmed that the original improved variety or even an HYV (e.g. Supanburi 1) had somehow been 'invaded' (S. Jamjod, pers. comm.).

Experimental crosses have shown wild rice from the Central Plain to be highly inter-fertile with Thailand's crop rice varieties, HYVs as well as local varieties (S. Jamjod and W. Sommut, pers. comm.). It is most likely that introgression, that is, hybridisation between *O. sativa* and *O. rufipogon*, is involved in the invasion. Studies at Chiang Mai University in collaboration with Washington University in St Louis are attempting to verify this by methods that include molecular analysis. In the meantime, farmers are already feeling direct adverse effects of the invasion in yield losses and increased cost of weed control. Some have also complained of price depression at the mill due to elevated percentages of grains with pigmented pericarp or 'red rice'. Preliminary participatory work of the Department of Agriculture is yielding promising results and indicates that the problem could be solved through crop management, with a focus on integrated weed control. Key elements in the integrated control of wild rice so far identified include using clean seed, reducing the wild rice seed bank in the soil and decreasing establishment of wild rice seedlings through land preparation and other weed control measures including strategic use of herbicides (C. Maneechote, unpublished). Assessment of possible adverse effects on the integrity of the local *Oryza* gene pool will, however, require in depth understanding of gene flows and associated population dynamics and evolutionary processes. An important question is how will the introduction of genetically modified rice affect this important gene pool. It might be imagined that introgression with herbicide resistant rice would create some super weeds that are difficult to control. How other transferred genes, for example, the insecticidal genes such as those from Bt or other pest resistant rice, will affect wild and cultivated *Oryza* populations as well as whole communities of beneficial insects and pests associated with them is much more complex, requiring in depth studies.

Shifting cultivation is one of Asia's traditional land use systems and one that has historically cultivated and conserved semi-domesticated and wild plant species along with various traditional crops. Studies during the 1960s and 1970s showed shifting cultivation to be productive and sustainable when there was enough land to allow rotations of 10–20 years cycles (Kunstadter, 1978; Nakano, 1978, 1980). However, the luxury of such long rotations has become increasingly unaffordable in most countries because of economic and political necessity. The decline in shifting cultivation means not only the loss of valuable biotic resources but also useful and potentially useful local knowledge associated with them. Understanding some of these land-use systems before they disappear may provide solutions to people's livelihood in these difficult areas.

For example, local upland rice varieties capable of yielding up to 4 t/ha on an acid (pH 4) infertile (2 ppm phosphorus by Bray II) soil have been found at a small village of Haui Tee Cha (19° 78' N, 93° 84' E), about 250 km south-west of Chiang Mai in Thailand on the Myanmar border (Yimyam et al. 2003). The study also showed that acid-tolerant rice varieties only partially solved the poor-soil problem. The high rice yields were associated with dense stands of pada (*Macaranga denticulata* (Bl.) Muell. Arg.), a fallow enriching tree in seven year rotation. The tree was found to be associated with mycorrhizal fungi. The symbiosis accumulates much more nutrients than other native vegetation. The local arbuscular mycorrhizal fungi population associated with the pada tree has been found to be exceptionally diverse, and some 30 species and six genera have so far been identified (Youpensuk et al. in press).

Water resources

With its mighty rivers annually fed by plentiful rainfall in many regions, the absolute magnitude of Asia's renewable water resource is considerable. Divided among its huge and rapidly growing population, however, the picture of water availability in Asia changes dramatically. In 1992 per capita water availability in Asia was 3240 m^3, one-third of the figure for 1950 (WRI, 1994). A threshold level for extreme water scarcity of 1000 m^3 per capita and scarcity between 1000 and 1700 m^3 per capita have been proposed by Falkenmark et al. (1989). On this basis, the countries that were already facing extreme scarcity by the turn of the millennium included Singapore, Tajikistan and Turkmenistan (WRI, 1998). Countries in or near the threshold of scarcity included South Korea, Thailand, Pakistan and India. With uneven distribution within countries, some areas in these countries and even those above the 1700 m^3 per capita such as China are already experiencing extreme water scarcity. Adding to the scarcity picture is dry season shortage that may last 5–6 months each year in some areas, for example, there is a single annual monsoon in major sections of Bangladesh, India, Laos, Thailand and Vietnam.

In many countries, exploitation of the underground water table has been supplemented by water supplies since the 1970s. Ground water supplies more than 30% of the annual usage in Bangladesh, India and Pakistan. Pumping the underground water table is estimated to supply some 80% of the water that irrigates Indian's green revolution. Overexploiting it has caused many problems. The water table in the Gangetic Plains has been falling by 30–40 cm each year (Chand and Haque, 1997). The Cang Zhou area in Hebei province of China has experienced a 70 m fall in the water table over a period of 10 years (Zhang and Zhang, 1995). In coastal areas of Gujarat and Tamil Nadu it has led to seepage of seawater into the aquifer (Repetto, 1994), and this has also happened in southern coastal areas in Vietnam.

In addition to the quantity of water, Asia is becoming increasingly concerned about water quality. Pollution of the source of domestic supply increases the cost of water treatments. In many places, including China, it has become an important constraint to growth of inland aquaculture.

The problem with the water resource is that it is related to the traditional treatment of water as a common resource. Conflicts arise out of the many users and stakeholders competing for diminishing supply, while others may freely contribute to its pollution with impunity. Until recently, the source of conflicts has been competition between alternative economic uses, between upstream and downstream, different economic sectors, and rural and urban areas. Growing demand for environmental uses and conservation has added to the complexity with new claimants who can often be the most vociferous. The sharing of common rivers by several countries brings forth another level of conflict. The final section of this paper will highlight problems associated with countries sharing a river like the Mekong and examine issues related to the management of increasingly scarce water resources.

Sharing the Mekong

The Mekong, originating in China, covers a distance of 4880 km before it reaches the sea in Vietnam. The total area of the Mekong watershed is estimated at almost 800,000 km^2, with average annual flow of 475,000 million m^3. Its riparian or basin countries include China, Myanmar, Thailand, Laos, Cambodia and Vietnam. China alone accounts for almost half of its length, where the river is called the Lancang, and 22% of the watershed area. Laos is the country with the largest share of the watershed (25%) and an average flow rate (5270 m^3/sec) double those in the Yunnan province of China, and in Thailand and Cambodia. The river is fed largely by the south-easterly monsoon, with a period of heavy rain and flooding from May to October.

The problem of sharing the Mekong is related to intra-basin uses and intra-basin diversion, which may directly affect the river flow rates, and the various ecosystems along its route. By the year 2000 the Yunnan province of China had completed two hydroelectric dams on its upper section of the river, was in the process of building two more, and had nine more under various stages of feasibility and preliminary study (ADB, 2000, cited by Kaosa-ard et al. 2001). Laos also depends on the Mekong to double its irrigation capacity from the current 100,000 ha to 200,000 ha as well as to produce electricity for export to Thailand and Vietnam. The Lao PDR has completed several hydroelectric dams on the Mekong's major tributaries, for example, Nam Ngum, Thuen-Hinboun, Houay Ho and Nam Leuk. The relatively dry Thailand, on the other hand, is looking to the Mekong to water its driest region of the north-east. The Kong-Chi-Moon Project aims to develop irrigation for 800,000 ha by placing at least 14 dams on the Chi and the Moon, tributaries of the Mekong, and increasing the flow of the Chi and Moon by supplying them with water pumped from the Mekong (Kaosa-ard et al. 2001). Concerns have also been expressed about the blasting of the river rapids to deepen the river channel in efforts to improve river transport between China and downstream countries.

Most vulnerable to adverse impacts of these exploitations of the Mekong are downstream users and ecosystems, especially in Cambodia and Vietnam. Cambodia's Tonle Sap, which covers some 2500 km^2, and its associated wetlands are one of the world's unique ecosystems as well as the major source of local livelihood, from both fishery and crop production. Major changes in quality and quantity of the river flow can wreak havoc on the whole ecosystem. For example, it has been estimated that a loss of 1 m in water depth will decrease the area of wetlands by 2000 km^2 (TDRI, 1998). Similarly, the 39,000 km^2 Mekong Delta of Vietnam produces 45% of the country's annual rice crop. One major problem in the Delta is the incursion of seawater in the dry season, which causes cropland to be affected by too much salt as well as acidification. Pumping of underground water is one cause, but diminished dry season flow of the Mekong also contributes significantly to the problem.

To deal with cross-border aspects of the problem, Cambodia, Laos, Thailand and Vietnam, signed a cooperative agreement in 1995. In the 'Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin', the countries pledge to consult each other about usage and diversion of water from the Mekong as well as from its tributaries. The impact of such an agreement, however, is very much weakened by the notable absence of upstream countries, in particular China.

Water resource management

Supply management of water in areas with seasonal rainfalls common in many parts of Asia, has focused on providing irrigation water for dry season cropping. There is a long history of irrigation by stream diversion with some systems in China being said to predate the Tang dynasty. Other systems may not go back that far, but many are more than 700 years old. One in the Chiang Mai Valley in Thailand has been found, by carbon dating, to be more than 1200 years old. Dam building, funded mainly by the state to store water and generate hydroelectricity, became highly fashionable in the 1960s. In many countries almost all of the rivers that can be have now been dammed. The building of dams has also been facing increasingly formidable opposition, even in countries well endowed with water resources such as Laos. The opposition is often strongly supported by well-funded and professionally organised international anti-dam movements. Some of the opposition demand transparency, justice for those affected by flooding and other changes as well as sound environmental impact assessment. Others are opposed to dams in principle. Many planned dams have been held up for decades. There have even been campaigns to open dams that are already in operation, with varying degrees of success. By necessity, national policy processes for water resource management has therefore turned towards demand management.

Agriculture is the main user of water in most countries in Asia, accounting for 75–85% of the annual water use in countries from Turkey to Vietnam. Major increases in demand have been predicted for other usage including domestic supply, industry, for generating electricity (called non-consumptive use, because the water can be reused) and to maintain ecological balances (mainly against incursion of seawater). For example, one estimate puts demand for water for domestic use in Thailand's Chao Phya basin, which includes Bangkok, in 2026 at 2.5 times that in 1996 and for industrial use at 1.5 times (Binnie and Partners Ltd., 1997). However, the actual usage in these sectors are small relative to agricultural use, and the projected increases have had little impact on the share of water among different sectors. The growing problem of water scarcity is nevertheless highlighted by local disputes over water that have been regularly erupting, for example, in Thailand in recent years (Kaosa-ard et al. 2001).

Conflicts between upstream and downstream water users are probably as old as irrigation. Traditional irrigation systems have developed regulations and laws to deal with water disputes. For example, according to the 13th century law of King Mengrai of Chiang Mai anyone caught taking water out of turn could be put to death (Nimmanhaeminde, 1976). Although the punishment has become less draconian—anybody found stealing water in the 1970s would be fined only 25–50 *Baht* (US$1.25–2.5, one half to one day's wage)—such mechanisms to handle conflicts continue to be effective within small communities and irrigation systems (Sektheera and Thodey, 1975). However, they have become increasingly unable to cope with complex disputes involving tens of thousands of hectares of irrigated land and new cropping systems that have greatly increased demand for water in the dry season. There are also many more and newer types of water users. The new users, farmers who have moved from other areas and operators of tourist resorts, are generally unfamiliar with local rules and regulations. There are some encouraging signs that many of the different groups of water users, supported by NGOs and government institutions, are beginning to get together to resolve their differences. Unfortunately, the conflict is sometimes further inflamed by different groups of water users being incited to more confrontation by NGOs with opposing agenda, as is the case in Mae Klang, south of Chiang Mai (Kaosa-ard et al. 2001). Communal regulations are also unable to deal with factories that discharge their waste into the river. Well-intentioned development schemes of the government and non-government bodies that have not considered their own impact sufficiently widely have added to the problem.

That conflicts occur among water users in Thailand is not surprising. At the heart of the problem is a relative scarcity of its water resources and a poorly developed legal system covering water use. Water is a common good. There is currently no legal protection for water users' rights, no framework to settle conflicts fairly among users, or a way to compensate those whose traditional rights to water, in quality or quantity, have been infringed (Kaosa-ard et al. 2001). The authors went on to criticise the water resource law currently being drafted as potentially ineffective for being too limited in its scope, especially in allowing for mechanisms needed to find solutions to local conflicts, especially participation from water users. Among Mekong countries, Laos and Vietnam probably have the most comprehensive laws on water use. These two countries, however, are extremely well endowed with water, especially Laos. The effectiveness of their water laws can only be tested during times or in places of water scarcity.

Conclusion

Asia's clever use of its limited land resource and rich biotic resource is embodied and exemplified by its introducing a land saving technology that gave birth to the first semi-dwarf wheat and rice in Japan in the early 1900s. This was later translated into the current green revolution. The future livelihood and well being of the people of Asia will not depend on how much water, land and biota we possess, but on how well they are used. The better we get to understand the local plants, fish, animals, microbes, soil, water and people the greater will be the opportunities to make the best use of these resources and to preserve and enrich them for the benefit of future generations. Sustainable management of Asia's natural resources depends on public policies as well as new information to be generated through research. To prevent local conflicts over increasingly scarce water resources, especially during the dry months, will require national legislation that allows for local participation in conflict resolution. To manage the larger watershed, for example, the Mekong Basin, effective collaboration between countries is essential. For this to be effective, reliable data on, for example, the effects on downstream ecosystems of soil erosion in the upstream watersheds or of blasting up-river rapids for shipping is needed. Lessons from Latin America show the potential for improving productivity of cropping systems on acid upland soils. But the technology cannot be simply transferred; understanding of local conditions and potential is needed before real improvement can be made. Better understanding of Asia's rich biotic resource, including rice and fish, may bring opportunities to increase productivity as well as to forestall potential problems that may rise out of continually changing crop management practices, including introduction of genetically modified varieties.

Abbreviations

ACIAR	Australian Centre for International Agricultural Research
CIMMYT	International Maize and Wheat Improvement Centre
GEF	Global Environment Facility
IRRI	International Rice Research Institute
IUCN	International Union for Conservation of Nature and Natural Resources
MRC	Mekong River Commission
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
WHO	World Health Organization
WRI	World Resources Institute

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Premises and realities of agricultural benefits from large dams

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Abstract

Feasibility studies of large dams attempt to optimise the sum of benefits accrued from the 'best management options' for reservoirs. The 'best management' is a result of a comprehensive analysis of economic, social and environmental benefits from power generation, agricultural production, flood and erosion control, water supply, river navigation, nature conservation, and seawater intrusion control. Agricultural benefits are estimated on the basis of increased availability of irrigation water in the dry season, reduced flooding of farmland, and diminished soil and riverbank erosion. The assumptions made during feasibility assessments of agricultural economic and social benefits may, however, never be realised. Downstream effects of large dams, suggest that farmers may not receive the benefits cited in the feasibility studies. On the contrary, increased hardship for many farmers is often the reality. In some cases, the river flow in the dry season has been reduced, and erosion and flooding of agricultural land have become more severe in both the wet and dry seasons. The disparity between plans and reality can be attributed to how dams operate. Studies on the causes of environmental damage and effects of different operation schemes are needed to prepare more realistic project plans and environmental impact assessments. The development goals for large dams can only be reached if the 'best management option' outlined in the feasibility studies are observed.

Introduction

FEASIBILITY studies of large dams in developing countries are commonly financed in whole or in part by public funds through development aid agencies and development banks. Loans for dams and irrigation structures may also be partially obtained from similar sources. The primary objective of public funding institutions is invariably to contribute towards poverty reduction and social development.

The collective development benefits of dams described in feasibility studies are dependent on a set of premises for the operation of dams. The reality of operations, however, appears to differ from the premises in several cases. The World Commission on Dams (WCD, 2000) documented widespread discrepancies between plans and performance of dams. Some downstream small-scale farmers appear to suffer, rather than benefit, from dam construction. Promised mitigation benefits also seem to be limited or even unrealised.

The aim of this presentation is to draw attention to the issue of deviating premises and realities in the operation of large dams with particular reference to unrealised benefits and substantial damage experienced by downstream peasant families.

Assessment of benefits

Agricultural benefits from dams—whether primary or secondary benefits—are assessed according to

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available land for irrigation, increased availability of water in the dry season and reduced flooding in the wet season (Figure 1). Topographic and soil maps show which land is available for irrigation. For most countries, topographic and soil data are generally accurate and reliable. Hydrology regimes before and after dam construction are provided through flow modelling by dam, hydropower and hydrology engineers. Using results from these models, agronomists convert figures for additional water available in the dry season into amounts of potential crops grown on available land for irrigation. Hydrological data are also used to assess reductions in flood and erosion damage. Estimated hydrology regimes after dam construction, compared to before construction, are normally characterised by:

- higher flow during the dry season
- lower flow during the wet season
- reduced peak flows (severe floods) during the wet season.

These three changes in hydrology constitute the main benefits for downstream dwellers as stated in both feasibility studies and environmental impact assessments. Regulated water flow is anticipated to lead to:

- less soil and river bank erosion
- less flooding of agricultural land
- less seawater intrusion in coastal areas
- better navigation on lowland rivers
- more stable water supply.

In feasibility studies, these benefits are portrayed as contributing to economic and social growth, and reducing poverty.

The negative consequences of large dams constitutes sensitive information in some countries. Disclosing negative effects and failing to operate dams in accordance with plans or conditions set by funding agencies may be seen as a disloyal criticism of government institutions. Collection and release of statistical information on downstream effects of large dams is therefore limited in some countries. The World Commission on Dams argued that downstream effects of large dams are relatively poorly understood. It should come as no surprise, then, that environmental impact assessments of proposed dams have often been no better than ‘educated guesswork’. Assessment teams may never have had the opportunity to study the environmental impacts of existing, comparable dams in sufficient detail. Environmental impact teams are sometimes unhappy with the amount of area-specific information that is made available to them.

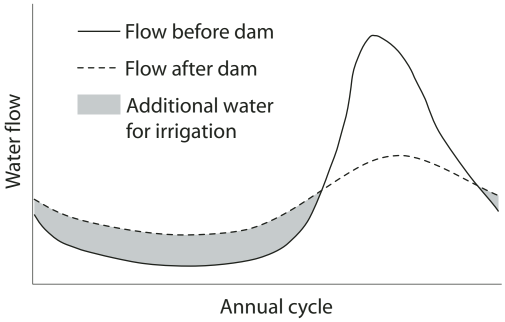

Figure 1. Schematic example of hydrological regimes before and after dam construction.

Recent studies of downstream impacts

Recent studies of downstream effects of dams have documented severe environmental, economic and social damage to downstream rural people (see e.g. Baird et al. 2002; CRES, 2001; Permpongsacharoen, 2000; Permpongsacharoen, 2002). People living below large dams appear generally unhappy about deterioration of their livelihoods, which is primarily due to changes in river hydrology. Their main problems appear to be:

- a dramatic increase in riverbank erosion
- less water in the dry season
- unpredictable floods in all seasons
- health problems associated with water contamination.

In sum, the negative effects have led to economic and psychological distress among poor and vulnerable people. The reported problems contradict statements commonly made in feasibility studies as well as in environmental impact assessments. It is disheartening for me as a former member of various feasibility and impact teams to observe the level of unpredicted suffering that occurs among downstream peasants. Below are some examples of apparently unforeseen negative consequences of dams that have been reported lately in South-east Asia.

Erosion and landslides

Water flow in downstream areas has become substantially more irregular due to rapid changes in discharge from reservoirs. Sudden changes in water flow on a diurnal basis in both the dry and the wet season are considered to be the reason for serious erosion and landslides along downstream riverbanks. After dam constructions, erosion and collapse of riverbanks have been reported along rivers that have been stable for decades. Some landslides have been extremely serious with loss of farmland, houses, and human lives. For instance, loss of land and houses in Thailand and Laos have been partly attributed to the Manwan Dam in China (Permpongsacharoen, 2002). Substantial parts of residential and agricultural areas below the Hoa Binh Dam (Vietnam) have also been eroded by the river. According to residents, riverbank erosion became serious about one year after the dam started its operation. At present, landslides occur irregularly below Hoa Binh. Although erosion is generally worse in the wet season, it is also a problem in the dry season.

Water flow and floods

Residents living downstream from the Yali Falls Dam (Vietnam) have reported that the river flow is reduced in the dry season. Floods during the rainy season have also occasionally become more severe (e.g. CRES, 2001; Baird et al. 2002; AMRC, 2003). The changes in hydrological regimes have led to negative environmental conditions. Hydrological regime changes include:

- water being released only during peak electrical demand
- no water being released from reservoirs during the night
- the downstream flow suddenly, and without warning, increasing in the dry season.

The water below the Yali Falls Dam has become more turbid after dam construction. Due to the low flow in the dry season, trash, leaves and dead animals are no longer carried away by the river. Organic material and dead animals decompose in stagnant water, and the river becomes seriously eutrophic and contaminated.

Health impacts

The deterioration in water quality has influenced the daily life of people below the Yali Falls Dam, especially by causing health problems (CRES, 2001; Baird et al. 2002). People become itchy when using water in the river for bathing and washing and when crossing the river barefoot. In addition, people appear to be now suffering more from diarrhoea and malaria.

Economic and psychological distress

Considerable loss of cultivated land below the Hoa Binh Dam has led to insufficient farmland in some villages. After landslides and soil erosion, people have had to leave their area to find jobs elsewhere. As a consequence, family life has becomes difficult and dependent on occasional employment—mostly temporary jobs with low pay. In some villages, only old people, women and children remain at home. Loss of boats and fishing equipment has also been reported during sudden and unexpected floods caused by the operation of dams.

In preparing for dam construction, governments often develop programs to encouraged riverside communities to engage in cash crop cultivation. Such endeavours appear to have had little effect partly because of organisational and transport problems. Slash-and-burn agriculture on hill slopes is often the only alternative for farmers.

People in downstream areas often live in a state of worry. Some families have had to move their houses several times. The possibility of new landslides is of great concern for many of the affected people.

People living near rivers often have to cross them to get to their farmland. Irregular changes of flow in both the dry and wet season make crossing difficult and sometimes hazardous. People may be afraid to cross the river by boat in the flood season due to the risk of sudden water release from upstream dams. In the dry season, the water level is too low to use boats, so people cross on foot. The walk may be risky since sudden water releases may occur. Small children are particularly vulnerable.

Mitigation

Downstream residents appear generally dissatisfied with the level of support from government agencies to mitigate environmental, economic and social damage of dam construction. Plans may be fine, reality is often not.

Technical mitigation measures to reduce riverbank erosion seems to have had limited success. According to local engineers, such measures cannot totally solve the problem.

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Discrepancies between premises and realities

Feasibility studies of dam projects commonly argue that increased flow during the dry season and reduced flow during the wet will constitute both economic and environmental benefits. Negative effects experienced by downstream farmers lead to the following observations:

- Feasibility studies are based on monthly flow values, which do not show daily or hourly fluctuations (Figure 2).
- A regulated river, with daily fluctuations in water flow ranging from zero to medium flood levels (Figure 2), may cause substantially more riverbank erosion than an unregulated river.
- Increased erosion and landslides during both the dry and wet season can cause substantial harm to downstream agriculture.
- Daily fluctuations in water flow make it difficult to use the water for irrigation.
- Daily drying of riverbeds causes death of aquatic life and unpleasant odours.
- Occurrence of full reservoir and concomitant heavy rainfall in the catchment may require rapid release of water above normal pre-dam peak flows. This may lead to serious erosion and property damage.
- Proper mitigation efforts are difficult to implement.

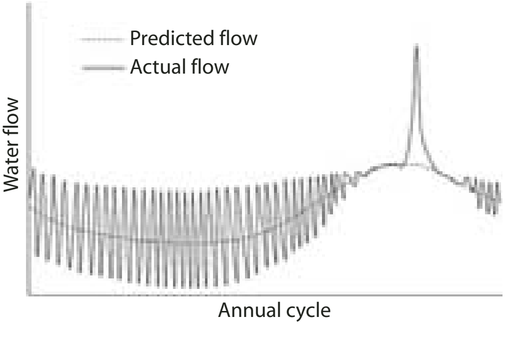

Figure 2. Schematic illustration of predicted and actual flow below a dam. The peak during the rainy season indicates a severe rainstorm causing gates to be opened. The sketch indicates weekly fluctuations for illustrative purpose only; actual flow may have a daily fluctuation pattern.

Impact assessments and environmental information

Environmental impact assessment reports may be criticised for not predicting environmental damage as indicated above. Reasons why assessment teams make inadequate predictions include:

- studies being done by consulting firms with a primary interest in dam engineering
- studies being done by foreign firms with limited local knowledge
- studies having a low budget and short deadlines such that team members do not have sufficient opportunity to study relevant local experiences
- environmental impact assessments and environmental monitoring data from earlier projects often being kept secret by regional and national government agencies.

Our understanding of downstream environmental impacts as a function of dam operation schemes is clearly insufficient. Countries seeking public funds for dam development should establish a national information database clearly describing cause and effect relationships.

Existing reports on downstream effects on people and land may not yet provide the documentation needed to have a practical effect on dam proposals and environmental assessments. Systematic studies covering different technical and natural conditions are needed. Empirical studies should be designed and presented in a way that they will be readily available for and easily applicable to feasibility studies and environmental impact assessments. Feasibility reports must include water flow predictions with sufficient time resolution that reliable forecasting and impact assessments are made possible.

Conclusions

Agronomic benefits and environmental impacts outlined in feasibility studies of dams may be based on theoretical premises. The use of monthly or weekly average flow hides the dramatic erosion effects of frequent and rapid changes in water released from dams. Feasibility studies appear to be based on unrealistic, well-balanced, multipurpose priority settings for dam operation, whereas actual operations are largely governed by power generation priorities. Empirical studies of relationships between dam operation schemes and downstream damage are needed to improve the quality of feasibility studies and environmental impact assessments.

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Using GIS technology to develop crop water availability maps for Lao PDR

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Abstract

Crop production in Laos is affected by adverse weather conditions. However, accurate weather conditions are not comprehensively documented, and this hinders crop research and production. The particular problems identified for lowland rice are drought in rainfed lowlands in central-southern Laos, and low temperatures during the dry season in the irrigated lowlands of Northern Laos. We have developed gridded surfaces (maps) for the mean monthly minimum and maximum temperatures for the whole country using GIS. We have also completed time-series gridded maps of monthly and weekly rainfall for the country for the 1994–99 period. These were developed from rainfall data from 26 meteorological stations and five hydrological stations in Laos, and 18 meteorological stations in Thailand. Potential evapotranspiration was calculated using the Penman–Monteith formula for 14 stations when daily time series data for the required input variables, especially sunshine hours, were available. Interpolated surfaces were generated for mean weekly potential evapotranspiration. The rainfall and potential evapotranspiration surfaces are used for developing maps of water availability periods for crops. While these climatic analyses provide a useful guideline for determining the crop growing period, annual rainfall varies greatly and variations in soil characteristics and toposequence position cause large spatial variation in water availability. Simulation results using a rice-growth model show a large variation in water availability that would cause large yearly and spatial variation in grain yield. Thus greater emphasis needs to be made for variation in water availability within microenvironments.

Introduction

CLIMATIC factors affect crop yield and determine areas where each crop can grow. For example, in Laos, rice yield is affected by drought and flood in rainfed lowlands in the wet season. Low temperatures in the dry season affect it in the high altitude irrigated areas in Northern Laos. Understanding these climatic constraints and documenting seasonal weather patterns would help those involved in developing crop industries.

Present research indicates that the most important climatic constraint for rice cultivation in high altitude areas is the low temperature, which reduces crop establishment; therefore, temperature maps were developed to identify areas of high risk for the dry season (November–April) irrigated rice. The maps and accompanying document have been published recently by NAFRI, Laos (Inthavong et al. 2001a).

In the rainfed lowlands, drought and flood problems are related to water availability in the field and hence the primary climatic factor is rainfall. However, water availability in the field at any time is also

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affected by topography, soil type, and water loss from the field. The main component of field-level water loss is potential evapotranspiration (PET). Rainfall and PET records in Laos are limited (Khounphonh et al. 2001) and this makes it difficult to develop maps for the whole country. This paper describes the processes of map development for these factors when data are limited, and some results on rainfed lowland rice production in Laos. One of the key factors is how long water is available in the field. FAO has developed a procedure to measure this, which we have used previously (Kam et al. 1999; Inthavong et al. 2001b). This is revisited with the new information on rainfall and PET for the country, particularly to determine when the wet season ends.

Water availability in the field is also strongly affected by deep percolation and lateral water movement (seepage), and the effects of these factors were demonstrated using the RLRice model (Fukai et al. 2002). The model was used for southern Lao locations to indicate how seasonal variation in rainfall and soil and topographical factors determine water availability particularly towards the end of season.

Materials and methods

Rainfall distribution for Laos

Rainfall distribution was analysed for Laos from the beginning of the year 2002 and is now completed. One of the problems was that rainfall data were available for different durations. Continuous measurements were available from stations that started measuring rainfall in 1950 but most stations did not start until the 1990s. Some had data sets of 10 years, while others had ones of eight, six or four years only. There were too few meteorological stations with long-term data for interpolation and mapping. Comparison of long-term mean monthly rainfall records (>15 years) with progressively shorter-term means has shown that generally the short-term means tend to be higher than the long-term ones. We determined that the shortest acceptable period, before the correlation coefficients between the long-term and shorter-term means dropped substantially, is six years. Thus it was decided to compromise and include 26 meteorological and five hydrological stations that have six years continuous data (1994–99) in the interpolation.

In addition, we included the station Bokeo, although it had only four years data, because of the paucity of stations in the north-western part. We also included rainfall data from 18 stations in north and North-east Thailand (locations indicated in Figure 1) to enable interpolation beyond the national boundary. This is particularly important for the central-southern part of Laos, which is narrow.

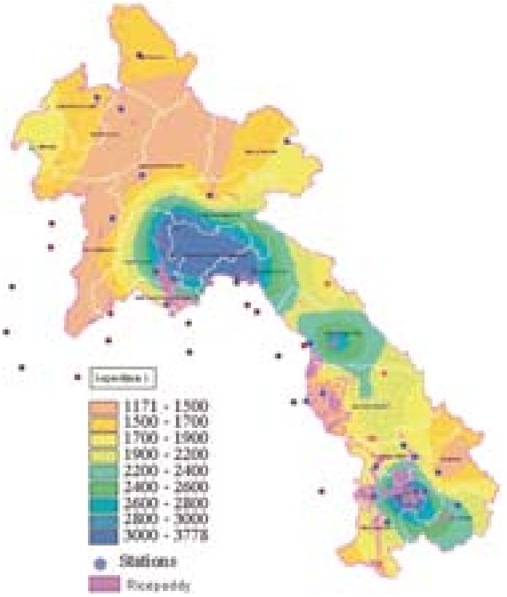

Figure 1. Mean annual rainfall map for Laos.

Spatial interpolation using variography and kriging (Goovaerts, 1997) was carried out on the point-based mean annual as well as mean weekly rainfall data from a total of 49 stations to generate gridded rainfall surfaces at 5 km resolution. Figure 1 shows the mean annual rainfall surface for Laos, while Figure 2 shows four of the 52 weekly rainfall surfaces, classified into discrete intervals.

PET estimation

Potential evapotranspiration was calculated from the Penman–Monteith equation (Grayson et al. 1997).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273}\right)U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34J_2)}$$

Where,

ET_0 = reference crop evapotranspiration [mm/day],

R_n = net radiation at crop surface

[MJ/m^2/day],
G = soil heat flux [MJ/m^2/day],
T = average daytime temperature [°C],
U_2 = average daytime wind speed measured at 2 m height [m/sec],
$(e_a - e_d)$ = vapour pressure deficit [kPa],
Δ = slope of vapour pressure curve [kPa/°C],
γ = psychrometric constant (= 0.66) [kPa/°C],
900 = conversion factor

Solar radiation measurements were not available for most locations and sunshine hours were used to estimate solar radiation (Grayson et al. 1997).

$$R_n = R_{ns} - R_{nl}$$

Where, R_{ns} = net incoming short wave radiation [MJ/m^2/day] and
R_{nl} = net outgoing long wave radiation [MJ/m^2/day]

$$R_{ns} = (1 - \propto) \times R_s$$

where, R_s = incoming solar radiation [MJ/m^2/day],
$\propto$ = albedo (0.23 as an overall average for grass, 0.05 for a water surface)

$$R_{nl} = f \times 2.45 \times 10^{-9}(0.34 - 0.14\sqrt{e_a})(T_{kx}^4 + T_{kn}^4)$$

Where, f = adjustment for cloud cover
= 0.1 + 0.9(n/N),
e_a = saturation vapour pressure [kPa],
T_{kx} = maximum day temperature [K],
T_{kn} = minimum day temperature [K]

$$f = 0.1 + 0.9\left(\frac{n}{N}\right)$$

where, n = sunshine hours per day [hrs]
N = total day length [hrs]

$$e_a = 0.611 \times \exp\left(\frac{17.27T}{T + 237.3}\right)$$

where, T = temperature in °C

Data for PET estimations are available for only 14 stations for the entire country. However, we considered that this number would suffice, as the variations in PET values, both inter-annual in time, and across space, are small (coefficients of variation not exceeding 30% throughout the year for most of the stations, except Soukhouma and Hatdockeo), in comparison with variations in rainfall amounts (coefficients of variation are around 100% during the rainy season and increase to 250–500% in the dry season). Spatial interpolation using the radial basis function was carried out on the estimated weekly PET values for the 14 Lao stations to generate 52 gridded PET surfaces at similar resolution as the rainfall surfaces.

Length of growing period (LGP)

The LGP was calculated based on a simple climatic water balance model that estimates the period during a year when rainfall exceeds 50% PET (FAO, 1978). The beginning of the growing season is defined as the time when weekly rainfall exceeds 50% PET at the end of the dry season, while the end of the growing season is defined as the time when weekly rainfall falls below 50% PET. In Laos, as in most of tropical and semi-tropical Asia, the LGP is a reasonably distinct, contiguous period that roughly coincides with the monsoon period. Also, the LGP, as estimated from climatic water balance, is not much affected or modified by low temperature constraints that might further limit the period of crop growth. The weekly rainfall and PET surfaces obtained in the present work were used as inputs for a climatic water balance model to generate the average LGP surfaces for Laos.

Variability of growing duration

For a given location, growing duration varies with rainfall. The end of the growing season is determined by rainfall towards its end. The year-to-year variation of growing duration was investigated first, using rainfall variation for Seno and Campassak from the past rainfall record and estimated PET.

We then estimated growing duration variation for the Seno District in Savannakhet Province using the RLRice model (Fukai et al. 1995). The model, particularly the water balance part is described in Fukai et al. (2002), and only a brief description is given here.

The model consists of several sections. Daily rainfall, mean temperature, solar radiation, and pan evaporation are weather inputs to the model. Both evaporation and transpiration are determined from daily pan evaporation, soil-water content, and canopy ground cover, which is calculated from the estimated leaf area of the crop. The transpiration rate decreases when soil-water content is less than 75% of the total extractable soil-water content. The deep percolation rate is a characteristic of the soil type at a location and is a required input for the model. The deep percolation rate is assumed to be zero when the free water surface is below the effective root zone.

The water-holding capacity for each soil layer has to be estimated and is an input. Evapotranspiration is reduced as soil-water content decreases. Lateral water movement (L) depends on rainfall, soil-water level, and the position of the lowland field in a toposequence. This is estimated from a coefficient C_L and rainfall (R) such that $L = R*(C_L - 1)$ if the soil is saturated with water and rainfall is large. Thus, the total water available to the paddy from rainfall is estimated as $R*C_L$; $C_L > 1.0$ indicates that the lowland field is located at the lower part of the toposequence and gains water from net lateral water movement. Net loss of water by lateral water movement is estimated as $R*(1.0 - C_L)$ where $C_L < 1.0$. When $C_L = 1.0$, the lowland field is located in a position where there is no net lateral water movement. Floodwater level at transplanting varies in each crop and is an input. The subsequent water level below or above the soil surface is estimated from rainfall, evapotranspiration, deep percolation and lateral water flow throughout growth.

Crop growth rate (CGR) is calculated daily from incident solar radiation, the proportion of radiation intercepted by the crop canopy and radiation-use efficiency (amount of biomass produced per unit radiation intercepted) when soil water does not limit growth. Radiation-use efficiency is affected by soil fertility and is an input for each location. When plants are water-stressed, CGR is calculated as the product of transpiration and transpiration efficiency (amount of biomass produced per unit water transpired). Yield components are directly estimated from CGR in the model. These yield components are, however, also affected by water stress, which occurs near and after anthesis. Thus, the proportion of unfilled grain increases as severe water stress develops near anthesis.

Seeding date and transplanting date are inputs.

While the model was developed for cultivar KDML105, it was used for the cultivar RD 6 in the present simulation. The two cultivars are similar, although one is non-glutinous and the other glutinous.

The model was calibrated for rainfed lowland conditions using data collected for three different locations, including Seno, in Laos. The simulated results have been compared with experimental results for RD 6 and give good agreement (Salum, pers. comm.). Experiments were conducted from 1996 to 1998, and some results were published (Inthapanya et al. 2000, 2001).

Several parameter values were estimated from comparison of the experimental and simulation results. The standard values of a few key variables were 1.5 g/MJ for radiation use efficiency, 3 mm per day for deep percolation rate, and a slightly lower position in the toposequence (coefficient of 1.3 where the location with coefficient of 1.0 assumes no net lateral water movement). In the experiment conducted in 1997, the initial free water level at the time of transplanting was 440 mm below soil surface, the date of seeding was 21 June and the age of seedlings at transplanting was 31 days. Using these same parameter values, the model was run for a number of years that showed contrasting rainfall patterns to examine the variation in water availability period and grain yield in rainfed lowland rice. The model estimates the date when standing water disappears from the rainfed lowland field. These dates were used to estimate variation in the end of the growing season. The model was further used for the effect of change in the deep percolation rate.

Results and discussion

Rainfall distribution

The mean annual rainfall map is shown in Figure 1. Annual rainfall ranges from about 1500 to 2200 mm in most Central and Southern provinces bordering the Mekong River, where the area of rainfed lowland rice is the largest. Within this lowland rice growing region, the north-western part of Savannakhet has rather low rainfall of around 1500 mm. By comparison, rainfall in northern Laos is generally lower. High rainfall peaks are located in the mountainous areas in both Northern and Southern Laos.

Weeks 15, 25, 35 and 40 are selected to show the change in rainfall patterns during the year at different locations in the country (Figure 2). Week 15 (mid-April, Figure 2a) marks the beginning of the wet season after a long dry one. Within the main lowland rice growing areas along the Mekong River, Bolikhamsay and northwestern Khamuane as well as Saravane and north-western Champassak receive early rainfall, whereas the western part of Savannakhet is still very dry, with a weekly rainfall of less than 15 mm. By week 25 (late June, Figure 2b) most of the area of Central and South Laos bordering the Mekong River receives a rainfall of 50 mm per week, except for western Savannakhet. In contrast, most rice growing areas of northern Laos still receive less than 50 mm of rain (50 mm of rain per week is considered adequate for growth of rainfed lowland rice). In week 35 (early September, Figure 2c) rainfall is high (more than 50 mm) over most of the country. Thereafter, rainfall decreases sharply and by week 40 (mid-October, Figure 2d) southern Bolikhamsay, Khamuane and Savannakhet receive less than 40 mm while rainfall is still more than 50 mm in most of Vientiane Municipality and Champassak. In Savannakhet and Khamuane, rainfall increases from about 20 mm a week in the west to over 40 mm in the east.

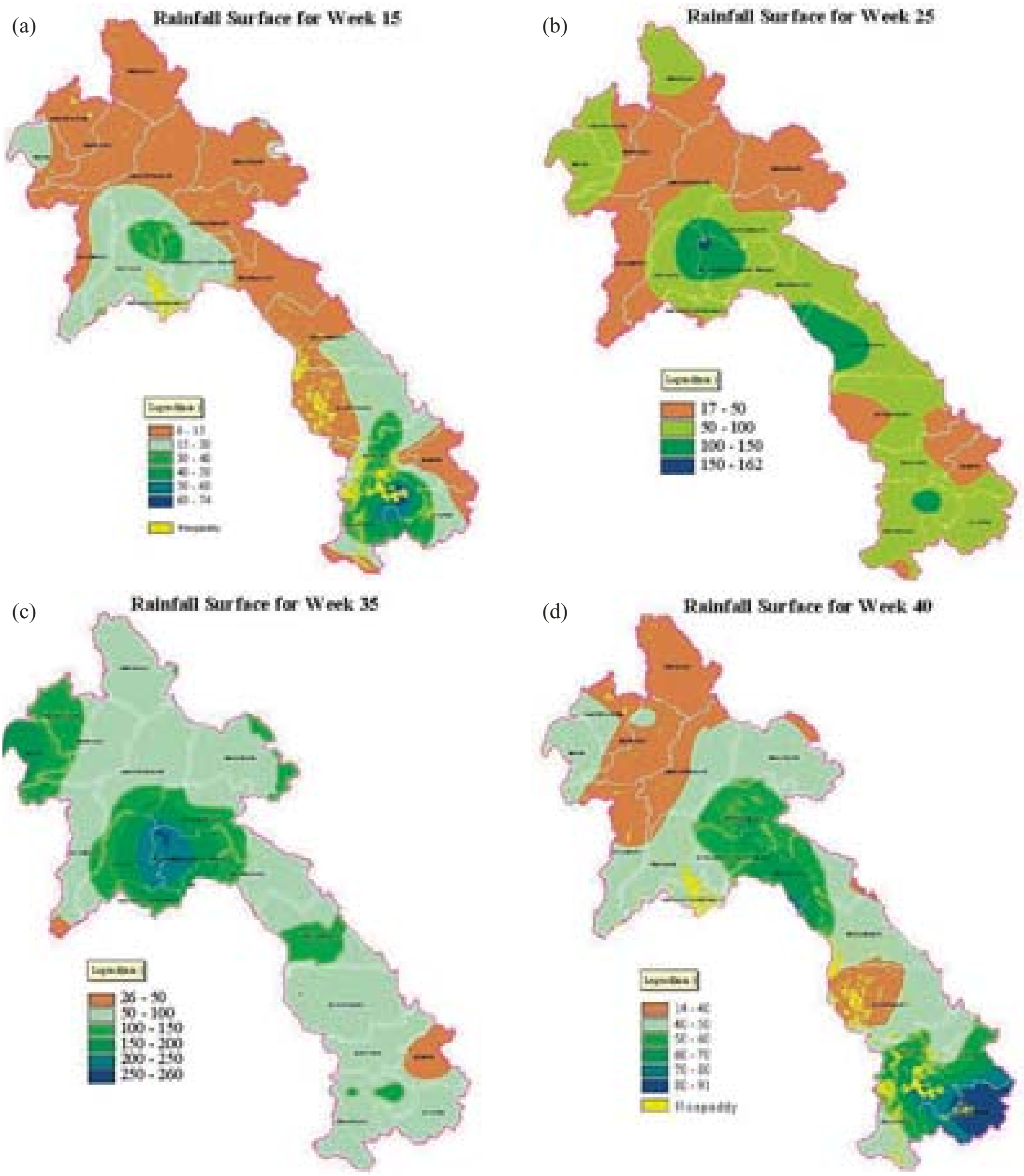

Figure 2. Rainfall distribution maps at weeks 15, 25, 35 and 40 in Laos.

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Potential evapotranspiration (PET)

Variations in PET across the country and within the year are rather small. In most weeks PET is greater in the southern than in the northern part of Laos. The same weeks as for rainfall are selected and PET maps are shown in Figure 3. In week 15, most rice growing areas along the Mekong River has a PET of 38–40 mm (Figure 3a). With the onset of the wet season, PET decreases slightly from week 15 to 25, particularly in western Savannakhet (Figure 3b). PET further decreases in week 35 and most rice growing areas have a 30–34 mm PET (Figure 3c). The trend continues to week 40 (Figure 3d).

Length of growing period (LGP)

The start of the growing period varies from week 11 to week 19. In the lowland rice growing areas along the Mekong River, Bolikhamsay begins the earliest as it has a slightly higher rainfall and lower PET than southern Laos (Figure 4a). The western part of Champassak has the latest commencement week, as the area tends to have a higher PET at around week 15. With the rainfall decreasing rapidly after week 40, the end of the growing season is week 42 for most of the country (Figure 4b). With higher rainfall in the eastern part of Savannakhet, the end of the growing season is slightly prolonged. Length of growing period, however, varies greatly (Figure 4c) because of variation in commencement of the growing period. Short growing periods of fewer than 180 days occur in western Champassak and Sayabooli where the growing period starts late, around week 17. With earlier onset of the growing period in Bolikhamsay, the growing season exceeds 210 days, whereas most other rice growing areas have a growing period of between 180 and 210 days.

Variation in growing duration

Weekly rainfall and PET are calculated from six years (1994–99) data for Pakse in Champassak Province (high rainfall area) and Seno District (low rainfall area) in Savannakhet Province. Figure 5 shows the pattern of rainfall and PET as well as 50% PET. Rainfall increases around week 18 and decreases sharply around week 40. PET is highest just before the beginning of the rainy season, and decreases gradually during the wet season. In Seno rainfall exceeds 50% PET from week 16 to week 41. A similar duration is seen for Pakse although fluctuations in the early and also late rainfall disrupt the continuity of the LGP. Alternatively, by considering the humid period (i.e. when rainfall exceeds PET), there is little difference between Pakse (week 19–40) and Seno (week 18–40). However, rainfall during the humid period is much higher at Pakse than at Seno.

The frequency of annual rainfall for the two locations is shown in Figure 6. While Seno has a lower mean annual rainfall, there have been years when the annual rainfall exceeded 2400 mm, and even 3300 mm (in 2 years) during the past 50 years. Pakse, with an annual rainfall of 1400–2800 mm, exhibits fewer extremes. These variations in rainfall result in a large variation in the duration of the growing period. Four years (1973, 1988, 1992 and 1998) of contrasting rainfall patterns and resultant variation in duration of the growing period are shown in the upper portion of Figure 7. In the first example, the duration is long, but the remaining three cases show that rainfall exceeded 50% PET in only a short period in the wet season.

Twelve years of contrasting rainfall patterns for the Seno district were selected for simulation using the RLRice model. The model used the same inputs and experimental conditions as an early study (Inthapanya 2001). There was no standing water at the time of transplanting in the 1997 study and hence we used free water level below soil surface as an input for all simulations. The results of the four contrasting years are shown in the lower part of Figure 7. In 1973, when rainfall was high throughout the season, there was standing water until well after the estimated flowering date. In contrast, 1998 was a low rainfall season, and standing water disappeared by flowering. 1988 and 1992 were intermediate, and standing water disappeared between flowering and maturity.

The simulation for grain yield is shown in Table 1. In years, such as 1973, when rainfall was high and there was a long duration of standing water, predicted yield was high (Table 1). On the other hand, when annual rainfall was low and standing water disappeared early in the season, such as in 1998, yield was 1.73 t ha^{-1}. Extremely high rainfall (3251 mm) in 1973, however, did not increase yield above that of years with 1500 mm. The flowering time was estimated by the model to occur around 12 October in most years, and thus predicted yield increased as water stayed longer in the field during the grain filling period. This confirms experimental results from Thailand (Jearakongman et al. 1995).

The standard parameter values used for deep percolation and lateral water movement for Seno Dis-

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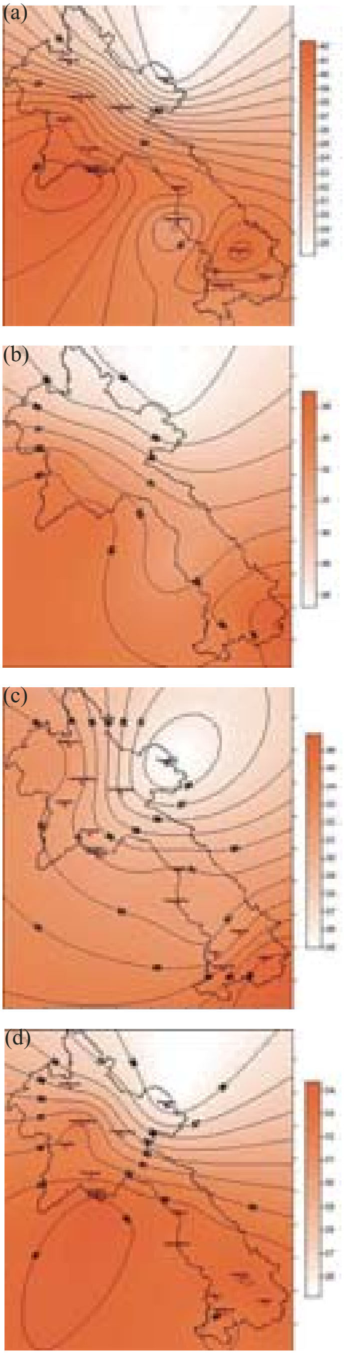

Figure 3. Changing pattern of potential evapotranspiration during the growing season (weeks 15, 25, 35 and 40) in Laos.

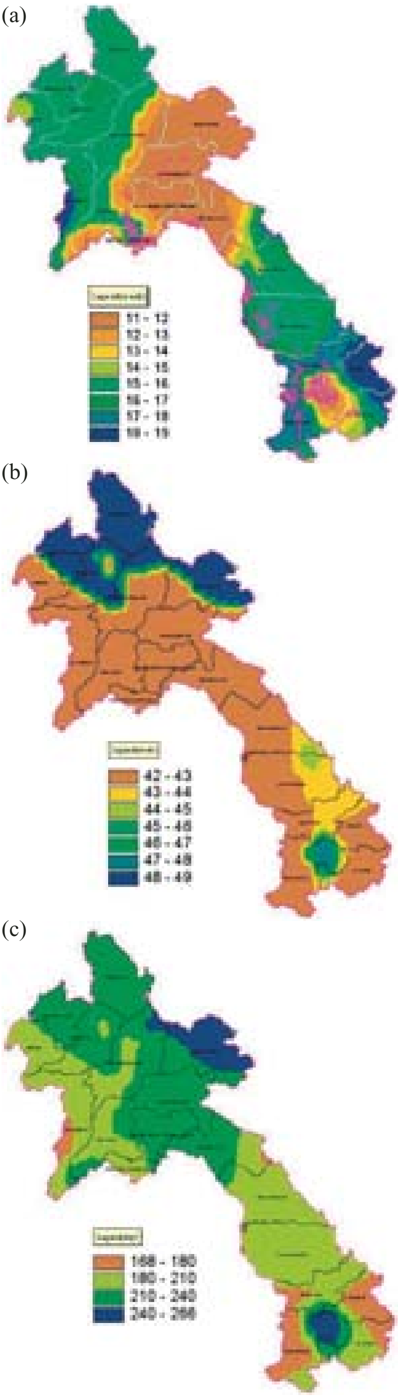

Figure 4. Start of the growing period (a) end of growing period (b) and total growing period (c) in Laos.

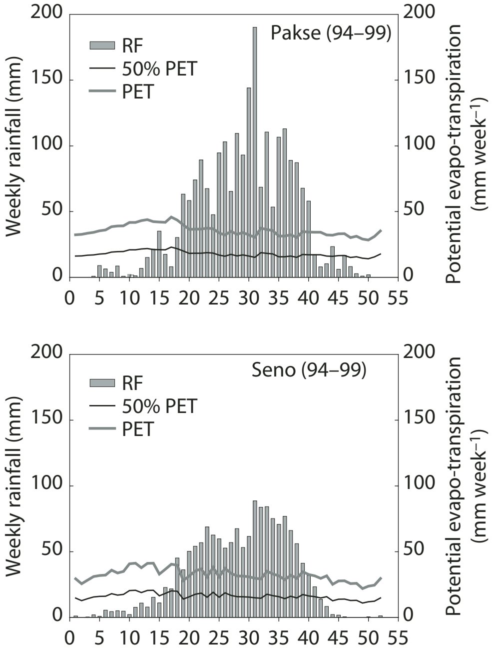

Figure 5. Rainfall (RF) distribution (average 94–99) and potential evapotranspiration at Pakse and Seno district in Laos.

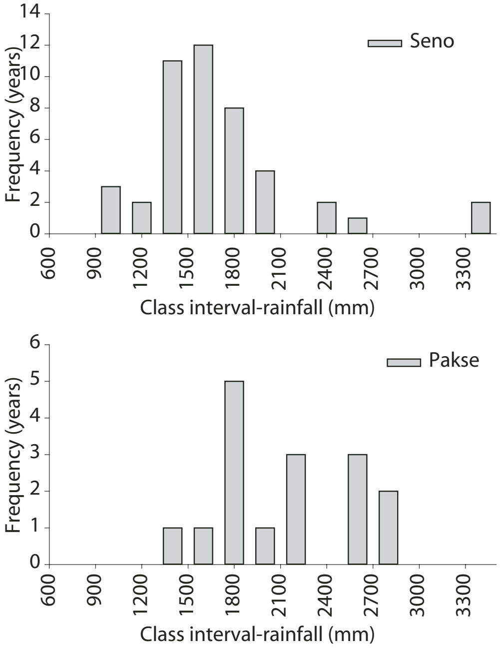

Figure 6. Annual rainfall distribution in Seno District and Pakse in Laos.

trict was 3 mm/day and 1.3 respectively. However our earlier simulation work indicated simulated grain yield to vary greatly with deep percolation rate and the position of the toposequence (Fukai et al. 2002). The model was used to examine the effect of different deep percolation and lateral movement using the data from Seno in 1976 (high rainfall) (Figure 8). The position of toposequence had a large effect on water availability, and at the top of toposequence water disappeared before flowering and yield was low (Table 2). However, standing water was maintained for a much longer period and yield was predicted to be high at the bottom position. The difference in date of water disappearance may differ for more than one month within a toposequence. Similarly, percolation rate markedly influenced water level; with a percolation level of 6 mm/day there was hardly any time with standing water and yield was reduced greatly. Soil texture affects the deep percolation rate which varies in the range of 1–6 mm/day for rainfed lowland rice in Thailand (Fukai et al. 1995). These soil variations as well as management options such as puddling and compaction of soils (Sharma et al. 1988) affect water availability in rainfed lowland fields. One of the problems of rice production in North-east Thailand is considered to be the high percolation rate of sandy soils. These results suggest that the water availability period can be greatly reduced in the sandy soils, resulting in low yields.

Conclusion

The study reported in this paper constitutes the first attempt to comprehensively assess water availability for agriculture for Laos. We were faced with data limitations, but the methodology that has been put in place allows for further upgrading of the map outputs as systematic and sustained collection of climatic data continues, thereby extending the period of available historical records. By computing the length of the growing period, as estimated from mean rainfall and mean PET, it is possible to delineate ecological zones for crop suitability. The LGP estimates show a rather small variation within the lowland rice

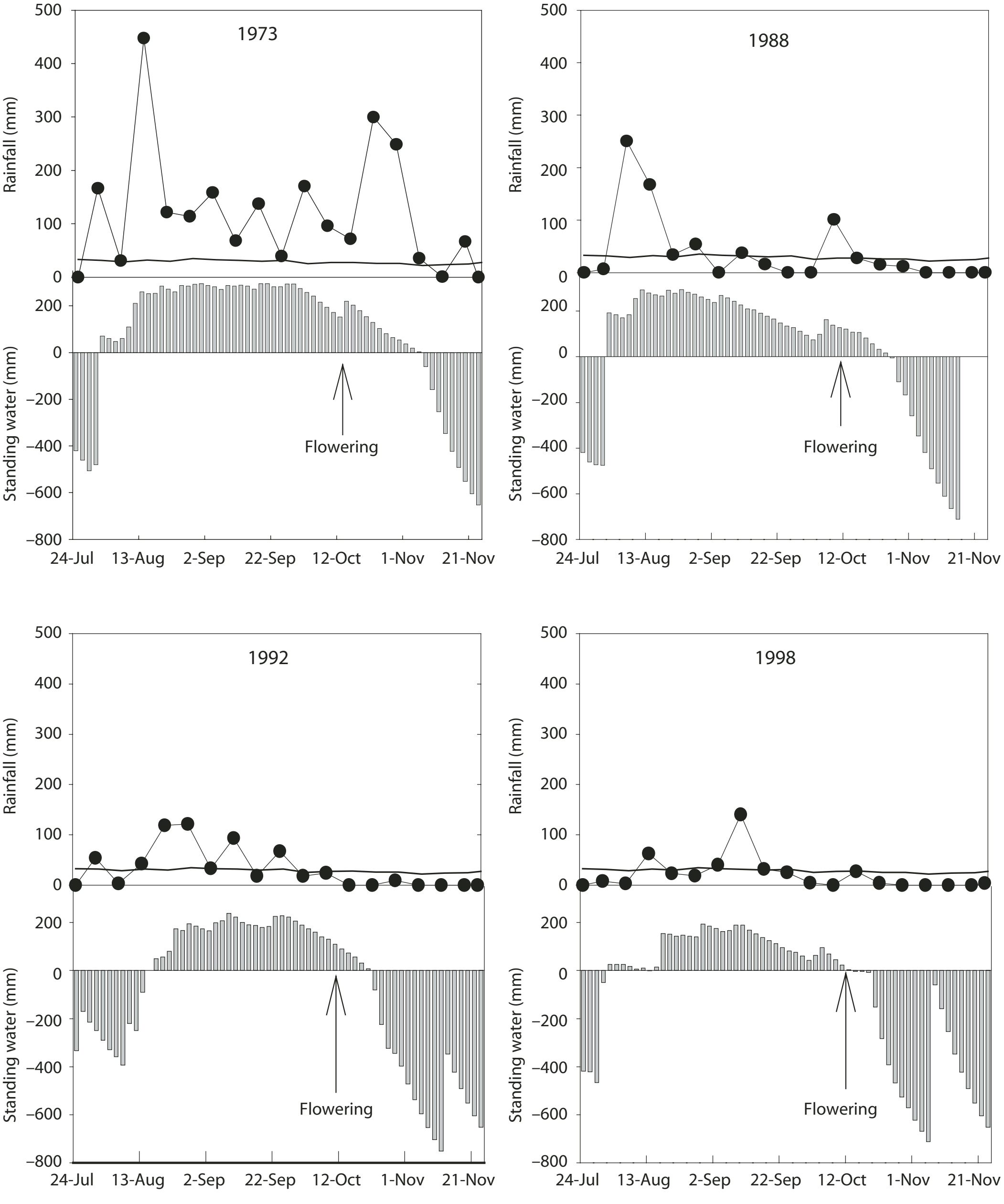

Figure 7. Rainfall and potential evapotranspiration (PET) and 50% PET (estimated) during wet season crops in four years and the simulated water levels for four years where contrasting yields were obtained from the RLRice model.

growing areas. It is also important to take into account that rainfall patterns vary greatly among years, and this can cause large variations in the length of the growing period. Furthermore, short-range variations in water availability occur within mini-catchments, as climatic factors interact with terrain and soil factors. At the landscape scale, variations across the toposequence positions, caused by soil texture and lateral water movement further modify and influence in-field water availability to crops. Thus greater emphasis needs to be made for water availability within micro-environments.

Table 1. Annual and October rainfall, date of disappearance of standing water, days to flower, days to mature and grain yield of TDK 1 as simulated for 12 contrasting years using the rainfed lowland rice model for Seno.

Year	Annual rainfall (mm)	Rainfall in October (mm)	Date of disappearance of water	Grain yield (t ha^{-1})
1973	3251.6	67.6	7-Nov-73	2.64
1976	1497.4	55.9	5-Nov-76	2.55
1985	1251.7	118.6	22-Oct-85	0.92
1987	1245.6	45.3	16-Oct-87	0.69
1988	1483.8	154.8	26-Oct-88	1.73
1989	1711.2	134.4	13-Nov-89	2.09
1992	1255.8	33.4	22-Oct-92	1.23
1994	1370.1	19.7	24-Oct-94	1.50
1995	894.0	9.6	22-Oct-95	0.92
1996	1312.5	103.6	7-Nov-96	2.02
1997	1046.4	102.2	12-Oct-97	0.46
1998	920.7	31.6	14-Oct-98	0.53

Table 2. Simulated date of water disappearance under different conditions of lateral coefficients and percolation rate and grain yield with 1976 rainfall data at Seno.

Percolation rate (mm day^{-1})	Lateral coefficient	Sowing date	Water disappearance	Grain yield (t ha^{-1})
3	0.5	22-Jun-76	2-Oct	1.16
	1		16-Oct	1.56
	1.5		5-Nov	2.65
Lateral coefficient	**Percolation rate (mm day^{-1})**	**Sowing date**	**Water disappearance**	**Grain yield (t ha^{-1})**
1.3	1	22-Jun-76	13-Nov	2.64
	3		3-Nov	2.54
	6		31-Aug	1.05

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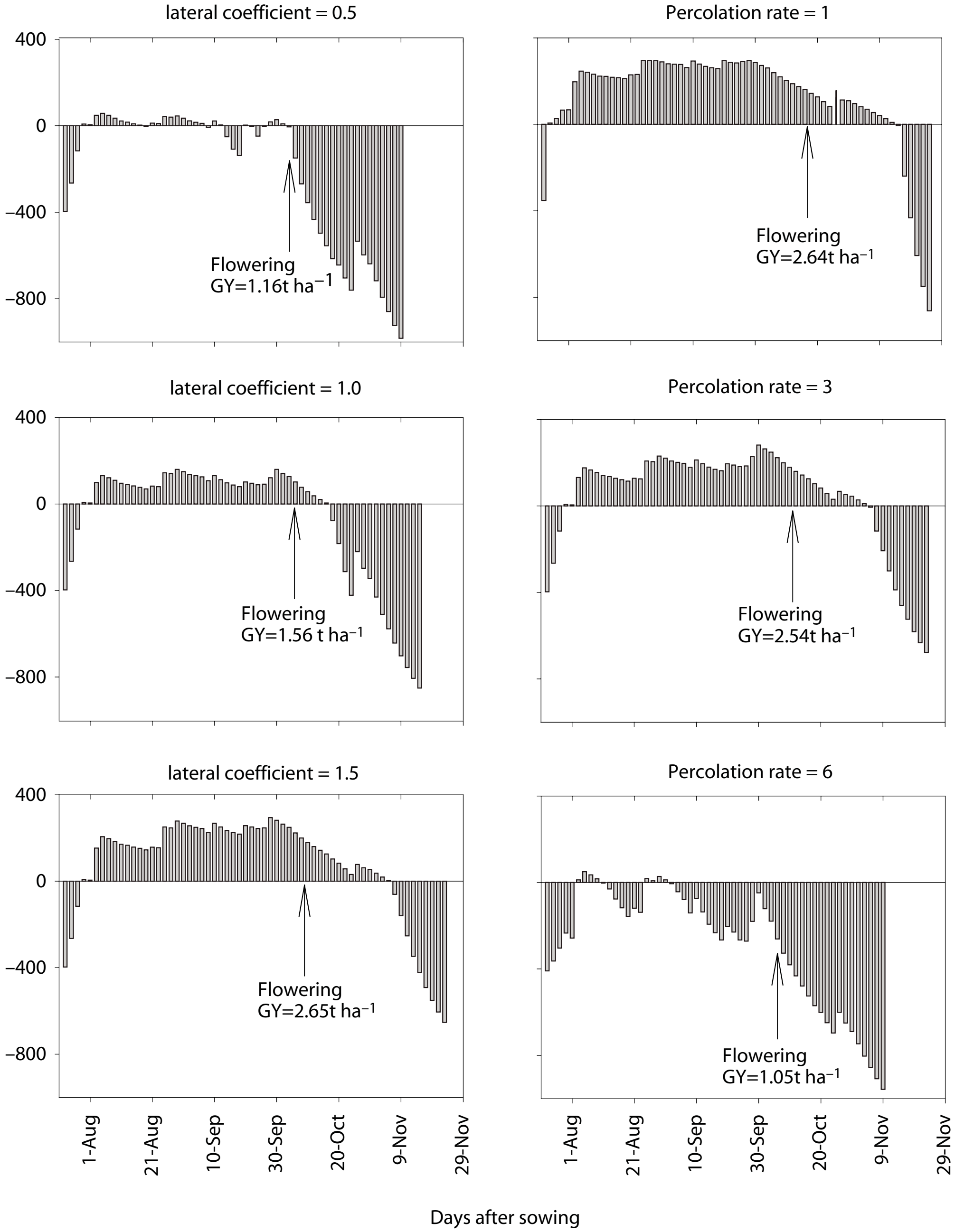

Figure 8. Water levels (mm) of six simulated experiments for grain yield using 1976 rainfall data. Lateral coefficients 0.5 (top position), 1.0 and 1.5 (low position) were used with the constant value of 3.0 mm day^{-1} for percolation rate and three percolation rates were used with a constant value of 1.3 for lateral coefficient for Seno, Laos.

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Roles of floods for agricultural production in and around Tonle Sap Lake

Takao Masumoto[1]*, Katsuyuki Shimizu[1] and Pham Thanh Hai[1]

Abstract

In monsoon Asia, agricultural water use is well integrated with other water uses. For watershed management, not only do paddy areas help regulate flooding by acting as a retarding basin (pond), but the rational supply of water resources is ensured by using the natural hydrologic conditions. This function is commonly found in low-lying paddy areas such as paddies in Japan, Cambodia, Vietnam and other countries. Typical examples for this are found in the Mekong River Basin (drainage area: 790,000km^2; river length: 4400km).

This paper discusses the role of floods for rice production in Tonle Sap Lake and its environs by analysing the following examples. The first is flood storage by Tonle Sap Lake, where a unique reverse flow from the river to the lake occurs during flood seasons. Paddies are in flooding areas and rice cultivation starts after the flood water recedes, so floods and agriculture are closely interrelated. The second one is the presence of reservoirs formed by dikes in paddy areas. These not only protect the urban area of Phnom Penh from floods, but also supply irrigation water. The third is the use of warp soil dressing by *colmatage*. *Colmatage* is a facility for digging out a natural levee and leading water from the Mekong and Bassac Rivers into areas behind the levees as the water levels in the rivers increase. Part of the water stored through colmatage during the flood season remains in the area even after the water levels in both rivers decrease, and this water is used for rice production during the dry season.

ALTHOUGH Asia covers only 24% of the world's land area, more than 60% of the world's population, about six billion, live in Asia. In particular, about 54% of the world's population is thought to live in the regions known as humid Asia or Monsoon Asia, covering only about 14% of the world's land area. Most of Asia's massive population is supported by intensive paddy rice cultivation, which originates from the warm and humid environment and offers high land productivity based on irrigation.

Rice cultivation of paddies in Monsoon Asia is not only an valuable form of agriculture offering high land productivity. It can also be seen as a sustainable and environmentally friendly economic activity that suits the climatic and topographical conditions of this region. This economic activity has continued to evolve for hundreds to thousands of years in various regions, as witnessed by archaeological traces of 7000-year-old rice cultivation in China. Even today, rice paddy cultivation forms a unique way of life supported by the endeavours of people living in symbiosis with water. This unique way of life, a complex amalgamation of sustainable human activity, society and the natural environment, ranks alongside rice as another product of paddy fields. Moreover, paddies also support the convenience of life for city dwellers by, for example, reducing floods and fostering groundwater. These 'products' cannot be sold in any market and their functions are referred to here as 'the multi-functional roles of paddy irrigation'.

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In this paper, the multi-functional roles of paddy irrigation in humid regions are illustrated, by comparing the hydrological environments, forms of irrigation, and characteristics of paddies. As well as using flooding for agricultural production as a good example of integrated water use management, we discuss the role of floods for rice production in Tonle Sap Lake and its vicinities by analysing three examples: flood storage by Tonle Sap Lake, reservoirs in paddy areas with dikes to protect urban areas from floods, and water management by *colmatage* (c*olmatage*, which is based on French technology, is a facility for digging out a natural levee and leading river water into areas behind the levee as the water level in a river rises).

Uniqueness of water use in paddies

Characteristics of paddy irrigation

Definition and hydrologic characteristics of Monsoon Asia

Mushiake (2001) asserts that regions like Monsoon Asia should be characterised by the region's uniqueness (including the nature of human activity), in addition to the climatic conditions that have been emphasised in the past. Thus, he suggests that it should be seen as a high precipitation region that has an annual precipitation of more than 1000 mm and belongs to a warm climate zone. This Monsoon Asian region is generally taken to include Japan, the Korean peninsula, China (except the north-western interior, the Yellow River basin, and surrounding areas), all of South-east Asia (the Indochina Peninsula and the island nations), Nepal, Bhutan, Bangladesh, Sri Lanka, and areas east of the Deccan Plateau plus south-western coastal regions of India.

The Asia Monsoon region embraces the Indian Ocean to the south, the expansive region of Tibet, the Himalayan mountain mass and continental China to the north, and the Pacific Ocean to the east. Most of it consists of high-precipitation warm regions that have an annual rainfall above 1500 mm, influenced by low pressure and monsoons accompanied by westerly winds (Figure 1). Meanwhile, the water balance (calculated by subtracting annual potential evapotranspiration from annual precipitation) generally exceeds 500 mm.

Paddy irrigation in arid and semi-arid regions

To understand the multi-functional nature of paddy irrigation in Monsoon Asia, it is helpful to compare it with paddy irrigation in the world's arid and semi-arid regions, such as in the USA, Australia, Italy and other countries in Europe (Figure 2). In the USA, paddy zones extend along the Mississippi River and are in five southern states as well as California. The rice cultivated area changes from year to year between 300,000 and 1,500,000 ha. In Australia, about 100,000 ha of paddy fields are concentrated in the Murray and Murrumbidgee River basins. With annual precipitation of about 400 mm, paddy irrigation is practised there. Rice cultivated in paddy fields covers more than 226,000 ha in Italy and 100,000 ha in Spain.

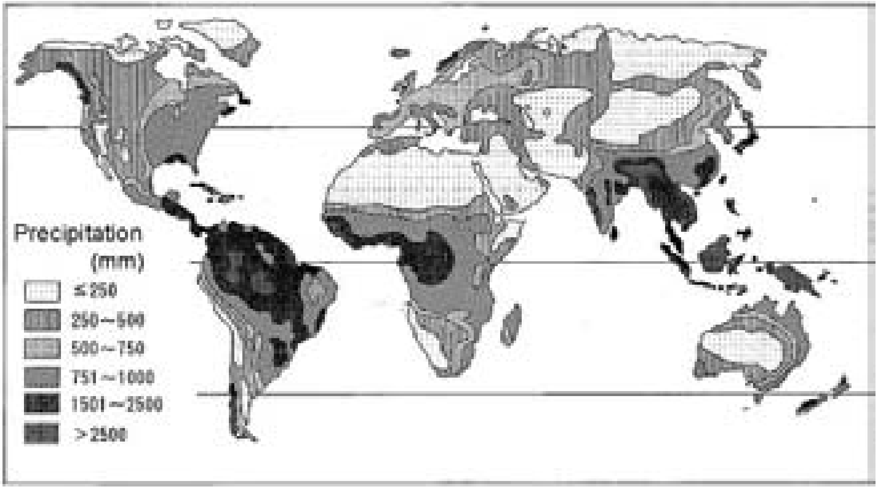


Figure 1. Distribution of annual precipitation in the world (Maruyama et al. 1996).

Figure 2. Distribution of paddies (Oxford Economic Atlas, 2002).

California is a semi-arid region with rainfall in winter but little in summer. The average annual precipitation is 575 mm. The south, in particular, has annual precipitation of only about 240 mm or less, and agriculture there would be impossible without irrigation facilities. Paddies and water supply channels are used as retarding basins and diversion channels for floodwater. Paddies also provide sanctuaries for migrating birds as well as for duck hunting. Although some features of paddy rice culture in California are similar to Monsoon Asia, the California paddies and water distribution and drainage system do not have the all-encompassing, multi-functional roles of paddy irrigation in Monsoon Asia.

In the rice cultivation zones along the Murray River, some flood water is stored during high flows. However, paddies are not seen as having a function for relief from flooding. Furthermore, groundwater percolation from paddies causes soil salinity to accumulate in surrounding non-rice arable land because the shallow ground waters are saline. Therefore, reducing deep percolation and waterlogging as well as underdrainage are management practices of concern. For sustainability of agriculture, this could be seen as an example of a negative effect being on a region's water resources.

Annual precipitation in the paddy zones of the European countries is 700–800 mm, though it exceeds 1000 mm in some parts of Italy. There is no overt concept of paddies contributing to flood prevention in the areas.

Characteristics of paddy irrigation

The principal grain crop in Monsoon Asia is rice. In fact, nearly 90% of the world's rice is produced in the countries of this region. The Asia monsoon region could be called a virtually homogenous region in that paddy rice cultivation extends over almost the whole of its area (Figure 2). Generally speaking, regions with annual precipitation of less than 400 mm are classified as perennial irrigation zones, those with precipitation between 400 and 1000 mm as unstable irrigation zones, and those with more than 1000 mm as replenishment irrigation zones. Of these, the whole of Monsoon Asia belongs to the last classification. What is more, the Asia monsoon region is also characterised by large seasonal and short-term fluctuations in the supply of water resources, as evident in the distinct dry and rainy seasons.

Multi-functional roles of paddies

Definition of multifunctional roles

In the past, agricultural lands were regarded as only producing food production, but are now considered to have several functions, such as flood protection, fostering of water resources, purification of water quality, prevention of soil erosion, prevention of land slides, mitigation of impacts of agricultural chemicals, ecological preservation, microclimate modification, preservation of landscape. However, these functions have conventionally been expressed only qualitatively and have not necessarily been proven. Recently, some studies to examine these issues have started.

In 2001 the Science Council of Japan delivered a report on the multi-functional roles of agriculture and forests to the Minister of Agriculture, Forestry and Fisheries. The report included a list of categories connected with the multi-functional roles of paddy irrigation. Based on this, the multi-functional roles of paddy field irrigation are defined as:

- water cycle control functions (flood prevention, groundwater recharge, prevention of soil erosion)
- environmental load control functions (water purification, processing of organic waste, climate modification)
- nature formation functions (bio-diversity, landscapes)
- social culture formation functions (health and recreation, participatory learning).

Specific examples of water cycle control functions

For flood prevention, retention (storage) capacity of water in agricultural lands can be considered from two angles:

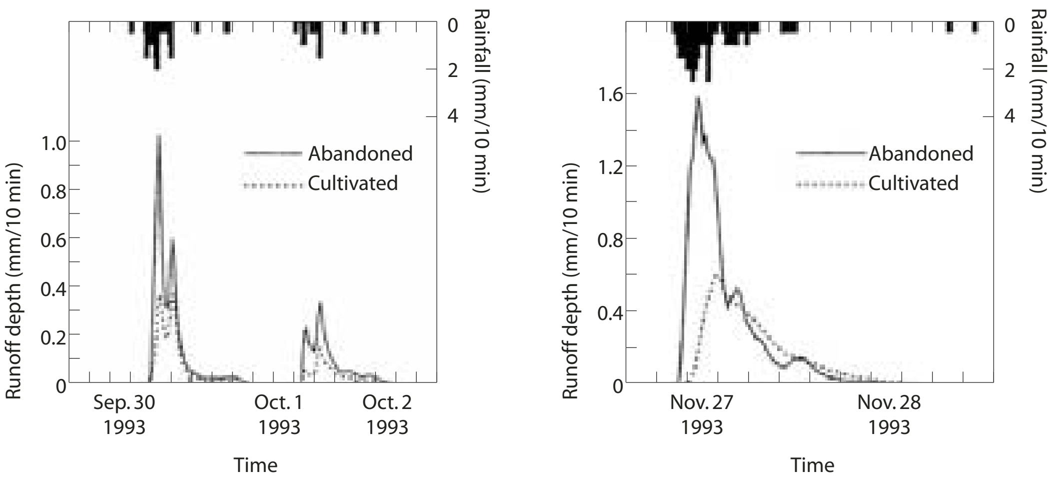
- change of runoff amount due to the change of land use and change of storage amount due to the change of hydrograph shape
- storage capacity of flooded water in agricultural lands as a retarding pond.

The first factor will cause a sharpening of the runoff hydrograph, thus causing an increase in the peak runoff and a decrease in the storage capacity. The second factor exerts its influence by increasing the retention capacity (including potential capacity) of the agricultural area and acting as a buffer to store flood water in the basin, like a retarding pond. This function is typically found in low-lying paddy areas such as those commonly found in Japan, Cambodia, Vietnam and other countries.

Attempts are being made not only to define multi-functional roles qualitatively, but also to evaluate them quantitatively. Some recent results (Masumoto, 2002) are discussed below.

When changes in runoff volume due to the abandonment of paddy farming were measured in mountainous parts of the Hokuriku region, an increase in total and peak runoffs for all observed floods was observed at times when paddy fields were wet (Figure 3). There have also been studies of examples in which low-lying paddy zones contribute to flood prevention in river basins, such as many basins in Japan, and the Mekong River basin. The first example showed that paddies on low-lying land functioned as buffers for storing floodwater and moderated flooding in urban areas. The second example demonstrated that temporarily stopping drainage of agricultural pumps from the paddy area to the river helped to reduce the damage. The third example is a classic example that paddies fulfil the function of storing flood water as well as supplying irrigation water.

Attempts have been made to evaluate the above mentioned functions at the basin level and, especially, to propose ways to evaluate flood prevention functions on a macro scale. The relationship between discharge in urban rivers and flood prevention capability


(a) An example in 1993

(b) An example in 1993

Figure 3. Comparison of runoff between cultivated and abandoned paddies.

of suburban paddies may be defined as the relation between drainage and storage capabilities. Figure 4 shows an example of this evaluation method applied to the basin of the Kinu River, a tributary of the Tone River in the north of the Kanto region, Japan.

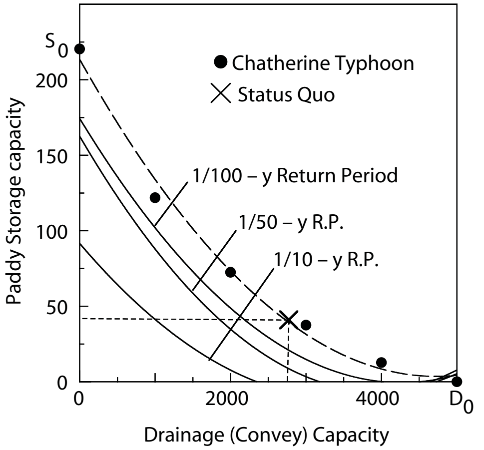


Figure 4. Drainage capacity (urban area) and storage capacity of paddies (Kinu River, Japan).

Moreover, there are some other examples of flood prevention functions of low-lying paddy regions in the Chao Phraya basin in Thailand, the Murray–Darling basin in Australia, the Rhine basin in Europe, the Chang Jiang basin in China, and the Ishikari basin and creeks in coastal lowlands in Japan.

Characteristics of Tonle Sap Lake and its environs

Up-stream of Tonle Sap Lake

The plain with Tonle Sap Lake in its centre is surrounded in the north by a Chuor Phnum Dangrek Mountain range with altitudes 500–700 m. From the south of its range down to the lake, the landscape is composed of numerous hills with altitudes 200–40 m to the plain. The plain is surrounded in the south by the Kravanh and Damrei Mountain ranges with the highest points 1500–1800 m. The valley bottoms in this plain are flat and swampy.

More than 16 rivers and streams in Cambodia flow into the Tonle Sap Lake/River, such as the Mongkol Borey River in the west of the lake, the Sreng River in the north and the Sen River in the east (Table 1). The area is covered by dense and semi-dense forests on the upper part of the Tonle Sap Lake watersheds (siliceous sandstones) and open forests, in which the trees are small and widely spaced, prevail in the southern part of the plain (shales and sandstones).

The rainfall is markedly influenced by altitude. Although the south and the highest part of the Kravanh and Damrei Mountain ranges receive more than 5000 mm per year, the north side of the ranges receives only about 1000–1200 mm. In the Dangrek Mountain range, rainfall is estimated as being around 1600–2000 mm per year.

Table l. Sub-basins in non-flooding areas.

Name of sub-basin	Watershed area (km^2)
Chinit River	6,770
Sen River	16,250
Staung River	4,370
Chi Kreng River	2,750
Siem Reap River	3,060
Sreng River	10,380
Sisophon River	3,120
Mongkol Borey R.	11,350
Battambang River	4,370
Daun Tri River	3,530
Pursat River	5,980
Baribo River	6,080
Prek Thnot River	6,670

Tonle Sap Lake

Tonle Sap Lake is the largest freshwater lake in South-east Asia. Its water level varies from an average depth of less than 2 m during the dry season to a maximum depth of 8–10 m at the end of the rainy season. It is connected to the Mekong River by the Tonle Sap River at the Chaktomuk conjunction in Phnom Penh, about 120 km to the south-west of the outlet of the lake (see Figure 5).

The lake and its flood plain cover about 18,000 km^2. They are surrounded by the national roads, Routes 5 and 6, which are 11 m above sea level, which corresponds to the limit of the open water of the lake at high level. The area of the drainage basin of the lake is currently 67,600 km^2.

The lake is fed throughout the year by the rivers of many watersheds connecting to it and by direct rainfall on its surface. It also acts as a retention reservoir

Figure 5. Tonle Sap Lake: location and link to the Mekong River.

(capacity of about 70–80 billion m^3) in storing flood water from the mainstream of the Mekong River, thereby reducing the flood damage for downstream areas. Part of the Mekong River flows into the lake in late May when the water level at the confluence at Phnom Penh rises to about 9 m and the flow reverses its direction from flowing in to flowing out to the Mekong and Bassak Rivers in around late October.

The large range of variation of water levels in the Mekong/Tonle Sap system allows for an unusual recession cropping system, whereby flood water can be stored at the edge of the flood plain and then used to irrigate the land uncovered by the receding flood. Both the filling of the storage and the subsequent irrigation can often be achieved by gravity without the need to pump.

Rainfall over Tonle Sap Lake is 1200–1400 mm per year. The annual evaporation varies from 1000 to 1300 mm in this area. At Battambang, the mean annual evaporation is 1260 mm. It is also estimated theoretically that the annual potential evapotranspiration is 1500 mm for the country (Mekong Secretariat, 1994).

Colmatage area (Chaktomuk area and the downstream)

The Chaktomuk area is, in the narrow sense, the junction of the upper and lower Mekong, the Bassac and Tonle Sap Rivers. Then, we define the whole area that includes the junction mentioned above, the Mekong River up to Kompong Cham and down to Tan Chau, the Bassac River down to Chao Doc and the Tonle Sap up to Prek Kdam, as the *colmatage* area.

It is reported that there are tidal effects up to Phnom Penh. The extent of this effect is not clear, but in the dry season, when the effect is most likely to be is greatest, a tidal range of 10–20 cm is reported at Phnom Penh. There are many areas that flood in this region. In the flood land of the main Mekong and Bassac River systems, earthworks include ponds to store water and minor embankments (roads) to control flooding. On the tributary rivers and streams, there are also embankments and ditches, which serve to retard and spread flood water for agriculture. These irrigation systems include *colmatage* ones (at more than 400 places, see Figure 6) that use dikes and sluices to provide controlled annual inundation.

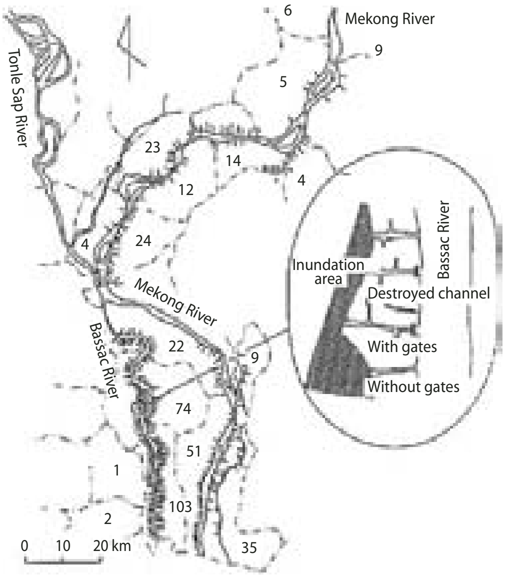


Figure 6. Colmatage channels.

Estimation of flooded water on paddies

Agricultural lands in Cambodia

Agricultural land use in and around Tonle Sap Lake and its vicinities are classified roughly as paddies and dry fields. Figure 7 shows land use in

Cambodia with the simple classification of forest, dry fields and paddies. The grid size of the digital mesh is 1 km. Focusing on paddies, there are various types of rice cropping patterns as shown in Table 2. Rice maturity types vary as early, medium and late ones, and are related to annual planting stages according to the availability of water and the height of flood levels. Areas in and around Tonle Sap lake and its vicinities are especially used for rice as flood waters recede and details of this are covered later.

Flooding

Floods in the past

During the monsoon period of August–November flooding is often caused by heavy typhoons, tropical storms and low depressions. The 1996 and 2000 floods were exceptionally serious in many part of the Mekong River Basin. In the past, floods in 1961 and 1966 were similarly large events as shown by an analysis of the flood levels of the Mekong River over the past 30–40 years. During that period, 1961, 1966, 1971, 1978, 1981, 1984, 1988, 1989, 1991, 1996, 2000 and 2001 are considered to be flood years in terms of the magnitude of the high water levels.

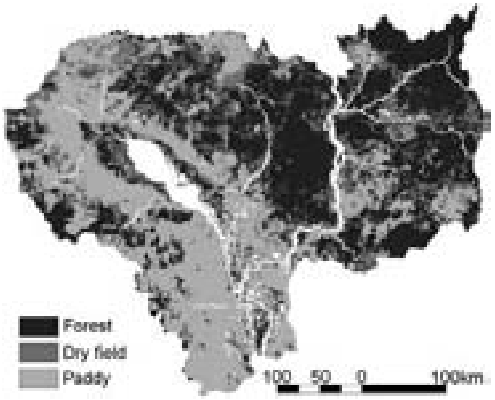


Figure 7. Land use in Cambodia (Source: USGS).

2000 flood

Discharges in the Mekong River usually start to increase in May or June, reaching their peak in August or September in the upper reaches, and in September or October in the lower reaches. The water level is usually lowest in April, and differs greatly between the wet and dry seasons, fluctuating by, for example, 11 m at Vientiane, 7 m at Phnom Penh, and 2 m in the delta areas of Viet Nam.

However, water level fluctuations in 2000 were even greater, causing severe inundation in the whole country of Cambodia and in the Delta of Viet Nam. Town flooding occurred at Pakse in the south part of the Lao PDR, and it reached to Stung Treng and Kratie in Cambodia. The area from Kratie through the Delta of Viet Nam was the most heavily flooded and damaged zone (Figure 8). As shown by the hatched area in Figure 8, flood waters finally covered 38,900 km^2. Note, however, that this large figure includes the water surface area of the rivers and Tonle Sap Lake.

The behaviour and causes of the big flood in 2000 have been examined (Masumoto, 2001). The uniqueness of this flood is shown by the relation between its topographic features and the concentration of flood waters in the lower flood-prone areas. The results showed that:

- return periods of the 2000 flood are estimated as three to 10 years in Thailand and the Lao PDR, 20–60 years in Cambodia, and 30 years in Viet Nam
- the main causes of the 2000 flood are considered to have been the rains starting about two months early, long-lasting heavy rainfall and the filling of the storage capacity of Tonle Sap Lake and its surrounding low-lying areas in July
- the Mekong River has unique topographic features, so that rain water was concentrated in the Tonle Sap area in Cambodia and the Delta area in Viet Nam.

Damage and benefit

The above-mentioned flood caused serious damage to the affected area according to official announcements. In Cambodia, 347 deaths were

Table 2. Type of rice fields and its production in Cambodia.

	Area (km^2)						Rice production (ton)	Rice yield (ton/ha)
Types of crop pattern in rice	Early	Medium	Late	Floating	Upland	Total		
	3,589	7,647	5,657	960	359	18,212	2,915,900	1.71

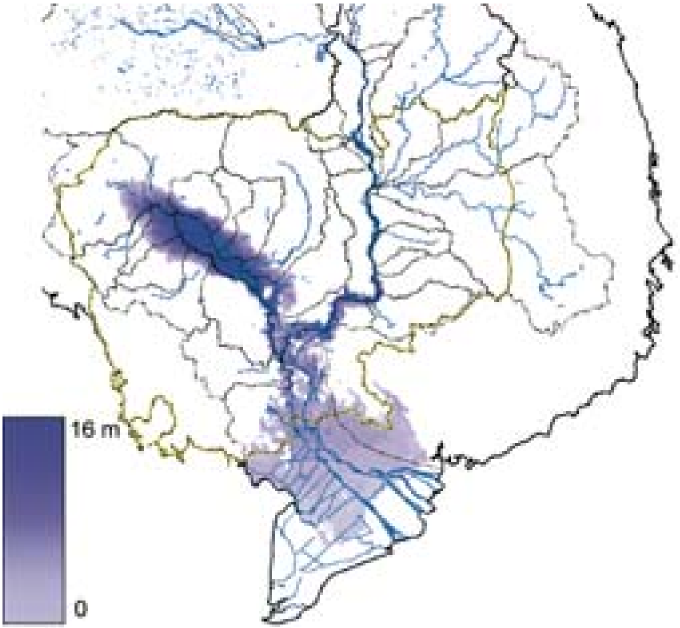


Figure 8. Estimated inundation depth and area in the 2000 flood

reported. More than 390,000 people (85,000 families) were evacuated from their homes and 3,450,000 people affected. Figures for agriculture show that 6.2×10^3 km^2 rice fields were flooded and 3.7×10^3 km^2 rice fields were totally destroyed. Furthermore, 2600 km of national and provincial roads were damaged. The total cost of damage is estimated at about 145 million US dollars. In Viet Nam, it is reported that 362 people were confirmed dead, and hundreds of thousands made homeless. In total, more than 5 million people in the Delta were reported as affected.

However, even floods of this size as well as normal floods bring benefits to this area in that they prevent flooding of other areas and provide water for agriculture. One benefit is that the flood water provides a water storage from which water is released gradually to the downstream, which enables farmers downstream to use the water. In the drainage system of the Mekong River, the relation of maximum capacities between river discharge and flood storage capacity is fixed, so that without the capacity of Tonle Sap Lake and its flood plain, other places would suffer from flood damage. Also, in the flooded areas as the water recedes to an appropriate level, the land is used for rice. However, if urban areas are flooded and have their infrastructure destroyed because there is insufficient water storage, much more severe damage is caused to the basin.

Estimation of inundation volume on paddies

To evaluate the role of agricultural lands in flood protection, we estimated the volume of flooded water on paddies. The estimation was carried out by summing up the height (100 m mesh) of floods (Figure 8, for example) in accordance with all meshes of paddies and dry fields (Figure 7). Figure 8 is an estimation made by using a model developed by the JICA–WUP team (MRC and JICA, 2003) for the 2000 flood. The estimation of inundation depth and area for the 1999, 2000 and 2001 floods indicate three flood types: small, large and medium. The area considered in the paper, is divided into two parts at Prek Kdam (at the middle reach of the Tonle Sap River), namely:

- Tonle Sap Lake and upstream from it
- *colmatage* area.

Tonle Sap Lake and its upstream region

Table 3(a) shows the results of calculating the area of flooded paddies, the volume on paddies and the ratio of flooded volume on paddies to the total flooded volume. In the 2000 flood, for instance, about 27% (502 km^2/18,700 km^2; see Tables 2 and 3) of paddies in Cambodia were affected and it is understood that paddies apparently stored 17% of the whole flooded volume in and around Tonle Sap Lake and the upstream. Even for the small flood in 1999, the ratio of the flooded volume on paddies counts for 11% of the total storage (apparent value at the peak).

Colmatage area

Flood water storage by paddies might be expected to be similar in the *colmatage* area (Table 3(b)) to that of the Tonle Sap area. However, while the total size of flooded paddies is almost the same between the Tonle Sap Lake and *colmatage* areas, the ratio of the flooded volume on paddies to the respective flood volumes in the *colmatage* area is bigger than that of Tonle Sap Lake and the upstream by more than 20%.

Total area

In total (Table 3(c)), the ratio of flooded areas to the total paddies in Cambodia varies from 32% (in 1999) to 51% (in 2000). That of the flooded volume on paddies to the total flood is about 20%, that is, we can say that one-fifth of the total flood volume is roughly stored on paddies in and around Tonle Sap Lake and its vicinities. In addition to the estimation of flooded volumes on paddies, flooding areas and its volume on dry fields are calculated. Then, the estimated results show that dry fields in and around Tonle Sap Lake are also flooded by the same or greater water volume as that on paddies, while the size of the flooded areas/volumes on dry fields is not large compared with that of paddies in the *colmatage* area. According to Table 2, rice yield is 1.71 ton/ha and market price is 316 Real/kg (0.079 USD/kg), so that the possible decrease would be calculated as 78.7–125.5 × 10^6 USD at the most (in the worst case) for paddies in Cambodia.

Multi-functional roles of paddies

Integrated water use

The discharge of the Mekong River is still unregulated, so the difference in the water levels between the dry and wet seasons is more than 7 m at Tonle Sap Lake. These hydrological characteristics can be

Table 3. Estimated inundation depth and area in the 1999, 2000 and 2001 floods.
(a) Tonle Sap Lake and the upstream

	Paddies in flooded (1000 ha)	Volume on paddies (10^9 m^3)	Ratio of its volume (%)
Small Flood in 1999	292	56.0	11.2
Large Flood in 2000	502	114.7	16.5
Medium Flood in 2001	450	97.6	15.1

(b) Colmatage area

	Paddies in flooded (1000 ha)	Volume on paddies (10^9 m^3)	Ratio of its volume (%)
Small Flood in 1999	314	57.1	38.5
Large Flood in 2000	450	99.9	42.4
Medium Flood in 2001	409	91.0	42.0

(c) Total (=(a) + (b))

	Paddies in flooded (1000 ha)	Volume on paddies (10^9 m^3)	Ratio of its volume (%)
Small Flood in 1999	606	113.1	17.5
Large Flood in 2000	952	214.6	23.0
Medium Flood in 2001	859	188.6	21.8

exploited in three ways to use rainy season flood water as dry season irrigation water.

The first method is water storage in Tonle Sap Lake. During the rainy season, the water level in the main stream of the Mekong River rises higher than that of Tonle Sap Lake, and reverse flow from the river to the lake occurs. Paddies are located in the flooded areas and rice cultivation starts after the flood water recedes, so floods and agriculture are closely interrelated.

The second is flood storage by flood protection dikes (small reservoirs) to the north of Phnom Penh (Figure 5). Two dikes were built to protect Phnom Penh from the floods, resulting in two reservoirs forming in paddy areas with an average water depth of 1.5 m. Through gate operations on the dikes, irrigation water is led to the downstream areas, thus enabling double cropping in the downstream area and single cropping in the reservoir area. Hence, the paddy fields have dual functions of protecting the urban area from floods and also supplying irrigation water.

The third way is to use warp soil dressing by *colmatage*. That is, water is led from the Mekong and Bassac Rivers into areas behind levees as the water levels in the rivers increase. Part of the water stored through *colmatage* during the flood season remains in the area even after the water levels in both rivers decrease, and this water is used during the dry season (see Figure 6).

In some ways, the flood protection technology used in the Mekong River basin is lagging that used in advanced nations where areas are separated and protected from flood damage. However, from the viewpoint of watershed management, not only do the agricultural lands provide a flood regulation function by acting as a retarding basin (pond), but also the rational supply of water resources is achieved by utilising the natural hydrologic conditions. The first item was evaluated above as Tonle Sap Lake and its upstream waters and the last two estimated as *colmatage* area in the previous section.

Roles of paddy field water

Additional economic benefit

Paddy field irrigation agriculture in the Asia monsoon region not only produces goods in the form of agricultural products, but also has multi-functional roles (additional economic benefits) that are difficult to evaluate in market terms. It forms unique societies/cultures and has the latent potential to sustain those values and produce paddy rice indefinitely. Therefore, it is important to evaluate holistically the multi-functional roles of agricultural lands, especially the use of low-lying paddy areas for flood prevention. This function must be evaluated as a potential value of paddy areas that can be used for watershed management.

First, in Monsoon Asia, a unique water use is found in that irrigation and floods are closely interconnected for water use. This is explained as multi-functional roles of paddies and is deduced by comparing several examples in Japan, Europe, Australia and the USA. Typical examples for this are found in the Mekong River Basin. The Mekong River has unique topographic features, so that water is concentrated in the Tonle Sap Lake area in Cambodia and the Delta area in Viet Nam. The 2000 flood was a good example of this phenomena and paddies prevail in such low-lying areas. As mentioned above, the flood water stored on paddies is used in two ways. One is that the stored water is used as a water resource for irrigation downstream, while water in the flooded areas is used for rice planting water when the water level decreases. So, in the Cambodia lowlands, farming starts when the water stored during floods recedes. Meanwhile, the floodwater stored in paddies acts, at the same time, as nursery grounds for farmed fish, or allows fishermen to obtain fish for their own consumption. In this way, agricultural production activity along the Mekong River is in symbiosis with ecosystems. In future, it is possible that maintaining this kind of system will be seen as extremely important.

Over the long course of history, ancient civilisations are said to have coincided with regions in which agriculture and irrigation were practised. From the perspective of water and paddy field agriculture, therefore, Monsoon Asia could be seen as having the potential to maintain civilisation in a sustainable fashion.

In other words, paddy field irrigation is characterised as having a large additional economic benefit. In warm and humid regions, torrential rains occasionally cause floods, but paddy fields also have the additional economic benefit of mitigating flood damage. The scale and reliability of these roles is proved by the historical fact that paddy field irrigation agriculture in the Asia monsoon region has been sustained and developed in various regions over hundreds to thousands of years.

Future basin management

A program of initiatives for emergency basin management during abnormal floods needs to encompass a whole region and include the paddy fields and the irrigation drainage system. A flood mitigation capacity similar to a retarding basin for rivers is needed. During torrential rains that cause rivers to overflow the agreement of everyone affected should be sought in advance. Compensation systems and other preparations should also be developed

In paddy dominant basins where mechanical drainage is practised in low-lying areas, flood plans for its connecting main river are designed for those on a 100-year probability scale. The maximum drainage volume for agricultural facilities is normally assumed on a 10-year probability scale (in some recent cases, 20–30 years). Thus, runoff that exceeds the drainage capacity on a scale of 10 years cannot drain outside the basin, and is forcibly stored in drainage channels and/or paddies.

In other words, farmlands that include agricultural drainage channels and paddies have the function of storing floodwater for drainage rivers, and, as a result, could be said to help reduce the risk of flooding in main rivers downstream. Furthermore, when the discharge exceeds the flow capacity of the main river channel during excessive flooding, water over its capacity is stored in low-lying areas of the basin as the floodwater rises above the levees, or as the levees themselves are breached. The most common land use in such flooded areas is paddies extending widely along the main river channel.

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Enhancing the agronomic productivity of degraded soils in North-east Thailand through clay-based interventions

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Abstract

Although North-east Thailand occupies one-third of the arable land in Thailand, income per capita for the region is no more than 40% of the national average and poverty affects 37% of the population. A major reason for this high level of poverty is the relatively limited natural resources of the region. The soils of North-east Thailand are dominated by sandy, light-textured soils with low organic matter and low clay. Consequently, they have a low water holding capacity, cation exchange capacity (CEC) and, hence, limited buffering capacity against both man-made and natural stresses. Using a paired site analysis, the degree of chemical degradation between an undisturbed (Dipterocarp forest) and disturbed (agriculture system) was assessed. It was estimated that the amount of soil organic carbon lost in the 0–10 cm depth interval ranged from 3.84 to 10.11 t ha^{-1}. This resulted in a dramatic decline in the CEC of the soil. Using a saturation index (S_u) that quantifies degradation based on CEC, the effects of changed land use resulted in S_u values ranging from 52.9–90.3% clearly indicating the impact of agricultural practices on a fundamental property of these soils. In an effort to remediate the chemical attributes of these degraded soils and enhance productivity, a series of field based experiments have been initiated in the Chiang Yuen area of North-east Thailand. Two structured field trials on remediating soil chemical degradation included the following treatments:

- current farmer practice
- termite mound soil
- composted leaf litter
- locally available lake dredged material
- locally sourced bentonite
- waste bentonite from vegetable oil processing
- soil slotting.

The trial land was planted with forage sorghum and two consecutive crops were harvested over the 2002 growing season. Dry matter production ranged from 0.14 to 0.22 t ha^{-1} in the control treatments of each trial—with the plants having almost completely failed because of drought—to 8.4 and 10.0 t ha^{-1} for the termite mound material and local bentonite plus leaf litter compost respectively. These dramatic increases in productivity are probably due to increases in CEC, plant nutrient supply and water holding capacity of the soil. The application of locally resourced high-activity clay materials at a ratio of 2:1 offers a potential way to increase the productivity of degraded light textured soils within the first growing season. This approach to soil rejuvenation could potentially be used to enhance food security at the household level and allow the development of conservation based farming systems.

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ALTHOUGH North-east Thailand accounts for one-third of the arable land in Thailand, income per capita for the region is no more than 40% of the national average and poverty is at a high level affecting 37% of the population (Matsuo, 2002). A major reason for this high level is the relatively limited natural resources of the region. Inherent fertility of soils is low, water resources scarce and rainfall patterns and distribution erratic (Panichapong, 1988). The soils of North-east Thailand are dominated by sandy, light-textured soils with low organic matter and low clay (Ragland and Boonpuckdee, 1987). Consequently they have a low water holding capacity, CEC and hence limited buffering capacity against both anthropogenic and natural stresses. Although the annual precipitation is 800–1400 mm, most of it falls during the six-months rainy season and is often erratic and poorly distributed resulting in seasonal drought periods.

Before the 1950s the region was dominated by climax *Dipterocarp* forest. These were highly productive ecosystems characterised by tight nutrient cycling through organic matter and efficient water use. Increased demand for arable land associated with population growth led to indiscriminate clearing of these forests and a decline in the fertility status of the soils and consequently, productivity. Continuous production of export crops such as rice, kenaf (rosella), cassava, and sugarcane has resulted in a rapid decline in the inherent fertility status of these soils, with an associated loss of productivity.

Rice is frequently grown in this region on land that has an undulating topography. Initially, farmers establish rice crops on such land at the bottom of depressions and subsequently progress up the slope towards the upland (Limpinuntana, 1988). Rice production in the bottom or lower paddies is considerably more stable than that grown in the upper paddy fields. Accordingly, rice can only be grown in the upper paddy fields for one to three years out of five because of insufficient water for transplanting (Limpinuntana, 1988). These upland soils have been extensively leached and eroded and consequently have a low inherent fertility, low CEC, sandy texture, low water holding capacity, low organic matter content and are acid. Consequently, farmers have moved towards low-input and long-duration crops such as cassava and kenaf.

To maintain the productivity of soils, farmers traditionally apply cattle manure and composts derived from household waste and leaf litter to both upland and lowland fields along with sparing amounts of inorganic fertiliser. The production of composts predominantly relies on the cycling of plant materials from areas in close proximity to the field and household organic waste products which may not be sufficient to provide adequate levels of nutrients for enhanced productivity. In addition, the effects of these organic amendments may not be long lasting because of rapid mineralisation and therefore need regular routine additions. For more intensive high-input systems on these light-textured soils, farmers have resorted to rehabilitating them by adding locally available termite mound material. This clearly demonstrates the ability of traditional farmer knowledge in perceiving and implementing strategies to address the issue of declining fertility associated with their production practices. These materials are commercially excavated from large mounds that are the products of termite activities (*Macrotermes* spp.). Farmers will apply up to 7200 t ha^{-1} to small plots where intensive vegetable production is undertaken.

In recent years the dredging of lowland reservoirs throughout Thailand to increase water storage capacity has been undertaken by local councils. The dredged materials, which have relatively high organic carbon and clay contents, become a waste material that requires disposal. These materials are often used in the construction industry as backfill. Recently, farmer groups have investigated the potential role of these dredged materials in improving the productive capacity of their soils. Their main attraction is that they are relatively cheap (US$1.00–3.00 per 6 t truck load, which is significantly cheaper than any chemical fertilisers with equivalent nutrient levels). This practice has rapidly expanded and is generally confined to areas close to the source. However, this practice can damage the soil if the dredged material contains high levels of iron pyrite (acid sulphate). This produces acid in an oxidising environment. In addition, once the process of dredging ceases there will no longer be a supply of this resource.

As farmers traditionally recognise the value of clay materials in restoring the nutrient and water holding capacity of degraded soils, a possible improvement to current practices is the use of high-activity clays. Bentonites are naturally occurring 2:1 layer silicate clays that have a high permanent negative charge due to isomorphous substitution that occurred during formation. As a result of this, they have a high CEC which is often dominated by essential cations such as

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Ca^+ and Mg^+. When bentonites are added to soils they are able to increase the nutrient holding capacity of the soils and therefore reduce potential losses of nutrients through leaching (Noble et al. 2000).

The focus of the current study is on quantifying changes in surface charge characteristics associated with changed land management under two contrasting cropping systems: rice and cassava. Through the construction of charge fingerprints and the subsequent use of the Saturation Index (S_u) (Noble et al. 2000) an estimation of the degree of charge diminution that the soils had undergone from a 'benchmark' state, in this case remnant *Dipterocarp* forest, can be achieved. A field trial was established at Chiang Yuen, North-east Thailand, to evaluate selected strategies that are currently used by farmers to remediate declining productivity, including the use of high activity clay as a soil amendment.

Materials and methods

Assessment of degradation

Six paired sites covering both upland and lowland cropping systems in North-east Thailand were selected for subsequent analysis (Table 1). The selection of sites was based on the criteria of:

- the existence of *Dipterocarp* forest in close proximity to an agricultural production system
- a well defined boundary separating the two production areas
- the same soil type in both areas
- little topographical difference (i.e. slope) between the two areas.

Samples were collected at five points in each area along a transect at right angles to the boundary separating the two systems. Sampling points were 5 m apart and at each point three augur holes (10 cm diameter) were made and soil samples collected at depths of 0–10, 20–30, and 50–70 cm and bulked to form depth-specific, composite samples. Three of the sites were from cassava-based systems (C1–C3) and three from rice-based systems (R1–R3).

Soil analysis

Samples were air dried and sieved to pass a 2 mm mesh. A bulked composite sample was made for each of the paired sites at 0–10, 20–30 and 50–70 cm depth intervals. Basic exchangeable cations were determined by atomic absorption spectrometry after replacement with 0.1 M $BaCl_2$–NH_4Cl as recommended by Gillman and Sumpter (1986). Acidic cations were extracted with 1 M KCl and the extractant titrated to pH 8.0 as described by Rayment and Higginson (1992). The effective cation exchange capacity (ECEC) was calculated as the sum of basic and acidic cations (Ca^{2+}+Mg^{2+}+K^++Na^++Al^{3+}+H^+). Soil organic carbon was determined by wet oxidation using the Walkley and Black method as modified by Rayment and Higginson (1992) and particle size as described by Coventry and Fett (1979).

Charge fingerprints were determined on the composite samples from each site using the method of Gillman and Sumpter (1986). Records of the amounts of acid or base added to the tubes during the equilibration phase were kept and these converted to $cmol_c$ H^+/OH^- added/kg of soil. These values were plotted against the equilibrium pH for each tube and the inverse of the slope of this relationship was taken to be the pH buffering capacity (pHBC) of the soil. Curves associated with the charge fingerprints were fitted using the curve fitting function of SigmaPlot 4.0 for Windows.

Soil chemical degradation index

A saturation index (S_u) as proposed by Noble et al. (2000) was used to quantify charge diminution from an agronomic ideal state. The S_u index has the following format:

$$S_u = 100 \text{ x } (C_{u5.5} - \Sigma)/C_{u5.5} \qquad (1)$$

where $C_{u5.5}$ refers to the CEC at pH 5.5 of the undisturbed (*Dipterocarp* forest) soil as determined from the charge fingerprint, and Σ is the sum of the base cations actually present in the system under review. A low S_u indicates closeness to the ideal condition for that particular soil.

Field trial

Two independent field trials were established at Chang Yuen Research Station of the Department of Livestock, Region 5, North-east Thailand in the 2001 and 2002 growing seasons. The trial site is in an upland position with a gently undulating topography. The trial consisted of a randomised block design with four replications. Each plot was 5 x 10 m with a 1 m break between treatments. In the trial established in 2001 the following treatments were applied:

Table 1. Selected information associated with location, parent material, land use and soil classification for the samples taken from cassava (C1, C2, C3) and rice-based systems (R1, R2, R3) in North-east Thailand.

Sample site and No.	Province	Thai soil form	Current production system	GPS location	Parent material	Land form	Previous vegetation	Years under production system	Comments
C 1	Sisaket	Korat	Forest	15° 16' 33" N 104° 01' 05" E	Alluvium	High terrace	Dipterocarp	Unknown	Community forest for 14 years
	Sisaket		Cassava		Alluvium	High terrace	Dipterocarp	40	
C 2	Sisaket	Yasothon	Forest	15° 17' 01" N 104° 01' 22" E	Alluvium	High terrace	Dipterocarp	Unknown	Community forest for 14 years
	Sisaket		Cassava		Alluvium	High terrace	Dipterocarp	40	
C 3	Sisaket	Korat	Forest	15° 16' 18" N 104° 01' 44" E	Alluvium	Middle terrace	Dipterocarp	Unknown	Community forest for 14 years
	Sisaket		Cassava		Alluvium	Middle terrace	Dipterocarp	38	
R1	Yasothon	Roi-et	Forest	15° 35' 59" N 104° 10' 38" E	Alluvium	Low terrace	Dipterocarp	Unknown	National Reserved forest
	Yasothon		Low land rice		Alluvium	Low terrace	Dipterocarp	37	
R 2	Roi-et	Roi-et	Forest	15° 47' 36" N 103° 57' 04" E	Alluvium	Low terrace	Dipterocarp	Unknown	Spiritual forest
	Roi-et		Low land rice		Alluvium	Low terrace	Dipterocarp	50	
R 3	Roi-et	Roi-et	Forest	15° 49' 29" N 103° 55' 51" E	Alluvium	Flood plain	Swamp forest	Unknown	Spiritual forest
	Roi-et		Low land rice		Alluvium	Flood plain	Swamp forest	100	

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Trial 1

- T1.1. Control 1—current farmer practice of tillage and fertiliser additions
- T1.2. Termite mound soil applied at 120 t ha^{-1}
- T1.3. Leaf compost applied at 10 t ha^{-1}
- T1.4. Dredged lake material at 120 t ha^{-1}
- T1.5. Waste bentonite at 50 t ha^{-1}
- T1.6. Waste bentonite at 50 t ha^{-1} + 5 t ha^{-1} lime

The termite mound soil was excavated from active mounds in the district and brought to the site. Compost was produced locally by farmers using leaf litter collected from remnant *Dipterocarp* forest and household vegetable matter. Over the past five years local governments in the north-east have been dredging water storage facilities to increase capacity. The dredged material is either dumped on farm land or used as landfill in building projects. Dredged material used in the current study was sourced from a local contractor. Waste bentonite is a by-product from the vegetable oil industry where activated bentonite is used to clarify oil. The waste product is acidic and is disposed of in landfills. Waste bentonite from a soybean oil processing plant in the Bangkok area was sourced and two treatments imposed: the waste product on its own, and the waste bentonite with lime applied to neutralise residual acidity (pH approximately 3.5) associated with the activated bentonite. All treatments were broadcast applied and incorporated into the top 20 cm using a rotary hoe. Forage sorghum was established in 2001, however, because of the poor season conditions, the trial had to be abandoned. The trial was re-established to forage sorghum in 2002 and these results are presented.

An additional study (Trial 2) was established in 2002 to investigate alternative soil amendment technologies that are currently being assessed in the north-east. The following treatments were imposed:

Trial 2

- T2.1. Control 2—current farmer practice tillage and fertiliser addition
- T2.2. Slotting
- T2.3. Slotting + 50 t ha^{-1} bentonite
- T2.4. Slotting + 50 t ha^{-1} bentonite + 10 t ha^{-1} compost
- T2.5. Local bentonite at 50 t ha^{-1}
- T2.6. Local bentonite at 50 t ha^{-1} + compost at 10 t ha^{-1}

Due to the unique particle size distribution of soils in the North-east, repeated tillage operations result in the development of a compact layer at about 15–20 cm and more importantly slumping or structural collapse of the soil that occurs shortly after the start of the wet season. This results in the tilled profile becoming compacted and hard-setting as it begins to dry out. By creating a slot through this compacted layer, roots proliferate better and the crops are able to extract deeper water and nutrients. In addition, the structure of the slots would reduce or even prevent structural collapse. Slots were carefully excavated by hand (Figure 1). The removed soil from the slot was then mixed with the equivalent of 12.5 t ha^{-1} of bentonite before being placed back into the slot. The remaining 37.5 t ha^{-1} was applied as a broadcast application and incorporated into the surface 20 cm. Similarly, for the slot + bentonite + compost, one quarter of the bentonite and compost was added to the slot and the remaining incorporated into the top 20 cm using a rotary hoe. All slots were positioned on the planting row. The bentonite used in Trial 2 was quarried locally in the Lopburi province and is commercially used in the prawn farming industry. The compost used came from the same source as in Trial 1.

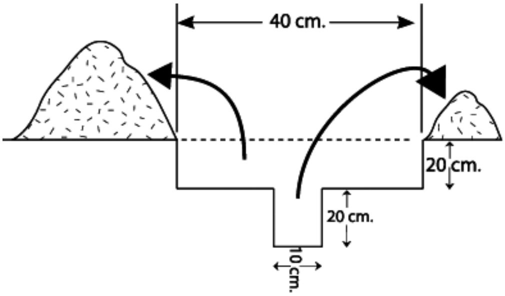

Figure 1. Diagram depicting the structure and dimensions of slots used in field Trial 2 at Chiang Yuen, North-east Thailand.

During the 2002 season forage sorghum was established on 7 June 2002 by sowing seeds in a small furrow and lightly covering them with loose soil. Plants were thinned one month later to a spacing of about 20 cm. An application of a proprietary formulated fertiliser (16–20–0; N:P:K) at a rate of 200 kg/ha was made to all plots one month after establishment and thereafter at monthly intervals. Hand weeding was undertaken throughout the growing season as and when required. Two biomass harvests were conducted during the growing season with the crop being allowed to grow out after the first harvest. The entire plot was harvested and material removed for fresh weight determination and a sub-sample returned to the laboratory for dry matter determination.

Analysis of yield data was undertaken using the ANOVA module of the GENSTAT package for each of the trials (Genstat Committee 1993).

Results and discussion

Assessing degradation

Site history

North-east Thailand has undergone dramatic changes in land use over the past 40 years. This has included a move away from subsistence based agriculture to commercial farming systems. Much of the land affected has been traditionally used for paddy subsistent rice production for more than 100 years. A move towards upland crop production was initiated about 40 years ago with cassava and sugarcane becoming dominant components of these systems in the past 20 years. The production system is characteristically a rotation one with a five-year cropping cycle followed by a two to three-year fallow as a way to improve the fertility of these light textured soils. The three upland sites all currently support cassava production. The adjacent 'benchmark' sites had previously been under cassava production but were abandoned about 14 years ago and have reverted back to regenerated *Dipterocarp* forest. In contrast, the three lowland rice production systems were established on lands that were previously dominated by *Dipterocarp* forest or lowland swamp forest.

Soil chemical and physical properties

The soil series represented at the 6 sites were the Roi-et (fine-loamy, mixed, isohyperthermic Aeric Paleaquults); Korat (fine-loamy, siliceous, isohyperthermic Oxic Paleustults); and Yasothon (fine-loamy, siliceous, isohyperthermic Oxic Paleustults) (Soil Survey Staff, 1990) (Table 1). All of these series were formed from old alluvium and occur on low, middle and high terraces respectively. These soils are dominated by coarse and fine sand with very low clay contents (range: 2.4–15.5%) (Tables 2 and 3). The texture is relatively uniform deep into the soil profile with the percentage of clay ranging from 2.4 to 15.5% (Tables 2 and 3).

Soil pH, organic C, exchangeable basic and acidic cations, effective cation exchange capacity (ECEC), pHBC, CEC_b and CEC_t for each of the depth intervals are presented in Tables 2 and 3. Differences in pH between the benchmark sites and adjacent cultivated sites were not marked and no clear trends in pH changes were seen (Tables 2 and 3). In three cases (C1, C2, R5) there was a small decline in the pH of the surface 0–10 cm between the forest and cultivated sites. For the three cassava sites (C1–C3) this may in part be attributed to the fact that the sites were previously cultivated. Differences in exchangeable acidity reflected trends in soil pH with an increase in exchangeable acidity and a decline in pH. Exchangeable acidity cations (hydrogen and aluminium) dominated the exchange complex at several of the sites as soil pH declined. Exchangeable basic cations were lower at the 0–10 cm level on the disturbed sites, but this trend was reversed with depth suggesting that leaching of basic cations from surface layers to deeper ones had occurred as a result of changed land use (Tables 2 and 3). Of the exchangeable bases, Ca^{2+} dominated the exchange complex. The concentration of K^+ on the exchange complex was very low in the surface 0–10 cm of cultivated sites, suggesting these soils would respond to prophylactic applications of potassium-based fertilisers and that there had been significant removal or loss of potassium with changed land use.

Over the intervening period since conversion from forest to continuous agriculture, soil organic carbon (OC) declined markedly in the upper soil layers (0–10 cm) (Tables 2 and 3). The loss in soil OC resulting from cultivation ranged from 3.84 t ha^{-1} at site R1 through to 10.11 t ha^{-1} at site R3, a site previously dominated by swamp forest (Table 4). Clearly such dramatic declines in OC would significantly affect properties associated with cation retention, pH buffering and the water-holding capacity of these soils.

Surface charge fingerprints

The dominant soil series of North-east Thailand are sandy with little OC, and have a clay mineralogy dominated by highly ordered kaolinite and oxides (Panichapong, 1988). These soils have only modest surface charge, with both permanent and variable charge components. For brevity, graphical representations of surface-charge fingerprints for each of the composite depths for the forest and cultivated sites are presented for two of the six sites (Figures 2 and 3). The general trend exhibited for each site is that the greatest degree of charge diminution occurred in the surface 0–10 cm depth interval. A distinctive characteristic of the curves derived for the 0–10 cm depth interval at the C1 site is that the negative charge generated varied from approximately 1.1 to 2.1 $cmol_c$ kg^{-1} and 0.5 to 1.2 $cmol_c$ kg^{-1} over the pH

Table 2. Selected chemical and physical properties of composite samples collected from selected depth intervals from paired sites in North-east Thailand that are currently under a cassava cropping system (C).

Site No.	Depth (cm)	Vegetation	$pH_{0.002}$	OC (%)	Ca^{2+}	Mg^{2+}	K^+	Na^+	Exch. acidity	ECEC	$CEC_{B5.5}$	CEC_T	pHBC ($cmol_c$/kg.pH)	C Sand	F Sand	Silt	Clay
					($cmol_c$/kg)									(%)			
C1	0–10	Forest	5.18	0.667	0.742	0.404	0.092	0.003	0.115	1.356	1.571	1.402	0.922	47.2	43.0	5.0	4.9
C1	20–30	Forest	4.95	0.399	0.184	0.231	0.041	0.004	0.628	1.087	1.132	1.043	0.665	45.9	42.4	4.3	7.4
C1	50–70	Forest	5.18	0.114	0.039	0.173	0.015	0.002	0.495	0.725	0.602	0.640	0.249	44.9	44.9	4.7	5.5
C1	0–10	Cassava	5.00	0.327	0.250	0.109	0.034	0.001	0.354	0.749	0.827	0.608	0.625	46.5	45.7	3.0	4.7
C1	20–30	Cassava	4.86	0.364	0.169	0.067	0.027	0.001	0.978	1.242	1.162	1.084	0.599	40.7	46.8	4.5	8.0
C1	50–70	Cassava	5.04	0.103	0.152	0.049	0.013	0.003	0.617	0.834	0.742	0.750	0.284	40.8	47.8	4.8	6.6
C2	0–10	Forest	5.05	1.081	0.798	0.454	0.068	0.003	0.219	1.541	2.091	1.767	1.142	39.5	46.4	6.4	7.7
C2	20–30	Forest	4.96	0.570	0.215	0.256	0.051	0.003	0.616	1.141	1.292	1.137	0.762	35.3	49.1	5.2	10.3
C2	50–70	Forest	4.91	0.210	0.093	0.119	0.015	0.004	0.684	0.915	0.969	0.858	0.508	37.8	45.4	5.2	11.6
C2	0–10	Cassava	5.02	0.427	0.338	0.113	0.036	0.003	0.435	0.924	0.912	0.768	0.829	44.6	48.3	3.2	3.9
C2	20–30	Cassava	5.01	0.397	0.619	0.196	0.023	0.004	0.452	1.293	1.373	1.216	0.796	36.9	46.1	5.3	11.7
C2	50–70	Cassava	5.02	0.204	0.498	0.179	0.014	0.003	0.574	1.268	1.201	1.124	0.546	30.2	49.1	5.2	15.5
C3	0–10	Forest	5.08	0.651	0.591	0.366	0.045	0.004	0.316	1.322	1.643	1.418	1.066	42.5	47.0	5.4	5.1
C3	20–30	Forest	4.98	0.285	0.085	0.146	0.024	0.003	1.043	1.302	1.187	1.059	0.659	40.4	47.4	5.3	6.8
C3	50–70	Forest	4.94	0.162	0.095	0.132	0.012	0.003	1.081	1.323	1.309	1.229	0.470	37.5	47.3	5.7	9.6
C3	0–10	Cassava	5.25	0.284	0.303	0.108	0.031	0.003	0.291	0.736	0.731	0.692	0.585	47.4	43.2	3.1	6.3
C3	20–30	Cassava	4.96	0.228	0.205	0.065	0.016	0.004	0.861	1.151	1.054	0.956	0.549	50.6	38.3	4.4	6.7
C3	50–70	Cassava	5.09	0.087	0.193	0.041	0.009	0.006	0.741	0.992	0.774	0.758	0.345	46.2	43.6	4.3	5.8

Table 3. Selected chemical and physical properties of composite samples collected from selected depth intervals from paired sites in North-east Thailand that are currently under a rice cropping system (R).

Site No.	Depth (cm)	Vegetation	$pH_{0.002}$	OC (%)	Ca^{2+}	Mg^{2+}	K^+	Na^+	Exch. acidity	ECEC	$CEC_{B5.5}$	CEC_T	pHBC ($cmol_c$/kg.pH)	C Sand	F Sand	Silt	Clay
					($cmol_c$/kg)									(%)			
R1	0–10	Forest	4.72	0.963	0.246	0.192	0.092	0.019	0.873	1.421	1.674	1.309	1.321	42.9	43.2	8.4	5.4
R1	20–30	Forest	4.89	0.346	0.056	0.081	0.032	0.011	0.695	0.875	1.035	0.826	0.683	44.7	43.3	8.1	3.8
R1	50–70	Forest	5.21	0.133	0.040	0.046	0.014	0.008	0.434	0.541	1.054	0.535	0.324	44.2	44.5	7.7	3.5
R1	0–10	Rice	5.09	0.668	0.601	0.110	0.040	0.036	0.212	1.000	1.210	1.072	0.759	52.2	37.7	6.7	3.5
R1	20–30	Rice	5.12	0.156	0.184	0.085	0.028	0.017	0.525	0.839	0.809	0.795	0.387	48.5	37.6	8.8	5.1
R1	50–70	Rice	4.95	0.103	0.319	0.120	0.044	0.016	0.897	1.395	1.070	1.028	0.342	45.2	40.6	7.7	6.6
R2	0–10	Forest	4.87	0.850	0.340	0.204	0.074	0.029	0.575	1.222	1.335	1.083	1.070	38.4	50.7	6.0	4.9
R2	20–30	Forest	4.91	0.337	0.041	0.051	0.030	0.020	0.539	0.681	0.743	0.640	0.552	38.7	52.1	5.4	3.8
R2	50–70	Forest	5.22	0.108	0.021	0.012	0.007	0.009	0.290	0.339	0.375	0.309	0.288	42.5	49.7	5.4	2.5
R2	0–10	Rice	5.18	0.214	0.142	0.027	0.040	0.011	0.190	0.410	0.481	0.455	0.407	42.1	49.5	5.7	2.7
R2	20–30	Rice	5.16	0.114	0.081	0.024	0.005	0.009	0.320	0.439	0.445	0.434	0.335	38.6	51.9	6.3	3.2
R2	50–70	Rice	5.39	0.042	0.021	0.007	0.003	0.007	0.208	0.247	0.361	0.384	0.218	43.0	48.1	6.2	2.8
R3	0–10	Forest	5.16	1.064	1.438	0.452	0.056	0.017	0.144	2.107	2.524	2.313	1.228	44.7	43.8	6.9	4.6
R3	20–30	Forest	5.10	0.178	0.154	0.094	0.014	0.009	0.224	0.494	0.618	0.532	0.393	43.9	47.2	5.7	3.1
R3	50–70	Forest	5.46	0.099	0.063	0.032	0.007	0.011	0.125	0.239	0.314	0.339	0.205	45.0	45.6	7.0	2.4
R3	0–10	Rice	5.03	0.286	0.161	0.045	0.017	0.022	0.863	1.108	0.672	0.626	0.446	48.2	41.6	6.3	3.9
R3	20–30	Rice	5.21	0.094	0.105	0.027	0.006	0.004	0.331	0.472	0.473	0.478	0.242	38.2	45.6	9.8	6.3
R3	50–70	Rice	4.93	0.091	0.717	0.269	0.023	0.041	0.681	1.734	1.718	1.674	0.288	31.6	44.7	12.1	11.6

range for the forested and cultivated sites respectively (Figure 2). Conversely, for the same depth interval, the negative charge generated for the R4 site ranged from 0.8 to 1.8 $\mathrm{cmol_c\ kg^{-1}}$ and 0.2 to 0.8 $\mathrm{cmol_c\ kg^{-1}}$ over the imposed pH range (Figure 3). The greatest difference in the shapes of the charge curves was observed in the surface horizons, this being ascribed to the higher OC content (Table 2 and 3) under the forest sites. This clearly quantifies the potentially deleterious effects of clearing, and subsequent use for agriculture, of forest lands that have soils with a relatively low permanent charge component. In short, the role of OC in maintaining negative charge on these soils is critical for retaining and supplying cations. That the greatest degree of degradation occurs in the surface layers is somewhat heartening since remediation of this charge decline is possible through either soil organic matter conservation or other engineering solutions. With increasing depth, the effect of a change in land use on the surface charge between the two sites decreased (Figure 2 and 3) thus confirming that the negative effects are confined to surface horizons.

Table 4. Net losses in soil organic carbon (OC) and saturation index (S_u) estimating the degree of degradation associated with changed land use from forest to cassava based (C) and rice based (R) cultivation for the surface 0–10 cm depth interval. Values in the table represent the differences between forested and agricultural production systems taken from three sites in each agriculture system.

Site no.	OC loss from 0–10 cm depth interval (t $\mathrm{ha^{-1}}$)	S_u for the 0–10 cm depth interval (%)
C1	4.42	74.8
C2	8.50	76.6
C3	4.77	72.9
R1	3.84	52.9
R2	8.27	63.0
R3	10.11	90.3

To compare surface charge diminution with depth due to changed land use, the $\mathrm{CEC_b}$ at pH 5.5 was calculated from the surface charge regression curves for each of the sites and are presented in Tables 2 and 3. The greatest differences between $\mathrm{CEC_b}$ at pH 5.5 were generally observed in the surface 0–10 cm (Table 2 and 3). These differences always diminished with depth other than at sites C1 and R3 where the $\mathrm{CEC_b}$ increased under the cultivated system. This can partly be attributed to the increase in clay content at depth under the cultivated system indicating a degree of heterogeneity of soils at these sites. The decline in OC with cultivation invariably alters the ratio of organic-to-inorganic surfaces, resulting in marked changes in the surface charge characteristics of the soil. Therefore, OC has a direct influence on the CEC of the soil as has been clearly demonstrated by Willett (1995) for light textured sandy soils of Northeast Thailand. Consequently, conservation of organic matter should therefore become the focus of land management strategies.

The charge fingerprint allows $\mathrm{CEC_t}$ to be estimated at the inherent soil's pH. If the basic and acidic cations removed by the $\mathrm{BaCl_2\_NH_4Cl}$ and KCl extractants respectively are all exchangeable cations then their sum (the ECEC) should be equal to $\mathrm{CEC_t}$ at soil pH, within the limits of the experimental error. A graph of ECEC against $\mathrm{CEC_t}$ at the soil's pH for the forested and cultivated soils shows excellent agreement between these independently determined properties for all depth intervals suggesting that most of the cations extracted were effectively on the exchange complex (Figure 4). Points showing the greatest deviation from the 1:1 line were from surface horizons suggesting some of the cations extracted were not associated with the exchange complex.

A potential measure of the degree of chemical degradation that a soil has undergone because of changed management is achieved by the quantification of acidification through the percent acid saturation of the CEC. A limitation of this method lies in the assumption that the CEC is a fixed quantity, and that degradation is associated with increasing occupation of it by $\mathrm{Al^{3+}}$, to the exclusion of important nutrients (basic) cations (Noble et al. 2000). However, the charge fingerprint demonstrates that CEC itself, particularly the agronomic important $\mathrm{CEC_b}$, decreases with pH. Hence, the saturation index (S_u) was proposed by Noble et al. (2000) to take into account the effect of changed land use on the intrinsic surface charge characteristics of a soil. The S_u values were calculated for the 0–10 cm depth interval using equation 1 and are presented in Table 4. The S_u index ranged from 53–90% when compared to the forest benchmark (Table 4). This degree of degradation is considerable and clearly shows the vulnerable nature of these soils to damage associated with changed land use.

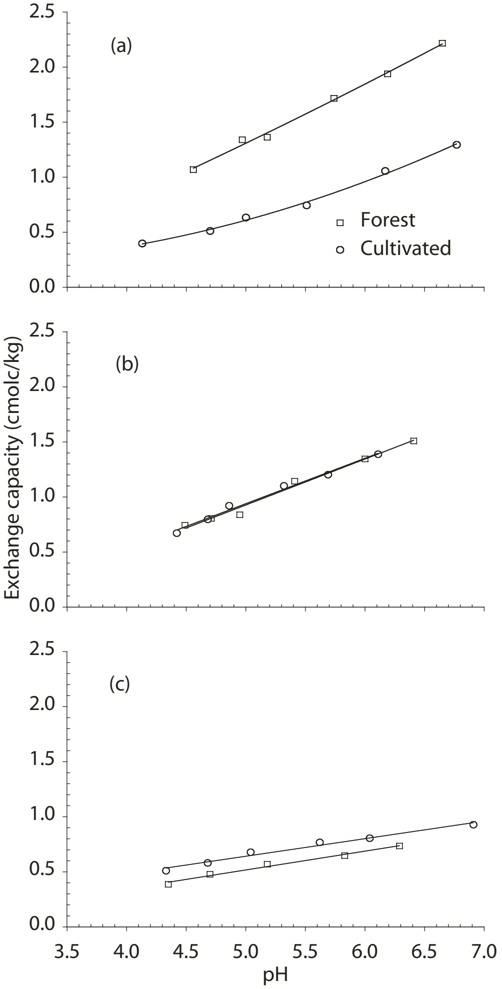

Figure 2. Surface charge fingerprints (CEC_b) at one site of a cassava based cultivation system (C) and adjacent forest sites for the (a) 0–10 cm; (b) 20–30 cm; and (c) 50–70 cm depths respectively.

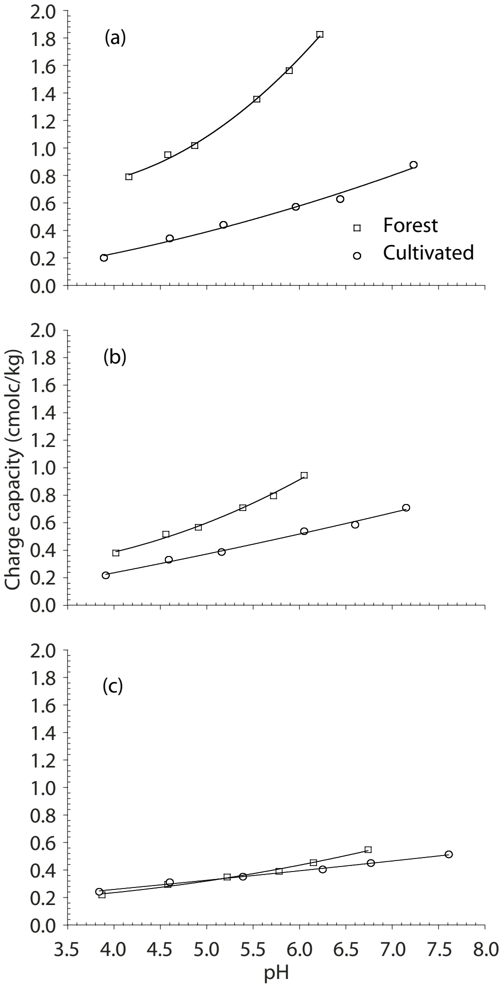

Figure 3. Surface charge fingerprints (CEC_b) at one site of a rice based cultivation system (R) and adjacent forested site for the (a) 0–10 cm; (b) 20–30 cm; and (c) 50–70 cm depths respectively.

Field trials—Chiang Yuen

The soil used in the study was classified as a Satuk (fine-loamy, siliceous, isohyperthermic Oxic Paleustults) (Soil Survey Staff, 1990) with a low CEC (mean of 1.80 $cmol_c$ kg^{-1} over a 40 cm depth) and acid in reaction (pH_{Ca} 4.0). Before the trials were established, *Stylosanthes* had been cultivated for forage production.

While soil moisture conditions were ideal for establishing the crop, growing conditions rapidly deteriorated after the crop emerged in the middle to latter part of June (Figure 5). Further dry periods were experienced for much of the month of July. This significantly affected the performance of the crop under different treatments, with crops on the bentonite treatments appearing to withstand the stress conditions more effectively.

Trial 1

The dry matter (DM) yields of the two harvests during the 2002 growing season for Trial 1 are presented in Table 5. A high degree of variability was observed between replicates of the same treatment this being attributed to the variable growing conditions and the unthrifty re-growth that was evident on some plots after the first harvest. Accordingly, the control and dredge treatments were unable to sustain a crop of forage sorghum beyond the first harvest while only a single replicate in the compost treatment was able to support sorghum re-growth (Table 5). Yields from the two harvests remained relatively stable with termite mound material (T1.2) suggesting a persistence of the response and better growing conditions. The addition of lime to the waste bentonite had a positive effect on DM yield over the two harvest periods when compared with the waste bentonite on its own (Table 5). An ANOVA was undertaken on the cumulative yield from the two harvests. Due to the skewed distribution of the data and therefore non-conformity to normality, a $\log_{10}$ of the data was undertaken resulting in a reduction of the coefficient of variation from 44.3 to 10.1% (Table 6). All applied treatments differed significantly ($p< 0.05$) from the control (Table 6) with the termite mound material resulting in significantly higher yields than all treatments. The second best performing treatment was the waste bentonite with lime applied to neutralise the excess acidity (Table 6).

These results clearly demonstrate the positive role of traditional termite mound soil as a way to remediate degraded soils. The application rate of 120 t ha^{-1} is extremely conservative when compared to rates of over 7200 t ha^{-1} that are commonly used by vegetable farmers in the region to increase productivity of soils.

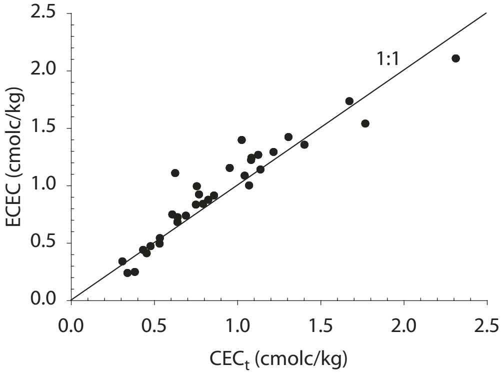

Figure 4. Relationship between the effective cation exchange capacity (ECEC) and the total cation exchange capacity (CEC$_t$) over all depth intervals.

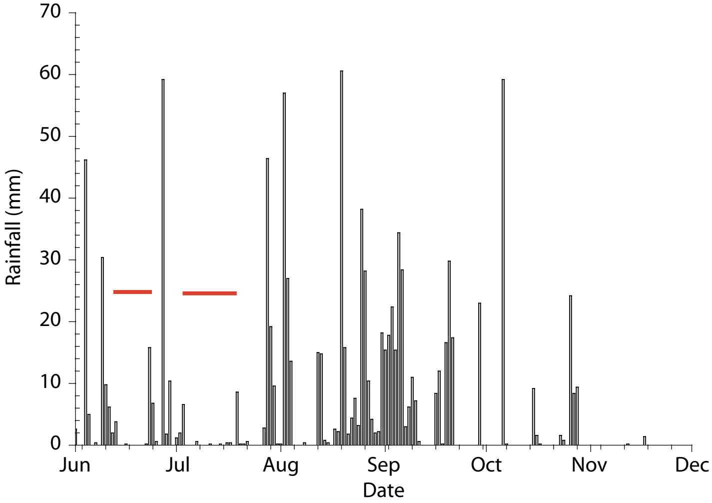

Figure 5. Rainfall distribution over the 2002 growing at Chiang Yuen, North-east Thailand. Bars indicate potential water stress periods during the early part of the growing season.

The benefits associated with these high rates of application warrant the initial financial investment as vegetable growers are often able to recover these costs within the first year (personal communications), and as increased productivity persists for between five and 10 years depending on the cropping intensity and quality of the material. This is certainly an economically viable proposition.

Table 5. Dry matter (DM) yields of forage sorghum for each harvest date (days after planting) over the 2002 growing season for Trial 1. Values in parentheses are the SE of the mean.

Treatment code	Description	100 DAP[a]	166 DAP
		DM (kg ha^{-1})	
1.1	Control	117.7 (27.8)	nh
1.2	Termite soil	3517.8 (468.8)	3195.1 (181.1)
1.3	Leaf compost	865.8 (469.0)	[b]513.3 (513.3)
1.4	Dredged lake material	643.8 (88.5)	nh
1.5	Waste bent	392.5 (93.3)	651.5 (376.8)
1.6	Waste bent[a] lime	1180.9 (221.7)	911.3 (551.3)

[a] DAP = days after planting

[b] A single replication was harvested due to failure of growth after the first harvest in the other two replicates.

nh = no harvest; bent = bentonite

Table 6. Cumulative adjusted mean dry matter and log transformed yield data for forage sorghum over the 2002 growing season for Trial 1.

Treatment Code	Description	Cumulative yield (kg ha^{-1})	Log transformed
1.1	Control	138.1	2.040
1.2	Termite soil	8379.1	3.823
1.3	Leaf compost	837.9	2.823
1.4	Dredged lake material	789.2	2.797
1.5	Waste bent	927.2	2.867
1.6	Waste bent + lime	2219.2	3.246
LSD$_{(0.05)}$			0.445
CV (%)			10.1

bent = bentonite

Trial 2

The results from the two consecutive harvests for Trial 2 are presented in Table 7. Once again the control (T2.1) with the few plants remaining and slotting treatments (T2.2) were unable to sustain yields beyond the first harvest (Table 7). There was a high degree of variability between replicates within the same treatments. It is of note that in both the slotting treatments that received bentonite (T2.3 and T2.4) yields between the first and second harvests increased substantially, possibly because the crop was able to take advantage of the effects of the imposed treatments as it developed. Contrasting this, the yields of the broadcast bentonite treatments with or without compost remained relatively stable over the two harvest periods. The cumulative yield for each of the treatments was subjected to ANOVA and required a log$_{10}$ transformation (Table 8). Those treatments receiving a broadcast application of bentonite (T2.5 and T2.6) gave significantly ($p<0.05$) higher increases in dry matter than all other treatments with yields of 9.9 and 10.0 t ha^{-1} respectively. Similarly, the slotting treatments that incorporated bentonite (T2.3 and T2.4) had significantly higher yields than slotting on its own (T2.2) and the control (T2.1) (Table 8). It would appear that the addition of bentonite enhanced the efficacy of the slots although one could argue that the response may in part be due to the presence of a localised region with high activity clays.

Table 7. Dry matter (DM) yields of forage sorghum for each harvest date over the 2002 growing season for Trial 2. Values in parentheses are the SE of the means.

Treatment Code	Description	100 DAP[a]	166 DAP
		DM (kg ha^{-1})	
2.1	Control	220.2 (37.7)	nh
2.2	Slotting	169.8 (32.9)	nh
2.3	Slotting + bent	389.2 (93.9)	2836.36 (320.1)
2.4	Slotting + bent + comp	1242.1 (307.1)	4085.7 (558.6)
2.5	Local bent	5443.9 (1395.3)	4380.0 (443.9)
2.6	Local bent + comp	5959.8 (1497.7)	4283.2 (733.8)

[a] DAP = days after planting

nh = no harvest; bent = bentonite; comp = compost

Table 8. Dry matter yields of forage sorghum for each harvest date over the 2002 growing season for Trial 2. Values in parentheses are the SE of the means.

Treatment code	Description	Cumulative yield (kg ha^{-1})	Log transformed
2.1	Control	222.5	2.323
2.2	Slotting	170.7	2.208
2.3	Slotting + bent	3367.5	3.503
2.4	Slotting + bent + comp	5461.5	3.713
2.5	Local bent	9915.4	3.972
2.6	Local bent + comp	10053.3	3.978
LSD$_{(0.05)}$			0.219
CV(%)			4.4

bent = bentonite; comp = compost

In evaluating results from both experiments the increases in yield associated with termite mound material and bentonite plus compost is of the order of 57 and 46 times higher than the current best practice (control treatments). These are exceptionally high increases and one should treat them with caution as the growing season was atypical. Notwithstanding this, the response to soil improvement technologies has been substantial and clearly demonstrates the responsiveness of these systems to such intervention. What is important for farmers is that tangible yield increases are observed within the first season after the imposition of treatments as this will strongly influence adoption. The fact that farmers will use termite mound material to improve their soils clearly shows their willingness to make a significant financial investment to facilitate improved productivity on the basis of an assured return. Applying locally available bentonite clay materials at lower rates of application than are currently used for termite mound materials may achieve the same outcomes with little if any negative environmental impact (i.e. the destruction of termite populations).

Conclusions

Light-textured, sandy soils are common throughout the tropics and constitute an important economic resource for agriculture despite their inherent infertility (Panichapong, 1988). During the period 1982 to 1998, 500,000 ha of climax *Dipterocarp* forest was cleared for agricultural activities in North-east Thailand, this largely being driven by a population increase of 4.8 million in the region (Office of Agricultural Economics, 2001). Changed land use has dramatically decreased the nutrient status of these soils. This has largely been caused by declining soil OC in surface horizons where the greatest degree of mixing occurs. Moreover, this study clearly demonstrated the fragility of these soils when cleared of their native *Dipterocarp* climax communities for agricultural production and supports the preliminary findings discussed for this region by Noble et al. (2000). These negative impacts on the soil resource base are not confined to particular parts of the landscape but have occurred in both upland and lowland areas.

The key driver associated with chemical degradation on these soils is charge diminution through a loss of OC due to continuous tillage. The restoration of soil organic matter status would significantly reduce the decline in CEC and cation loss due to changed land use. However, this is not easily achievable in tropical and sub-tropical environments where regular cultivation is used to prepare seedbeds and control weeds. The introduction of long-term grass leys in rotation with crops would increase the soil organic carbon content and directly benefit the charge characteristics of the soil, and carbon sequestration (Noble et al. 1998; 2003). However, for resource poor farmers in developing countries whose primary objective is house-hold food security, the implementation of long-term grass leys into their farming systems is often viewed as an unattractive option. In addition, in situ generation of organic matter on these degraded soils may not be possible without large inputs of inorganic fertilisers and water.

The extent of soil fertility decline is well recognised by farmers in the region as they have developed a strategy to reverse chemical degradation based on the use of termite mound materials and, more recently, the application of lake-dredged materials. Both these strategies have been assessed in the current study along with the use of high-activity bentonite clays either naturally mined or as a waste by-product. The application of permanently-charged high-activity bentonite clays to soil will have a positive effect on the surface charge characteristics of soils as demonstrated by Noble et al. (2001). In the current study relatively modest rates of application of these materials have been shown to result in significant enhancements in productivity on these degraded soils during a season that could be described as atypical and not conducive to maximum crop production. The use of these materials may offer an alternative to current traditional practices that could be viewed as ecologically unsustainable in the case of termite mound materials. In addition, lake-dredged materials will only be available while these activities continue in the North-east. There is also the risk of exposing acid sulphate materials that could significantly damage the soil if incorporated. Further assessment of selected strategies for remediating degraded soils by farmers in a participatory action research program is currently being undertaken in the region.

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Rainfed lowland rice-growing soils of Cambodia, Laos, and North-east Thailand

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Abstract

There has been little critical assessment of the similarities and differences between the lowland rainfed rice soils of Cambodia, Laos, and North-east Thailand and their implications for soil management. The purpose of this paper is to review the published literature on soil properties and their spatial distribution in Cambodia, Laos and North-east Thailand, the main soil and water related constraints identified for lowland rainfed rice, and the similarities and differences in soil management technologies that relate to water use. While rainfed rice is the dominant crop, rainfall and its seasonal distribution varies significantly across the region so that cropping patterns vary, especially those for pre-rice and post-rice cropping with field crops. However, for lowland rainfed rice, surface hydrology can vary with natural and artificial drainage patterns and subtle topographic variations to the extent that locally it may override the influence of rainfall. This can make it difficult to regionally assess the prevalent hydrological regimes. Cambodia has a higher prevalence of seasonally flooded, alluvial soils than North-east Thailand or Laos. Substantial areas of sandy, high permeability soils are used for lowland rice in the region, but especially in North-east Thailand. Standing rainwater drains quickly from the soils of these fields exposing the rice to drought and high rates of nutrient leaching. However, loss of soil-water saturation may limit rice yield by inhibiting nutrient uptake more often than drought, per se. The interaction between water supply and nutrient acquisition requires further investigation. Shallow ground water is a potential resource for supplementary irrigation but the scope for using it has not been adequately examined. In North-east Thailand and parts of Laos, salinity in the ground water may be the major limitation on its use. Prospects for growing field crops in the lowlands depend on the amounts and reliability of early wet season rainfall or on amounts of stored water after harvesting rice. Apart from drought, waterlogging and inundation are significant water-related hazards for growing field crops in the early wet season. In addition, soil-fertility constraints in the early wet season and dry season will likely differ from those encountered by rice due in part to the different soil-water regime they encounter.

Introduction

THE geographical proximity of Cambodia, Laos and North-east Thailand, and the prevalence of rainfed lowland rice as the major crop in their agro-ecosystems suggest that the cross-flow of research information among these regions should be helpful. Coordination and collaboration among these countries could minimise duplication of research, and maximise synergies in their collective research. Significant overlap in soil characteristics may facilitate the exchange of research information among these countries to their mutual advantage. This means there is no need for each country to try to maintain an elaborate soil management and agronomy research program. However, exchange needs to be based on a critical examination of the similarities and differences in their agro-ecological classifications, the prevalence of rainfed rice ecosystems, and in the soils used for rice and field crop production. Previously, there has been little critical assessment of the similarities and differences in soils of Laos, Cambodia and North-east Thailand and their response to soil management technologies. Since research on lowland rainfed rice (LRR) soils and rice growth on them is

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comparatively recent for Cambodia and Laos, such a detailed and critical analysis has not hitherto been feasible. The purpose of this paper will be to review the published literature on soil properties and their spatial distribution, the main soil-water- related constraints identified for Laos, Cambodia and North-east Thailand, and the similarities and differences in soil management technologies found to be effective. Areas of common strategic interest for research on soil management technologies will be identified and discussed. Most emphasis will be given to lowland rainfed rice.

Rainfall and surface hydrology

Total rainfall, and rainfall patterns vary across each of the regions (e.g. Limpinuntana 2001; Ouk et al. 2001; Schiller et al. 2001). In Cambodia, most rice growing areas have a mean annual rainfall of 1250–1750 mm but it increases up to 2500 mm in the south and east of the country. Annual rainfall in northern Laos is as low as 1200–1300 mm per annum, but other areas receive on average 1500–2000 mm (Inthavong et al. these proceedings). The extremes of rainfall in North-east Thailand are greater with most of the region receiving 1100–2100 mm annually. However, most of the south-west sector of the region receives 900–1100 mm annually making it the most drought-prone. The variations in annual average rainfall produce changes in cropping patterns, and options for pre-rice and post-rice cropping with field crops. For example, in the southern parts of North-east Thailand, reliable early season rainfall allows pre-rice cropping (Poltanee 2001) whereas in the central Khorat basin such cropping is less common. Similarly, the south-west and east of Cambodia have higher early wet season rainfall and may therefore be better areas for expanding field crops on lowlands. However, all parts of this region experience substantial year-to-year variation in total rainfall, and in the rainfall distribution pattern.

The rice-growing environment may be identified by using the rice ecosystem and sub-ecosystem classification system developed at IRRI in 1984 (IRRI 1984). Using this system, it is possible to make broadscale identification of the rice growing environments in the study area. The dominant rice ecosystems in Laos, Cambodia and North-east Thailand are rainfed lowlands (Wade et al. 1999). Previously, the area of upland rice in Laos was greater than that of rainfed lowland, but the statistics for 1999 indicate that the upland rice area was reduced to 21% and irrigated and rainfed lowland rice areas increased (Schiller et al. 2001) (Table 1).

Table 1. Rice areas (%) for different ecosystems in North-east Thailand (IRRI 1997), Laos. (Schiller et al. 2001) and Cambodia (Ouk et al. 2001).

	North-east Thailand	Laos 1999	Cambodia 1999
Irrigated	6	12	11
Rainfed lowland	83	67	84
Deepwater	0	0	3
Upland	11	21	2

In the rainfed, shallow, favourable, sub-ecosystem, rainfall and water control are generally adequate for potential crop growth, and only short periods of drought stress or mild submergence may occur. Favourable rainfed lowlands are most prevalent in Laos and comparatively uncommon in Cambodia and North-east Thailand. Clear delineation of these areas in Laos could yield significant advances in being able to deliver technologies where drought and submergence rarely limit rice (Table 2).

Drought-prone sub-ecosystems are prevalent in all regions, especially in North-east Thailand (Table 2). The rain period is long and bimodal, but erratic in its continuity, and this sub-ecosystem is common in North-east Thailand and Laos. In this sub-ecosystem, there may not be standing water at the appropriate time for transplanting, which often corresponds to the trough between the two rainfall peaks of the bimodal distribution.

In the shallow, drought- and submergence-prone sub-ecosystem, drought and submergence may occur on a particular field within the same growing season or in different seasons. This sub-ecosystem is important in North-east Thailand and Laos but is the most widespread of the sub-ecosystems in Cambodia.

While the sub-ecosystem concept is useful in regional classifications of rice growing areas according to surface hydrology, in practice sub-ecosystems are not clearly separated and it is sometimes difficult to assign even a single farm to a particular sub-ecosystem (Singh et al. 2000). Locally, surface hydrology can vary by such an extent as to override the influence of rainfall. Within a single farm or among adjacent fields, the upper terraces may be classified into the drought-prone sub-ecosystem and

Table 2. Relative occurrence (as percentage of total area) of the main rainfed lowland rice sub-ecosystems in South and South-East Asia.

Country	Shallow soils (0–25 cm) and prone to:				Medium to deep soils (25–50 cm)	Total area ('000 ha)
	No water stress	Drought	Drought + submerg.	Submergence		
Laos	33	33	33	0	0	277
Cambodia	10	29	57	0	5	747
Thailand	9	52	24	12	3	6039
Total	20	36	15	16	13	35 907

Source: Wade et al. 1999

the lower terraces may belong to the submergence-prone, or drought- and submergence-prone, sub-ecosystem. Most farms in these countries are composed of a mixture of these different positions in the toposequence in varying proportions. Location of on-farm drains, and of road embankments and drains under roads can markedly affect where the run-off is directed. Lowland rice is uniquely dependent on surface hydrology and the duration of standing water in relation to crop-growth stages (Fukai et al. 2000). The surface water depth in paddies changes continuously during crop growth (e.g. Seng et al. 1996). There is relatively little data with continuous recording of surface hydrology and even less has been systematically assembled to allow better classification of agro-ecosystems (Boling et al. 2000).

Local surface hydrology of rice fields can be described by the water balance equation (Fukai et al. 2000). The change in soil-water content or free water level above or below the soil surface in rainfed lowlands is described by the equation:

$$\Delta S = R - (E + T + P + L + O)$$

where ΔS is the change in soil-water content, R the rainfall, E the evaporation from standing water surfaces or the soil surface, T the transpiration, P the deep percolation, L the net lateral water movement in the soil (positive means loss of water from the particular field), and O the runoff of water over the bund.

Commonly, the sum of evaporation + transpiration is 5–8 mm d^{-1} but it decreases sharply with soil drying and when the plant experiences drought. Deep percolation (drainage) rates were 1–6 mm d^{-1} at locations in North-east Thailand (Fukai et al. 1995). Model simulations for Ubon in North-east Thailand show about a 50% increase in yield if a percolation rate of 6.3 mm d^{-1} under puddled conditions can be reduced to 1.4–1.8 mm d^{-1} (Fukai et al. 2000). High percolation rates are a common problem in the sandy lowland rice soils of Cambodia (White et al. 1997), Laos and North-east Thailand (Fukai et al. 1995).

Fields in the high or upper terraces of the lowlands lose much water, particularly after heavy rainfall, through surface runoff and subsurface lateral water movement, while those in the lower terraces may intercept the flows from the upper paddies (Fukai et al. 2000). Lateral redistribution of water results in water availability and rice growth duration varying by 30 days or more, within quite small areas. Experimentally, it is difficult to separate the lateral flow and drainage components of water balance. Accordingly, Fukai and colleagues used simulation models to estimate the sensitivity of yield to the effect of variation in one parameter while all others are held constant (Table 3). At Ubon in North-east Thailand, the influence of run-on to the lower terrace diminished as the deep percolation rate was reduced from 6 to 1 mm d^{-1}. With 1 mm d^{-1}, there was almost no water stress throughout the growth period and hence the effect of water movement was small. However, with 4–6 mm d^{-1}, there were periods with standing water interspersed with periods of water stress. In this case, simulated grain yield was strongly influenced by variation in lateral water movement.

Homma (2002) conducted a detailed study of variation in soil properties, water regimes, and rice growth and yield, across a toposequence in North-east Thailand with elevation differences of 1.5–6 m along 150–500 m transects. The study area, south-west of Ubon Ratchathani, occupied 9.3 ha and comprised 10 farms. During the wet season, the duration of flooding varied inversely with elevation (Table 4). The number of days of flooding was positively related to yield. However, the low elevation sites also had higher organic matter and clay content sug-

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Table 3. Simulated grain yield (t ha^{-1}) for rice cv. KDML105 under different degrees of lateral movement of water and deep percolation rate at Ubon, North-east Thailand. C_L<1 indicates net run-off, and C_L>1 indicates net run-on of water.

Deep percolation rate (mm day^{-1})	Coefficient for lateral movement of water (C_L)				
	0.5	0.75	1.0	1.25	1.50
1	2.28	2.46	2.46	2.46	2.46
4	1.78	1.85	2.15	2.37	2.41
6	1.56	1.73	1.79	1.88	2.12

Source: Fukai et al. 2000

gesting that the lower elevations benefit not only from run-on of water from higher elevations (Fukai et al. 2000), but that their soil properties would aid soil-water retention. Oberthur and Kam (2000) also report that soils in North-east Thailand are often much higher in clay and organic matter content in the low terraces than mid and upper terraces.

Table 4. Rice dry matter and grain yield at sites along a toposequence in North-east Thailand in relation to flooding regime, and soil organic matter and clay.

	Lower	Middle	Upper
Total dry matter (t/ha)	8.4 ± 2.4	7.2 ± 2.3	4.1 ± 2.4
Grain yield (t/ha)	2.6 ± 0.6	2.5 ± 0.9	1.1 ± 1.0
Flooded days	88 ± 3 3	66 ± 29	7 ± 15
Organic C (g/kg)	13.1 ± 4.9	6.7 ± 2.4	3.9 ± 2.2
Clay (g/kg)	26 ± 13.3	10 ± 12.0	3 ± 0.9

Source: Homma 2002

Surface geology and soil distribution

Whereas the Mesozoic sandstone and its weathering products dominate most of the surface geology of North-east Thailand, in Cambodia their influence is attenuated by Tertiary and Pleistocene igneous geology and by Pleistocene and Holocene sediments that mantle a considerable proportion of the major rice growing parts of the country (Workman 1972). Recent and Pleistocene alluvial/colluvial sediments that now form the parent material for most of the agricultural soils of Cambodia are substantially derived from the weathering and erosional products of the Mesozoic sandstone (White et al. 1997). However, low hills from felsic igneous intrusions particularly in south and south-east Cambodia have also supplied siliceous sediments for the recent and older alluvial/colluvial terraces. In the north-east and west of Cambodia, basaltic lava flows of the Pleistocene cover significant areas of older alluvial terraces. The soils formed on weathered basalt and on the alluvial/colluvial sediments derived from basalt differ markedly from those of the siliceous parent materials that dominate most other soils (White et al. 1997). Basaltic parent rocks are prevalent on the Bolovens Plain of Southern Laos, but uncommon in North-east Thailand. Finally, the sediments deposited by the Mekong River along its flood plain and in the basin of the Tonle Sap means that much of central Cambodia is dominated by recent alluvial/lacustrine sediments derived in part from the Mekong River basin and in part from the immediate basin of the Tonle Sap (Oberthur et al. 2000b).

A soil map (1: 250,000) based on the FAO World Soils Map (1988) was recently compiled for the lower Mekong Basin (MRC, 2002). Apart from Laos, this map was based on limited new soil surveying. Only North-east Thailand has complete soil survey and soil map coverage. In Cambodia the rice growing soils have been mapped (Oberthur et al. 2000b) based in part on an old, small-scale map (1:900,000) of soils in the whole country. Detailed 1:50,000 maps exist for three provinces of south-east Cambodia. Soil mapping is continuing in Laos, but the Mekong River Commission (MRC) map ensures that there is coverage of the entire lower Mekong Basin using a consistent classification.

Even at the level of soil groups, significant differences are evident between soils of the three regions (Table 5). In Cambodia the most prevalent soils are Acrisols, Leptosols, Cambisols and Gleysols. Cambodia has the highest proportion of Gleysols, and significant areas of Plinthosols, Planosols, Ferralsols and Vertisols. The latter are not important in Laos or North-east Thailand. Laos has the highest proportion of Acrisols, and Cambisols, but the lowest proportion of Gleysols, Planosols, Arenosols, Fluvisols and Vertisols. By contrast Cambisols are not important in North-east Thailand and Gleysols are not important in Laos. Fluvisols are not common in Laos, but are common and important in North-east Thailand and Cambodia for rice. North-east Thailand has the highest proportion of Luvisols, Arenosols, Solonetz and Lixisols, but the lowest proportions of Cambisols, Ferralsols, and Plinthosols. North-east Thailand has a large area of

Arenosols and Solonetz, whereas these are much less prevalent in Laos and Cambodia.

Table 5. Relative abundance (percentage land coverage within country) of soil groups within the countries of the Lower Mekong Basin (Mekong River Commission 2002). Soil groups based on FAO World Soil Resources map (FAO, 1988).

Soil groups	Cambodia	Laos	North-east Thailand
Acrisols	48.8	61.4	60.9
Leptosols	12.5	10.3	16.1[a]
Cambisols	11.2	20.9	0.5
Gleysols	9.5	0.1	4.1
Ferralsols	3.7	0.8	0.4
Planosols	2.8	0	0
Luvisols	2.5	2.5	6.3
Plinthosols	1.8	0.4	0
Vertisols	1.6	0	0.2
Arenosols	1.6	0.1	5.9
Fluvisols	0.8	0.2	1.0
Solonetz	0	0.1	1.1
Lixisols	0	0.3	1.7
Water	3.1	0.8	1.3
Rock/slope complex	-	2.1	

[a] mapped as slope complex

Even where there are apparent similarities in abundance of soil groups, at the level of soil units, there can be large differences. For example, in Laos and North-east Thailand Haplic Acrisols are the most abundant soil unit, whereas in Cambodia Gleyic Acrisols are more prevalent. Moreover, since the map covers the whole region, it may give a misleading impression of the prevalence of lowland soils. In Cambodia, the prevalence of Fluvisols in rice-growing areas is not evident in Table 5. Similarly in Laos, Linquist et al. (1998) reports that Alisols are the most prevalent rice soils in southern and central Laos whereas Luvisols are most prevalent in the north.

Soil properties

Rice growing soils in Cambodia exhibit varied properties (Table 6). Two-thirds of them are derived from old (Pleistocene) alluvial/colluvial deposits and 28% from recent alluvial deposits (White et al. 1997). Of the former, Prey Khmer and Prateah Lang which comprise 39% of the rice-growing soils have very sandy surface horizons, and the Prey Khmer is sandy in both the surface and sub-soil. One-third of the rice growing soils are strongly acidic in oxic conditions. Apart from the recent alluvial soils which have >23% clay and the highest CEC, exchangeable potassium (K) and Olsen phosphorus (P), all other soils have very low levels of exchangeable K and Olsen P. In field trials in Cambodia, strong responses to nitrogen (N) are generally reported in most rice soils (Seng et al. 2001b). However, only the recent alluvial soils belonging to the Krakor group respond to N alone. On Koktrap soils, on the sandy Prey Khmer, and on Prateah Lang soils, N alone either has no effect on yield or decreases it (White et al. 1997, Seng et al. 2001b). On all soils, apart from Krakor, responses to P alone may be obtained although the strongest responses generally require N and P, and on the lower fertility soils K and S (sulfur) fertilisers are also required. Soil physical properties are often limiting for tillage (Table 7), and several profile types have sub-soil features that limit root growth.

The surface soils of North-east Thailand contrast with those of Cambodia in that almost all the major soil series contain >60% sand (Table 8). This has led to the conclusion that soils of North-east Thailand are almost universally infertile (Ragland and Boonpukdee 1987). However, Oberthur and Kam (2000) challenge the previous generalisations about the sandy and infertile nature of soils in North-east Thailand. They report that short-range variation in texture is substantially greater than previous reports have suggested and that the lower elevations of toposequences, that comprise up to 25% of landscapes, have loam or heavier textures that are suited to rice production. This notion of variation in soil texture along a toposequence is consistent with the results from Homma (2002). The Phimai series which occurs on the recent alluvial plains of North-east Thailand is an exception to the general pattern of North-east Thailand soils. It has properties relatively similar to the recent alluvial soils in Cambodia, apart from higher exchangeable sodium (Na). However, the prevalence of Phimai series in North-east Thailand is low. Thirty-two per cent of the soils of North-east Thailand are strongly acidic (pH KCl <4.2) in their oxic state, and most of the soils were low in exchangeable K. There is a high incidence of B (boron) deficiency in soils of the uplands of North-east Thailand (Bell et al. 1990), but it has not been reported as a problem for rice in the lowlands.

Table 6. Chemical properties of major rice soils in Cambodia and the percentage of the rice area they occupy.

Soil type[a]	Landscape	Area (%)	Sand (%)	Silt (%)	Clay (%)	pH[b] (1:1 H2O)	Organic C (g kg^{-1})	Total N (g kg^{-1})	Exch K	Exch Na	Exch Ca	CEC[c]	Olsen P (mg kg^{-1})
									[cmol(+)kg^{-1}]				
Prateah Lang (Plinthustalfs)	Old colluvial/ alluvial	28	50	37	13	4.0	2.9	0.3	0.08	0.55	1.20	3.71	0.4
Krakor and Kbal Po (Entisol/Inceptisol)	Active floodplain	28	18	34	48	5.9	9.1	1.0	0.24	0.62	6.68	15.1	4.6
Bakan (Alfisol/ Ultisol)	Old colluvial/ alluvial	13	35	49	16	5.8	6.6	0.6	0.09	0.51	1.75	4.84	1.0
Prey Khmer (Psamments)	Old colluvial/ alluvial	11	73	22	5	5.6	4.7	0.5	0.04	0.05	0.61	1.45	1.3
Toul Samroung (Vertisol/Alfisol)	Old colluvial/ alluvial	10	28	29	42	5.5	8.8	0.9	0.17	0.29	7.10	16.0	3.1
Koktrap (Kandic Plinthaquualt)	Old colluvial/ alluvial	5	36	41	23	4.0	10.9	1.1	0.10	0.25	1.13	8.09	2.6

[a] Local name according to White et al. (1997). Names in parentheses refer to the *Key to Soil Taxonomy*.

[b] 1:1, soil to water, except for values in italics, which were obtained from 1:5, soil to $CaCl_2$.

[c] CEC = cation-exchange capacity.

Data source: Oberthur et al. 2000a; White et al. 2000 and Seng et al. 2001b

Table 7. Rice soils of Cambodia—constraints and opportunities for rice.

Soil[A]	Parent material	Profile	Main constraints	Opportunities
Prey Khmer	Old alluvial/colluvial from sandstone, granitic detritus	Sandy to 40–100 cm	NPKS deficiency, S, Fe toxicity, Low water holding capacity, leaching, transplanting difficulties as sand settles, coarse sandy phase	Compaction at depth, fertiliser in small doses, deep rooted cultivars, direct seeding, Clay layer at depth Use high tannin green manures that break down slowly, N placement an depth
Prateah Lang	Old alluvial/colluvial from sandstone and other mixed detritus	Sandy to 10–25 cm on clay sub-soil	NPKS (Mg, B) deficiency, S, Fe toxicity, Low WHC, leaching, hard setting, shallow phase, ironstone, transplanting difficulties as sand settles	Upland crops on loamy phase, drainage, direct seeding, post-rice crops, supplementary irrigation, split fertiliser, deeper cultivation Use high tannin green manures that break down slowly, N placement at depth
Bakan	Old alluvial/colluvial	Clay-loamy topsoil over clay or loam	Dispersive, poor structure, surface sealing, N, P, K, deficiency, S, Fe toxicity	Deeper ploughing, supplementary irrigation, land levelling, ratooning? Direct sowing, N placement at depth
Koktrap	Old (and recent?) lacustrine, tidal sediments	Black clay or loam (0–20 cm) over grey clay	Very low P, shallow hardpan, Fe toxicity, NK deficiency	Deeper ploughing Liming
Toul Samrong	Mixed alluvial/colluvial sediments of mafic origin	Well structured brown or grey cracking clay or loam over clay	Shallow root depth, tillage when dry, NP(K) deficiency.	Deeper tillage, level fields, supplementary irrigation
Orung	Recent or old alluvium	Loamy or clay over sand	NPKS deficiency, leaching, tillage, dispersive, hard setting, Fe toxicity	Supplementary irrigation
Labansiek	In situ weathered basalt	Deep, well structured reddish clay	NP(KS) deficiency, Root depth on petroferric hardpan in places,	Upland rice
Kompong Siem	Colluvial/alluvial outwash from basalt, marl, limestone or in situ basalt	Dark cracking clay (with stones and boulders in profile)	N(P) deficiency, Sticky when wet, Fe toxicity, cracks when dry, Zn deficiency	Supplementary irrigation, direct seedling. Drainage Dry season irrigation
Kein Svay	Recent alluvium with annual sediment additions	Deep brown loamy to clay texture	N(P) deficiency, submergence	Dry season irrigation
Kbal Po	Recent alluvium	Deep dark clay over lighter coloured clay	N(P) deficiency, potential acid sulfate in some places, sticky and low load bearing when wet, deep cracks	Supplementary dry season irrigation
Krakor	Recent alluvium	Deep loam—clay over lighter coloured sand, loam or clay	N(P) deficiency, potential acid sulfate in some places, sticky and low load bearing when wet	Supplementary dry season irrigation

Source: Based on White et al. 1997.

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Table 8. Typical soil properties of the main soil series of North-east Thailand (NET).

	Landscape	% of NET	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH (KCl)	Org C (g/kg)	Exch K	Exch Ca	Exch Na	Bray II P (mg/kg)
										(cmol/kg)		
Korat	Middle	21	0–19	65	18	17	3.9	5.3	0.03	1.3	0.2	5
Roi Et (R)	Low	21	0–19	68	12	21	4.6	3.3	0.2	1.6	0.2	16
Phon Phisai	Middle	9.4	0–14	41	32	27	4.8	36	0.3	2.4	0.3	15
Nam Phong	Middle	3.1	0–18	87	11	2	3.5	2.4	0.1	0.4	0.3	4
Ubon (R)	Low-middle	2.5	0–23	87	11	3	3.8	2.5	0.04	0.6	0.2	5
Warin	Middle-high	2	0–26	54	27	19	3.7	6.6	0.1	0.4	0.2	7
Satuk	Middle-high	1.8	0–26	74	22	5	4.0	2.7	0.1	0.8	0.2	18
Borabu	Middle-high	1.6	0–15	86	11	3	4.3	4.2	0.1	0.7	0.1	3
Phen (R)	Low	1.3	0–13	63	20	17	4.2	5.6	0.1	0.3	0.1	3
Phimai (R)	Flood-plain	1.3	0–18	7	28	66	4.1	14.5	0.5	15.3	3.7	3
Yasothon	High	1.2	0–11	61	33	6	5.3	8.0	0.1	4.3	0.2	3
Tha Thum (R)	Low	1	0–11	44	48	8	3.7	6.7	0.03	1.0	0.6	3
Kula Ronghai (R)	Low	0.7	0–19	45	43	13	4.1	3.0	0.03	0.6	0.2	3

Source: Mitsuchi et al. 1986

There is limited analytical data available on rice soils of Laos. Most of the present knowledge about the properties of these soils is inferred from rice yield and yield responses to fertiliser. Rice growing soils in Laos show a gradient in properties from the northern regions where 80% are loamy in texture to the southern region where only 25% are loams (Linquist et al. 1998). In Laos, 85% of rainfed lowland rice crops in the northern region and 100% of those in the central and southern regions responded to NPK fertiliser (Linquist et al. 1998). Nitrogen deficiency was the most prevalent, with 40–50% of crops responding to N alone and another 30% when P also was applied. Some evidence suggests S deficiency for rice in Laos, and leaf analysis suggests that magnesium (Mg) levels may also be too low for rice.

Water-related soil constraints and soil management technologies

Based on rainfall, its distribution and variability, it would be presumed that drought was the main water-related constraint affecting soil used for growing rice in the region. However, the more common effect of low soil-water may be to limit nutrient availability and uptake rather than to cause drought per se. Variations in soil-water saturation interact with nutrient availability (Bell et al. 2001). Fluctuating soil-water regimes will have major effects on the forms and availability of N (Seng 2000), P (Seng et al. 1999) and on iron (Fe) and Al toxicities (Willett and Intrawech 1988).

In the rainfed lowlands, significant periods of loss of soil-water saturation occur intermittently throughout the growing season (e.g. Seng et al. 1996; Fukai et al. 2000; Homma 2002). The implications of the temporary periods of loss of soil-water saturation for nutrient availability are not fully understood, although growth may be depressed as nutrient availability decreases (Fukai et al. 1999). Intermittent flooding of soils results in a significant loss of soil N (Seng 2000) and decreased P availability (Seng et al. 1999).

Willett and Intrawech (1988) and Seng (2000) suggested that the increase in soluble Al after re-oxidation of the soil was a possible additional factor limiting P uptake during periods of loss of soil-water saturation. Hence, while flooding rice soils in Cambodia and North-east Thailand has been shown to increase pH to >6 (Willett and Intrawech 1988; Seng et al. 2001a), there are concerns that periodic losses of soil-water saturation during the growing season will see toxic levels of Al return to impair root growth and P uptake of rice (Willett and Intrawech 1988; Seng et al. 1999; Seng 2000).

If P uptake is restricted by loss of soil-water saturation, particularly at transplanting, growth and final yield will be impaired (Seng et al. 1999; Seng 2000). However, the relative sensitivity of yield to P deficiency at different stages of crop growth is poorly understood. Improved understanding would permit better tactical decisions on correction during the growing season. The effect of periods of loss of soil-water saturation can be minimised by using cultivars that are efficient in P uptake and use, and presumably best able to cope with a temporary decline in P availability (Fukai et al. 1999); or by treating soil with straw (Seng et al. 1999). Straw keeps the redox potential lower during the period of soil-water saturation loss, thus apparently decreasing the extent of Fe^{2+}oxidation and minimising losses in P availability due to reaction with Fe oxides. Other forms of organic matter added to the soil at planting, including cow manure, or residues from pre-rice pulse crops or green manures like sesbania, can all help minimise losses of P during periods of soil-water saturation loss. The minimum amount of organic matter needed to make a difference is not known, but Seng et al. (1999) had applied the equivalent of 5 t of straw per hectare. Seng et al. (2004a) has also suggested that lime application may be useful on some acid soils to minimise the formation of toxic Al levels in soils when loss of soil-water saturation occurs. However, Seng et al. (2004b) also found that over-liming of the acid sandy soils could occur.

The high percolation rates of the deep sands (Arenosols) are a major limiting factor for rainfed rice. Loss of standing water and drought are the most important consequences. However, leaching of N and other nutrients may also limit productivity of these soils even when water is not limiting. The Prey Khmer soil in Cambodia has lower potential productivity even with fertiliser application than the other major sandy lowland soil, Prateah Lang (White et al. 1997).

Sandy soils that occupy a significant proportion of the region represent a continuing challenge for water and nutrient management. Productivity on these soils tends to be low, even when recommended agronomic practices are followed. Application of clay to these soils has been suggested as a semi-permanent treat-

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ment to enhance water and nutrient retention (Noble et al. these proceedings). Initial research on the sandy soils of North-east Thailand suggests very strong responses in growth can be achieved by clay amelioration. Work to show the benefits of adding clay is continuing. The use of claying presumes a ready local supply of clay. North-east Thailand has numerous deposits of high activity clay in lacustrine sediments (S. Ruaysoongnern, pers. comm.). The relevance of this technology for other parts of the region, particularly for the Prey Khmer (Arenosols) and Prateah Lang (Acrisols) of Cambodia, warrants further research.

Shallow rooting is a major constraint on productivity for rainfed lowland rice (Table 7). Alleviating soil physical constraints to root penetration may therefore increase rice productivity by increasing access to stored water and nutrients in the deeper layers of the soil profile. If roots can penetrate the shallow plough pan, then rice crops can extract significant amounts of N from below 20 cm (Ventura and Watanabe 1984). Kundu and Ladha (1999) reported that deep cultivation increases rice yields. In Korea, increasing cultivation depth from 14 to 19 cm increased root depth from 27 to 36 cm and rice yield from 4.5 to 8.1 t ha^{-1}. Increasing cultivation depth from 15 to 40 cm on a soil with a hardpan at 15 cm increased both N uptake and grain yield (Kundu et al. 1996). The scope for increasing cultivation depth with draught animals is limited. In Cambodia, a pair of working animals can achieve a cultivation depth of 7–10 cm (Rickman et al. 1997). However, increasing availability of tractors for primary cultivation is making deeper cultivation possible on rainfed lowland soils with shallow hardpans.

Salinity currently affects about 12% of the lowland soils in North-east Thailand but is predicted to spread to cover about 30% (Yuvaniyama, 2001). The cause of salinity appears to be related to a change in the landscape water balance after clearing of the forest for agriculture (Williamson et al. 1989). Rapid clearing in North-east Thailand occurred in the 1960s (Ruaysoongnern and Suphanchaimart, 2001). Before that the salt stored in the halite strata of the near-surface Mahasarakham formation was not mobilised because the vegetation used most of the rainfall allowing little to recharge to ground water. However, under rice-based and upland farming significant recharge of the ground water occurs annually and this has caused watertables to rise regionally. Where ground water reaches the soil surface or is within 2 m of the surface, discharge of salt occurs. The gentle relief of the North-east Thailand and the widespread shallow Mahasarakham formation place large areas of North-east Thailand at risk of salinity. The potential risk of salinity in Laos has not been reported although salinised soils are occasionally reported (MRC, 2002). In Cambodia the salinity reported is in coastal soils (White et al. 1997).

As the development of salinity in North-east Thailand is essentially a water balance problem (Williamson et al. 1989), its solution will most likely come from changes in land use that decrease recharge to regional ground water. Given the current prevalence of lowland rice cultivation, this will prove a challenge. Tree planting or revegetation with perennial vegetation across a significant portion of the landscape may be needed to restore water balance, but the minimum amount needed to be effective is not known. Currently, upland areas are mostly targeted for tree planting. Agroforestry planting in lowlands may also be needed to help restore water balance. However, the present research emphasis appears to be on selecting for salt-tolerant plants to grow in salt-affected soils rather than on finding effective ways to restore water balance (Yuvaniyama, 2001).

In the region, there is a significant shift away from traditional transplanted rainfed rice. Shortages of labour are driving the development of direct seedling technologies for rice establishment. The increased demand for cash income is driving moves towards crop diversification (Ruaysoongnern and Suphanchaimart 2001). For much of the rainfed lowlands, the frequent uncontrolled inundation of land makes rice the only feasible wet season crop. However, there are opportunities to adopt double cropping by planting the early wet season crops, or planting post-rice crops (Polthanee 2001). The productivity of these systems depends on the reliability and amount of early wet season rainfall, and on access to supplementary irrigation from either stored surface water or shallow ground water. Where shallow ground water persists after the wet season, productive field cropping systems have also been developed (Polthanee 2001). Double cropping obviously increases the potential for negative nutrient balances, exacerbating what is already a relatively common scenario in North-east Thailand (Lefroy and Konboon 1998).

Environmental sustainability

At present, fertiliser rates in rainfed lowlands are generally still low, leading Crosson (1995) to suggest that the negative environmental impact of fertiliser use on rice production is probably minimal. However, nutrient deficiencies are prevalent and farmers are increasing their fertiliser use and application rates (e.g. Ieng et al. 2002). In rainfed lowlands with access to supplementary irrigation, dry-season cropping is becoming more common (Pandey 1998). The environmental impact of these systems is under examination and may be a precursor of more widespread concern for agrochemical use in rainfed lowlands (Shrestra and Ladha 1999). Because these problems generally have not yet arisen in most rainfed lowland rice environments, now is an opportune time to develop strategies to prevent them becoming a concern. Periodic monitoring of water quality and identifying areas in catchment basins that contribute most to nutrient enrichment of water bodies should be implemented.

Shallow ground water is prevalent across the lowlands of Cambodia (Briese 1996) and North-east Thailand. In North-east Thailand much of this is unsuitable for irrigation because of its salinity and over half of the production wells drilled have low yields (Srisuk et al. 2001). There is a risk of over exploitation of the shallow ground water for irrigation. Villagers commonly rely on this resource for domestic water supplies, hence any loss of access to this resource, or compromise in its quality, would have serious implications.

Conclusions

Despite their close proximity and the prevalence of rainfed lowland rice ecosystems in Cambodia, Laos and North-east Thailand, there are significant differences between these three countries, and between areas within them in use of land resources. Rainfall patterns and soils differ sufficiently between them so that the proportions of rice sub-ecosystems and types of double cropping systems vary to suit each country. Lowland rainfed rice surface hydrology can vary because of natural and artificial drainage patterns and of subtle topographic variations to the extent that locally it may override the influence of rainfall, and make it difficult to regionally assess the prevalent hydrological regime. Cambodia has a higher prevalence of seasonally flooded, alluvial soils than North-east Thailand or Laos. Substantial areas of sandy, high permeability soils are used for lowland rice in the region, but especially in North-east Thailand. Standing water in rice fields of these soils drains quickly after rainfall exposing rice crops to drought and high rates of nutrient leaching. However, loss of soil-water saturation may limit rice yield by inhibiting nutrient uptake more often than drought, per se. Shallow ground water is a potential resource for supplementary irrigation but the scope for using it has not been adequately examined. In North-east Thailand and parts of Laos, salinity in the ground water may be the major limitation on its use.

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The development of tube-well irrigation systems in Cambodia

By Joseph F. Rickman[1] and Poa Sinath[2]

Abstract

The use of tube-wells for irrigating rice has been a recent development in several southern provinces in Cambodia. The first dedicated tube-well for irrigating rice was installed in the Prey Kebas district, Takeo province in 1995. During the next three years more than 1000 wells were dug and today it is estimated that between 2000 and 3000 wells are sourcing water from the underground aquifer near the Bassac River. Annual crop yields increased from 1.5 to 6 t ha^{-1} and annual financial returns from \$100 to \$550 ha^{-1}. In 1999 the Cambodia–IRRI–Australia project conducted a tube-well survey monitoring 62 wells in a 1200 km^{-2} area in Kandal and Takeo provinces. Well depth was monitored every month for a 12-month period. This survey was repeated in 2002 to determine the effect that the increased use of tube-wells was having on the underground water level. The results followed a similar recharge and draw-down pattern for each year and indicated that the Bassac River was recharging wells up to 30 km to the west. It also showed that the maximum draw-down depth was about five metres, which is the limit from which centrifugal pumps can draw water. The results of this study provide information that may help authorities develop a policy on underground water usage in Cambodia.

Introduction

THE use of tube-wells for irrigating rice has been a recent development in several provinces in Cambodia. Traditionally, rice was irrigated using water, which was either pumped directly from the Mekong River and its tributaries, the Tonle Sap lake, or pondage systems filled by channels that diverted water from the Mekong when the river level rose. During the Pol Pot era (1975–80) many above-ground, gravity-fed storage systems were built which trapped water during the wet season for use during the dry. In more recent times some larger dam structures and pump stations have been constructed and many old systems refurbished through aid programs. Provincial governments control these larger systems and farmers have found them to be unreliable in supplying water, especially in the latter part of the dry season. To overcome this problem, farmers have installed tube-wells in many areas to improve the reliability of irrigation water in the dry season.

This paper outlines the development of tube-wells for rice irrigation in the southern provinces of Cambodia and gives the results of studies on the underground aquifer within the region. The paper makes recommendations about the sustainability of the tube-well program.

Rice ecosystems in Cambodia

Cambodian rice lands are classified as either wet season rainfed lands or dry season irrigated lands (Nesbitt 1996).

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Wet season crops are grown in the rainfed uplands, rainfed lowlands, and deepwater areas and cover almost two million hectares or nearly 90% of the rice growing area in Cambodia. These areas rely almost entirely on rainfall to provide the water needs of the rice crop but some supplementation from tube-wells is now occurring during dry spells in several regions.

Dry season crops account for about 10% of the total rice area of Cambodia and contribute 16% of total rice production. Dry season crops were traditionally grown on the more fertile soils along the Mekong River and its tributaries, and near the Tonle Sap Lake. The installation of tube-wells has allowed the expansion of dry season crops away from the river systems.

History

Traditionally, irrigation water was pumped directly from rivers and lakes, and gravity fed to rice crops. In more recent times farmers have been able to source water from refurbished above-ground storage systems. However, farmers are reluctant to rely on water from many of these as provincial governments control these systems and water is not always available when needed, especially in the latter part of the crop-growing period. Normally, the first portion of water is gravity fed from the reservoirs and the farmer is not charged for that water. In the latter part of the dry season when the water level drops in these reservoirs, the water must be pumped and farmers must pay or supply fuel to the pump stations to pump the water. A review by the Cambodia–IRRI–Australia Project (CIAP) of the above ground systems in 1999, found that less than 25% of the capacity of these systems was being used. Farmers interviewed during this study said that they were not prepared to plant dry season crops and risk the possibility of not having enough water to irrigate later in the season. They preferred to own the water source and would install their own tube-wells if sufficient underground water were available.

During the 1980s many small diameter tube-wells and open wells were dug to provide a more continuous supply of water for rural villages, especially during the dry season. These were low-capacity systems and were often provided by international agencies such as the World Health Organization and several NGOs. Water was extracted by using either piston-type hand pumps or buckets and this provided a limited amount of water for nearby household gardens.

Tube-wells for irrigation are a much more recent development in rice growing areas of Cambodia. It was not until the mid 1990s that irrigation wells were installed and this was mainly along the Mekong and Bassac rivers in Kandal, Takeo, Prey Veng, Svey Rieng and Kampong Cham provinces. One of the earliest tube-wells for irrigation was installed in the Prey Kabas district, Takeo province, in 1995. This tube-well enabled the farmer to increase rice production from one rice crop, which yielded 1.2 t ha^{-1} in 1994 to 8 t $ha^{-1}$from three crops on the same land in 1996. Following the success of this first tube-well in Prey Kebas, many local farmers wanted financial support to help pay for the installation of tube-wells on their farms but no financial institution would lend money to any farmer for this purpose. Farmers were not prepared to share the cost of drilling a collaborative well as they felt management problems might arise in the allocation and sharing of water.

After discussions with several villages, CIAP in conjunction with a local NGO, the International Development Enterprise (IDC), decided to teach farmers how to drill their own wells. A training course for 18 farmers was held in the district and farmers helped each other install tube-wells on their farms. Appendix 3 provides a description of the tube-well technology used. After this some local farmers and villagers began contract drilling tube-wells. These tube-wells were normally drilled to between 25 and 40 m and used centrifugal pumps to extract water from a depth of 5 m. Most systems used portable pumps and engines, which are removed for security purposes when not in use. Within the first three-year period in the Prey Kabas district more than 1000 tube-wells were installed. Today it is estimated that between 2000 and 3000 tube-wells are being used for irrigation in the districts surrounding Prey Kabas.

During the period from 1995–97 there was one reported case of salinity in Prey Kebas district but that well was never identified. CIAP conducted many salinity tests on wells within the province but did not find any wells that had high salinity levels.

Economics of tube-well irrigation

Many of the farmers who installed tube-wells recouped the costs of the drilling, installation and purchase of the pump and engine in the first year of operation. Farmers who installed tube-wells

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increased their net return after they paid for all inputs, including labour, from about $100/ha/year to nearly $550/ha/year (see Appendix 4). Most farmers grew two crops of rice a year on the same land. Improved cultivars were planted in the dry season and traditional cultivars in the wet season. Grain yields in the rainfed systems in this district were 1.5–2 t ha^{-1}. Irrigated dry season crops yielded 3–3.5 t ha^{-1} while the wet season supplementary irrigated rice crop yielded 2.5–3 t ha^{-1}. The average price of rice varied from $140/t for the dry season crop to $158/t for the wet season crop.

Tube-wells cost about $200 to drill and another $300 for the pump and engine. The engine and pump last for seven to 10 years and cost about $0.50/hour to operate. It takes 20–25 h to pump one megalitre of water and in the dry season farmers normally apply 10–12 megalitres of water per hectare per crop. In the wet season the wells are used for supplementary irrigation during dry spells and will pump two to three times per season.

Aquifer study

With the rapid increase in the number of tube-wells in the Prey Kabas district, and experiences from other countries such as Bangladesh, in 1999 CIAP examined the effects that tube-wells were having on the underground aquifer west of the Bassac River in Kandal and Takeo provinces. This region had experienced the most rapid increase in the use of tube-wells for irrigation. The most likely recharge source for these tube-wells was the Bassac River.

The aim of the aquifer study was to determine the:

- sustainability of the present usage patterns by determining whether the water level in the aquifer was being fully recharged each year
- source of recharge water
- boundary limits of the rechargeable area.

Water levels were measured on a monthly basis in 62 wells from December 1998 to February 2000 and the same survey was repeated from March 2002 to March 2003. The study area was divided into three east–west transects from longitude 104° E to 105° E and extended north–south between latitudes 11.00° N and 11.29° N. The total area was about 1200 km^2. Appendix 1 is a map of the area.

The distance from the water surface in each well to the ground level at each site was measured using a tape measure and plumb bob, and then compared to the water level in the Bassac River for the corresponding time period. The river level was measured at a bridge crossing on a tributary 200 m west of the main river (latitude 11.29° N, longitude 104.56E). This is about 10 km south of Phnom Penh.

Discussion

The results for the aquifer surveys showed a similar pattern of water draw-down and recharge in 1999 and 2002. Appendix 2, Figures 1 and 2 show the aquifer study results. The water level in the Bassac River rose 7–8 m during the wet season. The lowest water levels were recorded during March to May with the peak flow recorded from August to November.

The wells showed a draw-down in water depth of 2–3 m and recharged to within 2 m of the surface during the wet season. The tube-wells east of the 104.4 longitude, which ranged from 10–25 km from the river, followed a similar pattern to the water level in the river. The wells west of the 104.4 transect, which were more than 25 km from the river, tended to recharge much faster with the onset of the wet season than those wells closer to the river. The location of these wells suggests that they may be influenced more by local run-off from the surrounding environment than by the water level in the river.

Wells in the 10 km and 10–25 km transects showed a lag period between the increase in river height and increase in water levels in the wells. In both years the wells recharged to their maximum height during October to December. This was one to two months after the river reached its maximum height. The wells in the 10–25 km region took longer to recharge and discharge than those in the 10 km zone (see again Appendix 2: Figures 1 and 2). There was no attempt to establish the topographic difference between well depths as the study was interested in draw-down and recharge over time.

Combining the results of the two-year study with the average rainfall, a generalised view of the expected relationship between rainfall, rise in river height and the recharge and discharge patterns of the aquifer was obtained (Appendix 2, Figure 3).

Conclusions

It was concluded that:

- the wells less than 25 km west of the river appear to be directly affected by the water level in the river

- the aquifer appears to recharge fully each year to 2–2.5 m from the surface
- if centrifugal pumps are used in the present manner (located at the surface) the maximum draw-down will be approximately 5 m.

Recommendations and observations

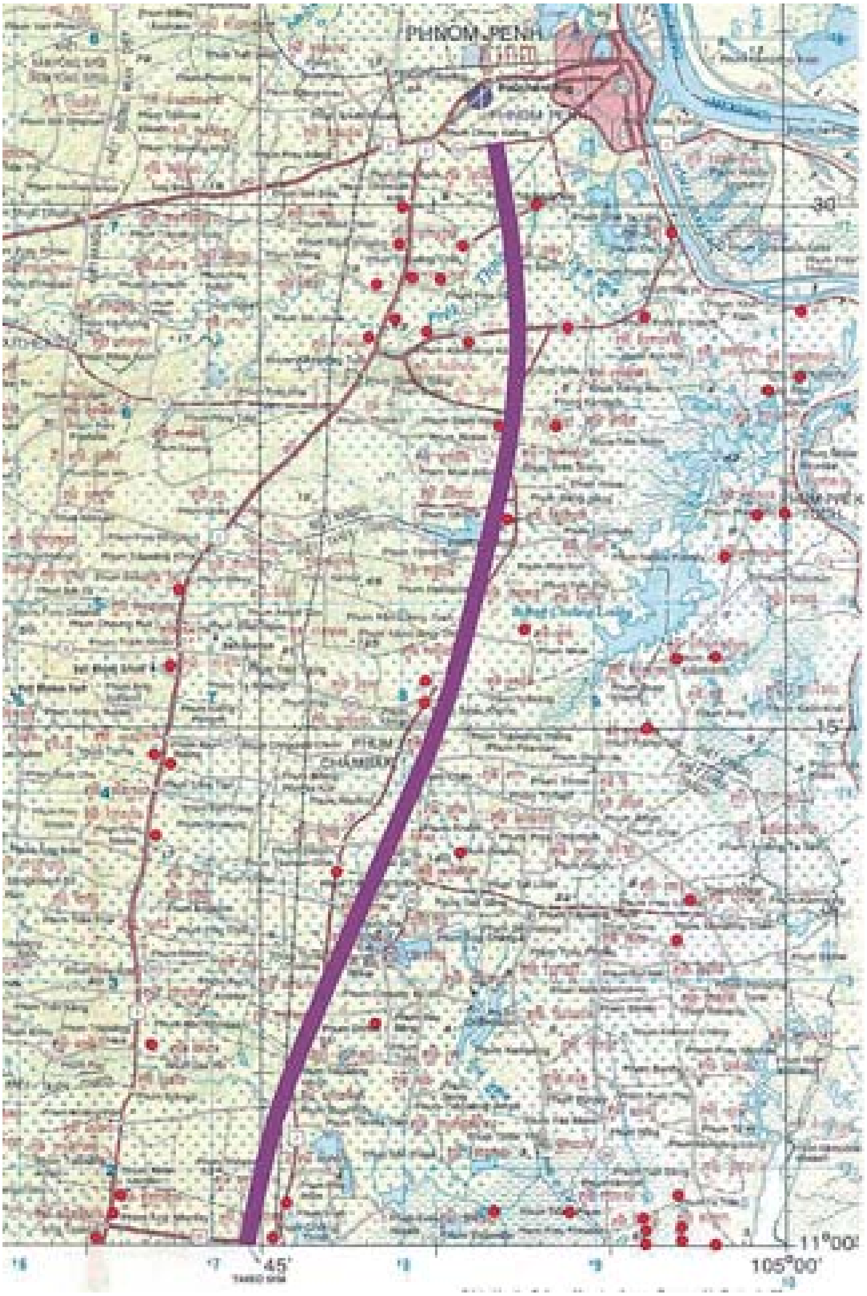
Problems may occur if more farmers use tube-wells or some farmers use deep-well pumps. Deep-well pumps could drop the aquifer level below 5 m, which would reduce the availability of water to farmers using traditional centrifugal pumps.

There would appear to be limited opportunity to increase the recharge capacity or efficiency of the aquifer as the river height drops rapidly after the end of the wet season and water may be flowing back from the aquifer to the river. One option is to pump water into above-ground storage systems during the wet season. Another option is to use weirs to increase the water height in the river; however this would be costly and interfere with other river uses.

Reference

Nesbitt, H.J., ed., 1997. Rice Production in Cambodia. Los Baños, Philippines, IRRI.

Appendix 1: Map of site area and well locations



Appendix 2. Aquifer study results

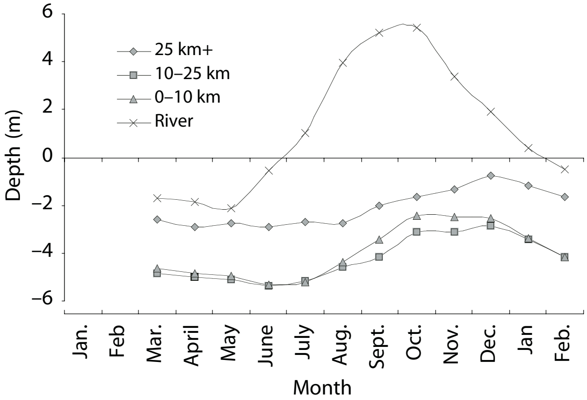


Figure 1. Bassac River height and tube-well depth in 2002.

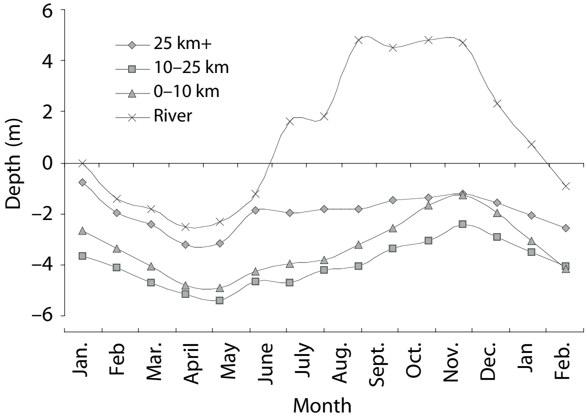


Figure 2. Bassac River and tube-well depth in 2000.

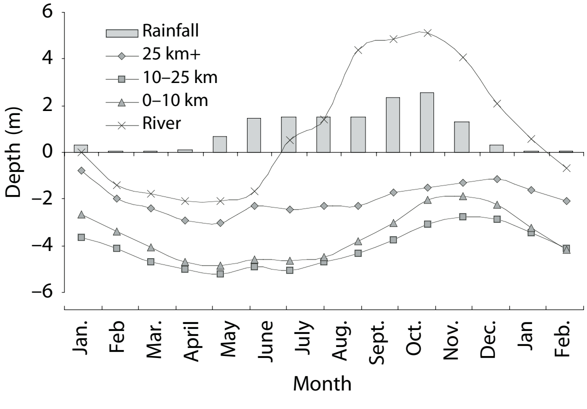


Figure 3. Average Bassac River depth, tube-well depth and rainfall for 1999 and 2002.

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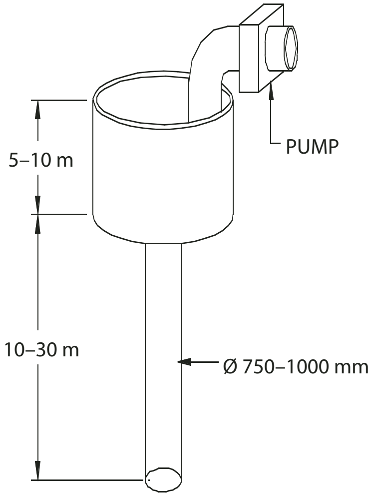
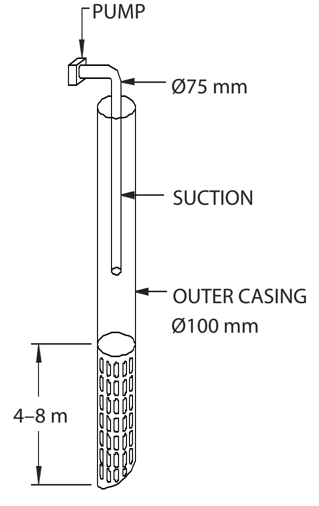
Appendix 3: Tube-well design and performance characteristics

Tube-well design

There are three basic designs of tube-well systems being used:



1. Open well inlet tube



2. Conventional

Open well inlet tube. The upper section of this system is a 5–10 m deep, open well lined with concrete. The diameter of this portion of the well is 1.5–2.0 m. The tube-well is then installed through the base of the open well to a further depth of 10–30 m. The bottom section of this tube-well is normally gauzed or slotted. These tube casing sections are normally 75–100 mm in diameter and do not have a foot valve. Centrifugal pumps are used to draw water from the open well section.

Conventional tube-well. The most common system used is a tube-well with a 100 mm outside casing installed to a depth of 25–40 m. The bottom 4–12 m section is either commercially purchased slotted pipe or standard PVC pipes slotted using a hacksaw blade. Water is then pumped from a 75 mm suction pipe, which may be fitted with a foot valve.

Combined casing and suction tube. This system normally uses a 75 mm PVC pipe installed to a depth of 25–45 m. The lower section of pipe is slotted. Water is drawn directly from this tube and these wells do not incorporate a foot valve.

Tube-well installation.

Tube-wells are dug and drilled by both machine and hand. The upper section of the open wells is dug by hand and the smaller tube-well section either drilled by hand or a machine. The 75 mm tube holes are often drilled by hand but the 100 mm tube holes are normally drilled by machine.

Pumps

Farmers use portable centrifugal pumps on all of these wells. The centrifugal pumps operate to a maximum suction depth of 5 m. Pumps are only installed during irrigation and removed for security reasons when not required. The most common pumps used are locally fabricated 75 mm centrifugal pumps driven by Chinese 10–13 hp diesel engines.

Well output and cost

The outputs from the wells are 3–600 Lpm and most farmers irrigate for 20–30 hr ha^{-1}. The rice crops are irrigated on a 10–12 day cycle. The pump units cost from $US300 for the Chinese engine and locally manufactured pump to $US600 for the fully imported systems. The cost of digging and installing the tube-wells ranges from $US150–300 per developed well.

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Appendix 4: Cost and returns for rainfed, irrigated rice growing in Prey Kebas district.

Operation	Rainfed system ($/ha)	Dry season-irrigated ($/ha)	Wet season-supplementary irrigation ($/ha)
Crop returns ($158/t WS, $140/t DS)	276.5	455	434.5
		Cropping costs	
Land preparation	60.0	60.0	60.0
Plant establishment	37.5	15.0	37.5
Weeding	15.0	30.0	15.00
Fertiliser	15.0	30.0	30.0
Irrigation		100	20
Harvesting	50.0	60.0	60.0
Total cost	178.5	295	222.5
Net return ($/ha)	99	287.5	259.5

Improved crop production under water constraints

Shu Fukai[1] and Suan Pheng Kam[2]

Abstract

Different technologies are available to increase crop production where water is a major constraint, but they are not universally applicable; rather each is suitable for a particular water environment/crop combination. This paper reviews recent developments in our understanding of the crop–water environment and crop responses to water constraints, and provides several examples of technologies that have improved or could improve crop production under water limitations.

In semi-arid areas crop yield can be increased by fallowing to increase stored soil water, and by increasing the row spacing to use soil water slowly. These technologies ensure that water is available until crop maturity. Under more favourable humid environments, the total amount of water is commonly sufficient, but there are often periods of water shortage that affect crop yield. A small amount of supplementary irrigation available at the critical stage could markedly stabilise production. The current rainfed lowland system uses water inefficiently, and there is an opportunity to develop an aerobic system which uses limited water more efficiently. A few examples of genetic improvements to increase crop production under water limiting conditions are also given.

Water environment characterisation is important for determining which promising technologies are likely to be successful for a particular location/crop combination. Many experiments are often needed to cover the temporal and spatial water environment variations. The technology development can be achieved by an interdisciplinary team of scientists: without the consolidated efforts of a critical mass of scientists, new technologies will be slow to develop.

Introduction

CROP PRODUCTION under water constraint has been improved by developing irrigation systems, managing crops appropriately and improving cultivars. With increased population pressure and urban encroachment, there is an urgent need to further improve agricultural production in drought-prone upland and rainfed lowland areas. The looming water crisis of the 21st century, however, means less irrigation water is available for agriculture. There are limited prospects for large-scale irrigation projects, and the danger of indiscriminate tapping of groundwater resources without knowing enough about recharge capacity, and therefore resource sustainability. Furthermore, global climate change seems to make intra-annual (i.e. seasonal) rainfall distributions more erratic and inter-annual variations less predictable, resulting in greater uncertainty and risk for rainfed agriculture.

There is no simple solution to the problem of low crop productivity under water constraints. For a specific crop at a location, the problem may currently appear overwhelmingly large and the solution far distant. However, there are two encouraging developments. There are now several successful examples of increasing productivity under water constraints. They often involve new options for crop management, cultivars for rainfed crops, or alternatives to presently cultivated crops (Loomis 1983). Exam-

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ining these successful systems may provide a guide for the development of new technologies to alleviate the problem of water scarcity at a given location. Another encouraging development is that our understanding of crop water needs and crop responses to drought has increased greatly recently (Fukai et al. 2001). The conventional crop productivity per unit land area needs to be broadened to crop-water productivity, that is, to include a per unit water consumed basis. This means knowing how much water is used in the field during crop growth, and often how much is needed before planting.

This paper describes water environment characterisation and crop response to water deficits and then describes how some crop management technologies and cultivar improvement have been developed or appear promising for water limiting environments. We consider technologies that can be adopted at the farm level, and do not discuss development of irrigation schemes or other infrastructure development. Takase (these proceedings) describes some of these aspects for Asian agriculture.

Four steps may be considered for technology development to increase crop production under water constraints (Figure 1). The first is problem identification. The problem should be large in scale, researchable and have a large impact once it is tackled. An example may be that establishment of direct seeded rice is a major problem because of the lack of water at the time of seeding. The problem identified should be generally crop specific and management specific. The second step is to examine appropriate technologies that could minimise the problem. Some examples of potential technologies are mentioned in this paper. The third step is to characterise the water environment that causes the problem to the crop; this helps determine which technologies would be effective and where the technologies should be tested within the region. The fourth step is to evaluate, adapt and refine the selected technologies at a number of locations. The technologies thus developed need to be accepted and adopted by farmers before they can have any real value.

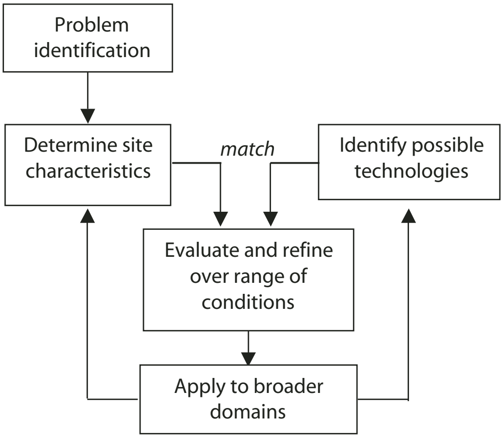

Figure 1. Schematic diagram for the approach suggested in this paper to develop technologies to improve agricultural production under water constraints.

The main focus of the paper is drought rather than flooding and the main crop considered is rainfed rice.

Characterisation of plant-available water environments and crop responses to water stress

Broadscale characterisation of water availability for crops may be based on meteorological factors, and GIS technology has helped in developing water availability maps. More detailed characterisation of drought patterns can be determined at the field level, and we now have a good understanding of crop responses to drought. These are briefly described in this section.

Meteorological factors—rainfall and potential evapotranspiration

The yields of rainfed crops are variable because of rainfall (temporal and spatial) variation as well as soil (spatial) variation. Mapping mean monthly rainfall is commonly the first step in characterising the water environment, but variation in potential evapotranspiration (PET) also needs to be considered when estimating water availability; hence the concept of climatic water balance as the difference (or ratio) between rainfall and PET. Broadscale agro-climatic characterisation, based on climatic water balance and length of growing period using long-term averages of input variables, provides a first-cut identification of rather large zones to determine the main climate-driven constraints and crop domains.

GIS mapping of water availability

Where comprehensive data are available for the region concerned, GIS helps to analyse and delineate these domains to estimate more accurately the area affected by water constraints. For example, the International Water Management Institute (IWMI) published a CD-ROM of the *World Water and Climate Atlas* of grided surfaces (at 0.1667 degree or 18.52 km resolution) of climatic water balance (http://www.iwmi.cgiar.org/Watlas/atlas.htm). Singh et al. (1999) used climatic water balance to determine periods of water availability at district level for eastern India. In Bangladesh, the length of the growing period based on climatic water balance developed by Brammer et al. (1988) was refined and implemented by GIS to produce maps showing drought-prone areas for transplanted rice (T aman) grown in the main (kharif) rainfed season, and for winter season (rabi) crops (Karim and Iqbal, 2001).

Within these large domains, more refined characterisation is needed to determine the nature and severity of the water constraint. The refinement is both in the scale aspect, for example, considering smaller time steps and using time series data to capture temporal (intra- and inter-annual) variability, as well as considering interactions of climate with soil factors in determining shorter-range spatial variation in water availability. Kam et al. (1999) developed a weekly based water balance model to estimate water availability and storage in rainfed lowland rice fields, taking into account climatic (rainfall and potential evapotranspiration) and soil (water holding capacity and seepage and deep percolation loss) as well as field bunding factors. Implemented within a raster-based GIS environment, the model produces grided weekly soil-water storage surfaces. Such surfaces have been generated for North-east Thailand and for the eastern Indian states of Bihar and West Bengal, and more recently for Lao PDR.

The utility of these domain characterisation efforts is to identify research needs and design intervention strategies to overcome the nature of the constraints—for example, terminal, mid-season drought—to the extent that they affect crop performance and yield. For example, using the weekly water balance surfaces for North-east Thailand, Kam et al. (1999) identified three main zones in terms of nature and severity of drought affecting rainfed lowland rice cultivation, and the implications of targeting varietal characteristics as well as crop establishment and management strategies to cope with drought in each of the zones.

Drought patterns and strategies at the field level

Two contrasting types of drought are terminal drought where severe prolonged drought develops towards the end of growing season, and intermittent drought where there may be short drought periods between rainy ones. The strategies to increase yield depend on the drought type. For terminal drought, the crop cycle needs to fit within the period when water is available; thus a common strategy is early planting and use of quick maturing crops to ensure crop maturity occurs before severe drought develops. This is often so for drought development in semi-arid areas and also at the end of the wet season in sub-humid and humid areas of South and South-east Asia. In South-east Asia, intermittent drought commonly occurs during the wet season and is often unpredictable, varying from season to season. Thus many examples need to be considered before any firm conclusion can be drawn.

Simulation modelling can be used to determine the pattern of water stress development within a crop season. Chapman et al. (2002) used such an approach to identify drought patterns for sorghum in Queensland. Using weather data of more than 100 years, they identified three major drought development patterns: severe terminal drought, mild terminal drought and mid-season drought. The simulation results suggest that these three types of droughts occur at about the same frequency. This information can be used to determine the appropriate maturity groups to escape from severe terminal drought. Variation in the frequency of occurrence of the three groups within the whole region can be used for refining maturity group requirements.

Pattern of water use and development of plant water stress

While total water availability for a crop often determines its potential productivity, the pattern of water availability within the crop cycle influences the actual crop yield. Thus water availability needs to be matched with the crop water requirement to achieve full yield potential. Crop water requirement increases with canopy development, and the maximum water requirement often coincides with flowering time when the crop is also most susceptible to water deficit. If water stress develops around flowering time, spikelets often become sterile and crop yield may be greatly reduced. Increased water availability at around the time of flowering can increase yield substantially. This matching of crop water requirement with water availability in the soil is particularly important under the condition of terminal drought. Loomis (1983) illustrated how water use pattern could be altered by crop manipulation and growing crops at different seasons.

Water stress develops when there is insufficient soil water to meet crop demand. In addition to soil water content, plant development and atmospheric conditions affect the plant water status. Often an avoidance strategy, that is, avoiding water stress developing by reducing water use early in the crop cycle, is used for stable crop production in dry environments, particularly for terminal drought.

Yield determining factors under water limitation

Crop yield (Y) in the field may be considered in terms of three major components with respect to water utilisation:

$$Y = WU \times WUE \times HI \quad (1)$$

Where WU is total water use by the crop in the field, mainly due to evapotranspiration but also includes seepage and deep percolation loss; and WUE is crop water use efficiency,

WUE = TDM/WU, that is, the amount of total dry matter produced divided by the amount of water used to produce it; and

HI is the harvest index,

HI = Y/TDM, that is, the proportion of total dry matter—and a measure of the economic value of the crop.

Yield (hence productivity) may be increased by maximising total water use, increasing water use efficiency, and increasing harvest index.

Total water use. Total water use (WU) is made up of transpiration (T) by the crop and of soil evaporation (E), run-off (RO) and percolation (P).

$$WU = T + E + RO + P \quad (2)$$

The water supply is contributed by rainfall and irrigation during the crop cycle plus soil water available at the time of planting. There is a strong association between photosynthesis and transpiration at the leaf level as well as at the canopy level. Thus increased WU will result in increased biomass production if T is increased.

Water use efficiency. WUE increases if more biomass can be produced per unit total water use during crop growth. This can be achieved in two ways:

- Any method of managing water for crop use that minimises soil evaporation, seepage and percolation loss will increase the efficiency of water use by the crop. These components do not contribute to crop production, and hence should be minimised so that the proportion of total water used for transpiration can increase.
- There are also large variations in transpiration efficiency, defined as the ratio of photosynthesis to transpiration at the leaf level. Crops grown under high vapour pressure deficit (VPD), for example, in arid climates, will have a much lower WUE (even though yields are much higher) than crops grown under humid (lower VPD) conditions. Plant nutritional status and level of pest and disease infestation also influence WUE; with healthy crops having higher WUE. Crop species also differ in WUE, particularly the WUE of C4 species is higher than that of C3 species.

Harvest index. HI is an inherent property of the plant/crop variety, and is modified through genetic manipulation to increase the efficiency of conversion of biomass to the plant organ that contributes to the crop yield.

In addition to the genetic factor, HI is determined greatly by the pattern of water use. Particularly under terminal stress conditions, severe water stress that affects growth in the grain filling stage reduces HI. Reproductive-organ development is particularly sensitive to even mild water stress, and this results in severe yield reduction with resultant reduction in HI.

HI often depends on total WU and WUE. For example, if a small amount of extra water is available during flowering to grain filling, total WU may be increased only slightly but this may minimise the adverse effect of drought on grain yield and HI may increase substantially.

Opportunity for intervention—case studies

Crop management

There are several examples of crop management options having been successful or appearing promising in developing productive and stable cropping systems under water constraints. They are described in association with the three components that determine grain yield under water constraints. Table 1

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summarises the main technological interventions associated with the three factors.

The technologies are listed in order of those suited for less favourable conditions of water availability, such as semi-arid areas, to those suited for more favourable areas but with some water limitation. This includes environments where supplementary water is available. Full irrigation environments are not included in this review.

Fallowing—increasing initial soil water available to crops

A common practice for increasing the total WU for upland crops in semi-arid areas is fallowing, whereby the land is kept idle for several months to accumulate water in the soil before planting the crop. Increasing the initial soil water gives the crop a better chance of producing higher yield than if there is continuous cropping without fallow. This will reduce cropping intensity, but fallowing can stabilise crop yield. With water accumulated during the fallow period, the soil water content at the time of planting is often much higher when WU is increased. For wheat crops in southern Australia, 1 mm of the extra water stored in the soil because of fallowing commonly produces an extra 10 kg/ha of grain.

Fallowing is more successful in areas where soils have high water holding capacity, and fallow efficiency (i.e. the ratio of amount of stored water in the

Table 1. Technology interventions available to increase crop yield under water constraints and its effect on three factors (wu—water use, WUE—water use efficiency, and HI—harvest index). ++ strong positive effect, + positive effect, – negative effect.

	Technology	WU	WUE	HI
Water availability	*Cropping practice & water management*			
Less favourable	Fallowing	+		
	Moisture conservation techniques, e.g. minimum or zero tillage, mulching	+		
	Increased row spacing		–	++
	Change to field operations that are less water dependent esp. for rice, e.g. direct seeding	–	+	+
	Use of short duration crop	–	+	+
	Water harvesting and supplementary irrigation	+		+
	Limit periods of standing water for rice		++	
	Remove other stresses, e.g. nutrient deficiency, pest & disease, weed control		++	
More favourable	Double cropping	++		
	Genetic manipulation			
Less favourable	Early maturing	–		++
	Improve tolerance to water stress	+		+
	Change plant architecture to reduce transpiration loss	–		+
	Change root architecture to increase water uptake	+		
More favourable	High yield potential			++

soil because of fallowing to the total amount of rainfall during the fallow period) of 10–20% is common in heavy textured soil (Table 2 from French 1978). This often results in 50–100 mm extra water stored in the heavy textured soil.

Table 2. Water accumulation due to fallowing before planting wheat in South Australia (from French 1978).

Site	Soil texture	Additional water due to fallow (mm)	Additional water (as % of rainfall during fallow)
Wanbi	Coarse	10	2.6
Minnipa	Coarse	6	1.4
Gladstone	Fine	34	8.0
Turretfield	Fine	31	8.0
Maitland	Fine	92	19.3

Bare fallow which was used in the past in semi-arid areas is, however, susceptible to soil erosion, particularly after rain storms, and the cost of mechanical cultivation is also high. Herbicide fallows to control weeds are common where stubble from the previous crop may be maintained without incorporation in the soil to protect the fallowed land. The stubble would contribute to reduction in soil erosion and increase in infiltration of rain water while reducing soil evaporation. Thus reduced tillage with use of herbicides often results in increased fallow efficiency with an increase in stored water at the time of planting.

Increased row spacing to improve water balance late in the crop cycle

For a given crop duration, a common strategy particularly for upland crops under terminal drought conditions in semi-arid areas is to reduce crop water use early in the crop cycle, so that stored water in the soil is still available towards the end of the crop cycle when rainfall is likely to be low or negligible and does not meet the crop water needs. Reduced fertiliser use, low planting density, and use of wide rows are often practised mainly for this reason in water limiting environments.

Sorghum, maize and cotton are commonly grown in wide rows in drier areas. Every second row may be omitted to create skip rows, or sometimes two rows are placed close together (twin rows) with wider gaps between the neighbouring twin rows. In these wide rows ground cover by the leaf canopy is less and hence crop water use is reduced, particularly during early stages of growth. However, high soil evaporation in frequent rainfall areas may reduce the effect on saving water. Yield is often increased by prolonging water availability into the maturity period, with resultant increase in HI.

Many experiments in northern Australia comparing the yield of sorghum grown under 2 m, 1 m and 0.5 m rows confirmed that wide rows are suitable for low yielding environments whereas narrow rows are suitable under high yielding environments with little or no water limitations. If yields are less than 1 t ha^{-1}, 2 m wide rows are likely to produce the highest yield, but if the yield level is higher than 3 t ha^{-1}, 50 cm narrow rows would be better.

Short duration crops adapted to dry conditions and planted at appropriate time

A crop will receive more rainfall by planting at an appropriate time whereas delayed planting in a wet season is a common problem, resulting in reduced yield. In areas where the growing season is limited, planting a short duration crop or cultivar early in the wet season is required. The challenge that farmers in rainfed areas face is to know when to plant a short season crop especially in areas where the onset of the monsoon varies from year to year. Many farmers use indigenous wisdom (e.g. farmers in Eastern India watch for the appearance of the Rohan star (Narahari Rao et al., 1999) in mid-May as an expectation of pre-monsoon precipitation for carrying out nursery planting and land preparation for rice) or a short-term weather forecasting system.

One way to avoid delayed planting of rice is to change to direct seeding. Transplanting requires soil saturation and this often results in transplanting two to three months after the start of the wet season. However, rice can be direct seeded much earlier, either before the rains begin (dry seeded) or after (wet seeded). If the wet season is very short (e.g. in eastern Indonesia) dry seeding before the beginning of the wet season allows the crop to utilise the whole wet season. However, a change to direct seeding needs to be accompanied by changes in other crop management practices, especially weed management. In North-east Thailand farmers who direct seed without managing weeds effectively find that they have to resort to transplanting after two to three years because of a build-up in weed populations.

Development of water stress differs greatly among crops. This may be related to variation in root depth; deep-rooted crops will be able to extract soil water from depths that may not be accessed by shallow-rooted crops. Some crops are also more sensitive to mild soil water deficit than others; for example upland rice stressed quickly with even mild soil water deficit whereas maize and sorghum may not be affected (Inthapan and Fukai 1988).

Water harvesting and supplementary irrigation at the farm level

In the humid and sub-humid tropics, wet season water stress is often caused by intermittent drought that develops at the beginning of, or during, crop growth, causing crop failure or a large yield reduction. Total rainfall is often high, but unevenly distributed. Thus one key technology is to harvest surface water that can be used for the crop when it is needed.

Harvesting of surface water can be promoted with on-farm storage ponds. These have been established in various countries and have markedly increased crop productivity (Bhuiyan 1994). Tied ridges in furrows can reduce run-off, and are practised in some countries in Africa. In Cambodia and elsewhere tube wells are increasingly installed to tap underground water. Supplementary irrigation, even involving small amounts of water, can have a large effect on the economic yield through increased HI, particularly if a crop is relieved from water stress at the critical stage. Supplementary irrigation is particularly useful as water can be applied when it is needed by the crop, and timely irrigation can enhance yield greatly or in an extreme case save an otherwise crop failure. Supplementary irrigation can also be vital in developing stable and profitable double-cropping systems in Cambodia (Chea Sareth et al., these proceedings).

In general, WUE is inversely related to dryness of the air (VPD), and hence crops use water inefficiently under hot, dry conditions. But yields are often high under these dry conditions because radiation for photosynthesis is high. This has obvious implications in selecting the cropping time, and also the timing of supplementary irrigation. For example, in northern Thailand and Laos, irrigating a crop with limited water at the end of the wet season when the temperature is low is much more efficient than at the end of the dry season when VPD is high.

Elimination of standing water in lowland rice

Lowland paddies with bunds are efficient in collecting excess rainwater that may otherwise run off. As rice is highly susceptible to mild soil water deficit, bunded lowland paddies constitute an efficient way of ensuring water availability to the crop. The water is also used for land preparation, transplanting and weed control. However, lowland culture is not efficient in using the collected water. While it is difficult to separate out the use of all water balance components, the lowland rice model (Fukai et al. 1995) indicates that only around 50% of the water available for crop growth (from transplanting to maturity) is used as transpiration and hence photosynthesis and biomass production. Most water loss is as evaporation from the water or soil surface, and from deep percolation and seepage, particularly if soils are not well puddled. Thus, lowland rice has a low WUE, and to achieve high yield a large WU is needed.

It is known that rice can still grow well without standing continuously in water provided water is readily available to its roots. The study of aerobic rice provides an opportunity to develop a stable rice cropping system with reduced water needs, particularly where limited irrigation water is available. Aerobic rice is practised over 100,000 ha in North China. It grows in non-puddled, non-flooded soil with moderate external inputs and limited supplementary irrigation when rainfall is insufficient. The field may be bunded or non-bunded. The yield may be 4.5–6 t ha^{-1} which is 20–30% lower than that obtained in irrigated lowland, but is much higher than that of upland rice without irrigation. The irrigation water needs of aerobic rice may be only half that of irrigated lowland, and hence the efficiency of irrigation water use is high. Without puddling and standing water, roots can extend deeper, providing access to subsoil moisture and hence more efficient water use.

A stable rice-based cropping system with increased WUE may be achieved by the use of a raised bed system with furrow irrigation. In a study of saturated soil culture where standing water is maintained only on furrows between raised beds with around 1.8 m width, irrigation water consumption was reduced by 30% with yield penalty of less than 10% in northern Australia (Borrell et al. 1997) (Table 3). The system was successfully tested in eastern Indonesia (Borrell 2001).

The major problem in the raised bed system as in other types of aerobic rice is the control of weeds. The problem may be minimised with appropriate rotation systems with upland crops such as soybean or maize which the raised bed system can accommodate easily. Nevertheless the need for herbicides is generally likely to increase.

Table 3. Water use (mm). Grain dry mass (g m^{-2}) and efficiency of water use for grain production (WUE_g, g m^{-2} mm^{-1}) for two seasons and five methods of irrigation. Borrell et al. 1997. PF: permanent flood at sowing (S), three leaf stage (3L) or panicle initiation (PI). SSC: saturated soil culture (raised bed system). II: intermittent irrigation.

Method of irrigation	Water use	Grain dry mass	WUE_g
Dry season			
PF-S	1351 d[a]	875 b	0.65
PF-3L	1320 d	822 b	0.63
PF-PI	1170 c	789 b	0.67
SSC	904 b	734 b	0.92
II	764 a	507 a	0.66
Mean	1102	746	0.69
l.s.d. ($P < 0.05$)	94	177	ns [b]
Wet season			
PF-S	1286 d	612 c	0.48
PF-3L	1228 c	456 b	0.37
PF-PI	1075 b	421 ab	0.39
SSC	833 a	402 ab	0.48
II	873 a	363 a	0.41
Mean	1059	451	0.43
l.s.d. ($P < 0.05$)	49	64	0.07

[a] Means within a column and season not followed by a common letter are significantly different ($P < 0.05$).

[b] ns denotes F-test was not significant ($P > 0.05$).

Another requirement of the system is that the land be levelled for even distribution of water. Precise control of the water level is needed for the raised bed system if standing water in furrows is to be maintained in the larger paddies to ensure continuous water supply to the roots. With the raised bed system, a new nitrogen management system is needed (Ockerby and Fukai 2001). Thus it is imperative that a new system such as using a raised bed requires efforts by many scientists to refine the technology.

Developing a stable aerobic system is more difficult in rainfed lowlands where irrigation water is not available and risk of water stress is high. Rice is susceptible to an even mild soil water deficit. For example in studies with sprinkler irrigation in Australia, upland rice yield was reduced as the frequency of irrigation was decreased from three times a week to once a week while maintaining the total water use (Table 4, Fukai 1996). While most other deep-rooted upland crops that are less sensitive to water stress can be grown with an irrigation frequency of once in two weeks, rice is susceptible to water stress and yield decreases with a short period of water shortage particularly during panicle development stage. Thus, unless irrigation water is available and the crop can be irrigated when there is a period of no or little rainfall, lack of standing water in the aerobic system will predispose the crop to drought with even a short rainless period. Therefore the aerobic system in rainfed lowland may reduce water needs, but the technology will accompany a greater risk of crop failure and large yield reduction. We need to develop a system in which at least some part of the water that is saved by eliminating standing water is stored and is available to the crop as irrigation water during rainless days. As mentioned earlier, on-farm storage tanks could be used to collect the water and stabilise production.

Table 4. Grain yield of rice (cv. Mizuhatamochi) grown under four irrigation frequencies between 60 and 103 days after sowing. Values are mean of four replications and standard deviations are shown in brackets (after Fukai 1996).

Frequency	Yield (g/m^2)
Three times a week	902 (154)
Two times a week	775 (35)
Once a week	707 (145)
Once in two weeks	597 (51)

Reducing other constraints to increase crop water use efficiency

Any adverse conditions that affect crop growth will generally reduce WUE and cause a large reduction in yield. For example, weeds competing with crop plants for water reduce WUE of the crop. Other biotic constraints often greatly reduce photosynthesis with even a small effect on transpiration reducing the WUE. Thus, one of the key elements for increased WUE and hence higher grain yield under water limiting conditions is to minimise these biotic constraints. Similarly, nutrient deficiency or toxicity often reduces WUE.

Fertiliser management for rainfed crops has been studied extensively. In most rainfed lowland rice areas, crop yield responds to nitrogen (N) and phosphorus (P) application particularly in areas where initial soil fertility is low such as in Central-Southern Laos (Linquist and Sengxa 2001) and Cambodia (Seng Vang et al. 2001), although the probability of non-response appears higher in North-east Thailand.

This may be associated with generally drier conditions in North-east Thailand than the sub-humid areas of Laos and Cambodia. Fertiliser management, particularly N management, under water constraints depends on whether water or the nutrient is the major limitation of crop yield. If soil N is very low while water limitation is mild, it is likely that an adequately high rate of N application results in higher grain yield. But if water is the major limitation, then the N fertiliser rate should be reduced. It would be useful to identify the major limitation first (i.e. irrigated vs rainfed and non-fertilised vs fertilised) before the rate of fertiliser is considered. In most cases the fertiliser rate recommendation is made after water availability conditions are considered.

Water availability varies greatly yearly and within a region, and thus many fertiliser rate experiments need to be conducted systematically. If an upland crop is grown under terminal drought conditions, and hence its growth relies heavily on stored soil water, application of high N may result in rapid exhaustion of stored soil water and severe water stress may develop well before crop maturity. However, in soils with low N status, applying N promotes water uptake from deep soil layers or more thoroughly from upper layers because of promotion of root growth. Slow release fertiliser is advantageous as it releases more nutrients when the crop requirement is higher.

When there is standing water in rainfed lowland rice, it may be possible to make a spot application of fertiliser to correct nutrient deficiency observed within the field. This is a common practice to reduce spatial heterogeneity of crop growth. In some cases tissue may be analysed to determine the amount of N fertiliser at panicle initiation. Chlorophyll charts are now widely used to assess plant N status. Precision nutrient treatment to match demand helps increase crop yield when both nutrients and water are limiting crop yield.

Double cropping under more favourable water conditions

Under more favourable water conditions, including longer rainy seasons, it may be possible to double crop to increase WU of the combined crops. The combined duration of two crops in the tropics is often three months longer than for a single crop. However, there may not be enough water to grow two crops in sequence without increased risk of crop failure and this risk generally increases with increased total crop duration. A common way to develop successful double cropping is to grow a quick maturing cultivar as at least one of the two crops, and plant the first crop early, especially using, for rice, direct seeding instead of transplanting. To reduce risk further the time from the harvesting of the first crop to the planting of the second crop should be minimised, and even direct sowing of the second into the first crop or relay cropping may be practised. The availability of supplementary irrigation such as the use of underground water from tube-wells or from small surface ponds can greatly enhance double cropping (Chea Sareth et al. 2003). The choice of crop species is also important. If the growing season for the second crop is short, a quick maturing crop such as mungbean is suitable. However, if there is a chance of flooding, quick maturing rice would be better (Chan Phaloeun et al., these proceedings).

In Pakistan, northern India and the Gangetic Plains in Eastern India, Nepal, Bangladesh and central to southern China, rice–wheat double cropping has become common in recent years. The thermal conditions in these areas suit the rice and wheat combination. While most areas have irrigation water, in some areas crops are grown rainfed. The rice–wheat system has increased rapidly since the 1960s with the development of short-duration cultivars of both species. Sustainability and productivity of the system is documented in recent publications (Timsina and Connor 2001, Ladha et al. 2003). With puddling commonly practised for transplanting of rice, wheat establishment may be poor because of impaired structure of the soil. One of the key issues for success of this double-cropping system is to have wheat in a timely manner. Wheat establishment is improved if seeds germinate before surface crusting occurs as a result of drying the soil surface after having standing water for the rice crop. Zero or reduced tillage for planting of wheat is now widely practised. Another option is relay planting of wheat before rice matures, or surface seeding of wheat in an untilled rice field immediately after harvesting of rice. Thus the key is planting of wheat early to avoid high temperatures during grain filling as a delay in wheat growth results in reduced yield (Table 5).

Table 5. Grain yield (kg/ha) of rice and wheat, sown early or late, under rainfed and irrigated conditions for 1994–97 in Bangladesh (after Timsina et al. 2001). Each yield is a mean of yields of different cultivars and N application rates.

		Sowing time	1994	1995	1996	Mean
Rice	Rainfed		3510	2563	2402	2825
	Irrigated		6312	3466	2438	4072

		Sowing time	1994/1995	1995/1996	1996/1997	Mean
Wheat	Rainfed	Early	3021	2801	2246	2689
	Irrigated	Early	3562	2726	2692	2993
	Rainfed	Late	2761	2537	2273	2524
	Irrigated	Late	3149	2349	2270	2590

Genetic improvement

Matching cultivar phenology with water availability

Under water limiting conditions particularly under terminal stress, quick maturing cultivars may escape from the end of season drought. They require less water with reduced crop duration. The development of drought late in the season often affects reproductive organ development and grain filling, resulting in reduced grain yield with low HI.

Photoperiod sensitivity is another way of ensuring that crop maturity occurs at the onset of the dry season. An advantage of photoperiod sensitive cultivars is that they flower about the same time regardless of planting time (see Fukai 1999 for review in the case of rice). This long planting time window provides much flexibility in farm operation and photoperiod sensitivity is an important mechanism for poor, rainfed farms to minimise the risk of a season with no food for the family. However, if photoperiod sensitive cultivars are planted late in the season, potential yield is reduced due to the short vegetative growth period. Thus, if a season turns out to be favourable, then yield may not be as high as that of insensitive cultivars that may take a longer time to flower (Makara et al. 2001).

Quick maturing cultivars are often associated with high HI, and this often compensates for a reduced TDM. Modern, high-yielding cultivars are often of short-duration with a semi-dwarf and have higher HI compared with taller traditional cultivars. Thus, under non-water limiting conditions, these cultivars tend to produce higher yield (Jearakongman et al. 1995) with similar or reduced water use. Photoperiod-insensitive, quick-maturing rice cultivars, such as IR66, can mature in 100 days and thus allow double cropping in some parts of the rainfed system in Asia. In Cambodia, IR66 is planted in the early wet season, followed by more traditional photoperiod sensitive cultivars suitable for the wet season. This development has contributed greatly to the use of early maturing cultivars with a corresponding decline in late maturing cultivars. Thus the cultivation of late maturing cultivars (flowering after November 15) decreased from 1.57 million ha in 1967 to 0.60 million ha in 1999. The increased adoption of early and intermediate maturing cultivars contributed greatly to the increase in rice production in Cambodia (Makara et al. 2001).

Development of higher yielding cultivars under water limiting conditions

The use of quick maturing cultivars for terminal drought conditions has been mentioned above. Fukai et al. (2001) further identified cultivar characteristics that are associated with high yielding potential for drought-prone rainfed lowlands (Figure 2). When reduction in yield by drought is rather small, for example, less than 30% of the irrigated yield, cultivars that have higher potential yield are likely to produce higher yield than other cultivars under mild drought conditions. However if drought stress develops suddenly or is prolonged and yield may be reduced to less than 50% of the irrigated yield, then there is more interaction between cultivar and environment.

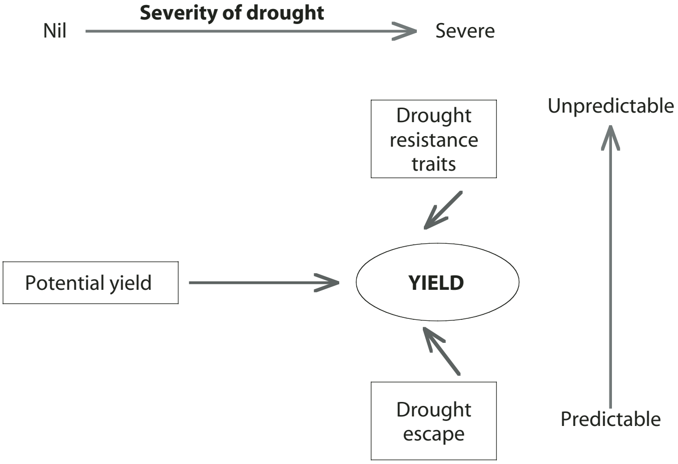

Figure 2. Factors determining genotypic variation in crop yield of rainfed lowland rice. In areas where drought is mild, genotypic variation is more determined by variation in potential yield obtained in well-watered conditions. When drought timing is predictable, drought escape by use of appropriate phenology is advantageous. When drought is severe and unpredictable, genotypes with drought resistance characters produce higher yield. After Fukai et al. (2001).

If stress is not predictable, cultivars with drought tolerance have a better chance of producing higher yield. The drought tolerance mechanism may be associated with higher leaf or panicle water potential in the case of rainfed lowland rice (Pantuwan et al. 2002). Cultivars that can maintain higher leaf water potential under drought conditions tend to have a shorter delay in flowering if drought develops just before flowering. Thus flowering delay can be used as a selection criterion as it is much simpler to measure than leaf water potential.

Rice breeders have been successful in developing widely adapted cultivars for rainfed lowlands. In Cambodia, breeders in the Cambodia–IRRI–Australia Project and subsequently in CARDI have successfully identified higher-yielding, intermediate-maturing cultivars. Together with the use of early-maturing, photoperiod-insensitive cultivars in the early wet season and dry season, rice production has increased greatly in recent times, and has met Cambodia’s domestic needs.

In Laos, cultivars that are widely adapted to rainfed lowlands produce higher yields under most growing conditions, and are generally more responsive to fertiliser than traditional local cultivars (Schiller et al. 2001). They have contributed to increased rice production after their wide acceptance by farmers.

Development of cultivars resistant to other constraints

As for crop management, rice cultivars resistant to other constraints, including disease resistance (e.g. to blast) and tolerance to nutrient toxicity/deficiency, can increase productivity under water constraint. With changes in technology, for example, adoption of direct seeding as a result of labour shortage for transplanting, a new cultivar is needed. A major constraint for direct seeding in rainfed lowland rice is weeds and lodging. Thus crop productivity under water constraints would be increased with development of cultivars that can tolerate weeds and resist lodging under direct seeding.

Evaluation of potential technologies

Technology selection and testing

The key to effectively increasing productivity under water constrained conditions lies in matching what is known of the conditions at the target location with an appropriate selection of ‘best-bet’ interventions. Some of the best-bet interventions have been mentioned in the previous section. In selecting which technologies to adopt or modify, similarity in water environments is important. Technologies developed for similar water, and socioeconomic environments are likely to be adopted successfully in the target region.

Well-designed experiments conducted at a stratified range of environments increase our understanding of why appropriate options are workable or feasible. This understanding is distilled into working principles and decision rules. These are then validated at more locations and incrementally refined, as feedback from field experience provides better insight of both target site characteristics and the need to adapt the technologies.

The choice of crop is important, as it is likely that intervention is crop specific. Market demand for the crop in the near future needs to be considered in detail before technology development is carried out.

Scaling out

While a set of technologies may appear well suited at the particular location of intensive study, the results obtained at the field level need to be scaled up for wider dissemination to larger domains. The extrapolation or recommendation domain concept is based on the possibility of finding areas and sets of conditions where new technologies can be applied (Latham, 1998). Extrapolation domains are determined not only by the biophysical characteristics of the production environment and its inherent variability, but also by the production system features and farmers' socio-economic characteristics.

Identifying similar places based on biophysical characteristics

The interactions of climate, terrain and soil resulting in hydrological processes at the landscape and field level largely govern the availability of water to the crop. Understanding these processes is fundamental to identifying the appropriate interventions—selection of crop type, variety and accompanying management practices—that are meaningful to the farmer. For rainfed lowland rice, even minor variations in micro-topography over short distances can profoundly influence in-field water availability and yields, as evidenced from recent studies in Jakenan, Indonesia (T.P. Tuong, personal communication). Such experiments need to be conducted at least for a few seasons and then at a few locations.

Identifying similar production systems or practices

The prevailing and predominant land use, production systems and practices also constitute the characteristics of the extrapolation domain. For example, more water efficient strategies and technologies targeted at monoculture rice production systems would differ markedly from those targeted at production systems combining rice and non-rice crops. Areas where farmers practise field operations that depend on standing water (e.g. transplanting), which may be delayed or disrupted due to water shortage, would need specific water-conserving interventions. In systems where crop industry changes are considered, the available markets for perishable food will be important in defining the production system.

Identifying similar socio-economic conditions

The intention is not to search for an exact match but is based on key socio-economic characteristics that are most likely to enable certain production systems or technologies to be adopted. Technologies introduced must be affordable to the target farmers, or new crops introduced need to take into consideration access to market.

Inevitably, technologies and other innovations that are successfully adopted will eventually change the objective conditions and characteristics of the target domains, which opens up further opportunities for improving productivity and farmers' livelihoods and/or the long-term sustainability of the production environment.

Conclusion

The examples shown in this paper indicate that there is ample scope for improving yield by proper crop management and genetic improvement for a wide spectrum of water constraints. This may be associated with increased total water availability for fallow or slow water use in wide rows in terminal stress conditions in semi-arid areas. Similar points may be made for using quick maturing cultivars to escape from the terminal drought in humid–sub-humid tropics.

In humid–sub-humid tropics total water availability may often be high, but the problem is that water availability to the crop is not sufficient at critical stages, and intermittent stress develops resulting in crop failure or severely reduced grain yield. Relatively small amounts of irrigation water can stabilise crop production greatly. The use of small irrigation systems either through tube well pumps or surface water harvesting is an important potential contribution to enhancing water productivity.

Crop production under water constraints can be increased when other constraints are removed. This may be achieved by appropriate crop management methods and developing cultivars resistant to the adverse conditions. These complex situations can be best handled by a group of scientists with different skills and expertise. Improved understanding of crop–water relations and associated factors is important in developing sound technologies.

The team approach is also needed when technology is developed to solve a particular problem of local importance. The technology is often modified to suit regional needs, and is best adopted by the farmers. Identifying market demand for a particular crop is also a key part of the successful technology development.

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Improving rice productivity under water constraints in the Mekong Delta, Vietnam

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Abstract

The problems/constraints affecting rice production in the Mekong Delta of Vietnam vary across ecosystems and the solutions therefore vary. Research needs to address the particular problems of each ecosystem. The aims of this study of production relationships include: (1) the identification of controllable and uncontrollable factors of production that significantly affect yield, and (2) the rice varietal improvement to abiotic stress. Vietnam has a relative advantage in having highly irrigated areas for rice production. In the 1980s the irrigated area expanded by 2.9% annually, and during the 1990s this growth rate was 4.6% annually. During the 1990s, investment in irrigation has increased from 1538 billion VND to 2506 billion VND. It was estimated that irrigated rice land has increased from 40% to 90%. For the Mekong Delta, this rate is around 70% while the lowest belongs to the High Plateau and north-eastern south.

Drought and salinity are now considered as more important than flood damage to rice productivity in the Mekong Delta, due to having a flood-escaping strategy and using short duration genotypes before and after flood. Therefore, attention is being paid to rice breeding to improve rice productivity under salt stress and drought at the seedling stage.

Introduction

THE problems/constraints affecting rice production in the Mekong Delta of Vietnam vary across ecosystems. Therefore, the solutions will vary accordingly. Our research addresses the specific problems for each ecosystem but generally concentrates on flood and drought.

The aims of the study of production relationships include:

- the identification of controllable and uncontrollable factors of production that significantly affect yield
- rice varietal improvement to the abiotic stress.

In 1999 rice covered 7.64 million ha of Viet Nam with the Mekong Delta and Red River Delta accounting for 53.38% and 14.03%, respectively. The Mekong Delta and Red River Delta are considered as the biggest granaries of the country. The change in government policy from having a centrally planned agricultural production system consisting of state farms and cooperatives to a more liberalised system has increased rice production, particularly in the Mekong Delta. Its rice production accounts for 51.85% of that of the Viet Nam and its aqua product for 61.7%. Its fruit cultivation area is 38.56% of Viet Nam's total. The importance of these two areas for rice reflects their having extensive areas of favourable alluvial soils: 1.18 million (30.1% of the region's total area) hectares in the Mekong Delta and 0.91 million hectares (48.5% of the region's total area) in the Red River Delta.

In the unfavourable areas with various soil types such as acid sulfate ones, low pH, aluminium toxicity, iron toxicity, and low phosphorous are considered as the main limiting factors for rice growing—apart from salt intrusion due to water shortage in the

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dry season. Currently, water management and agronomic practices have been recommended. Some improved genotypes have been identified to improve tolerance to drought, salinity and acid sulfate but they are not stable.

Natural calamities such as typhoons, storms and floods are also perennial risks to rice production. Post-harvest losses of rice in Vietnam range from 13 to 16% as compared to 10–37% in South-east Asian countries, mainly due to losses during harvesting, drying, storage and milling.

Varietal improvement has provided farmers with the best materials available from pure line selection, introductions, and local hybridisation. About 5000 accessions of local rices and 100 populations of four wild rice species: *Oryza rufipogon, O. nivara, O. officinalis, O. granulata* have been collected, catalogued and evaluated. This resource material has provided donors for biotic and abiotic stresses (Buu et al. 2002). Rice germ plasm evaluation assisted by DNA markers has been conducted at some institutions in Vietnam, to supply reliable information to rice breeders while selecting appropriate materials.

The extra-early rice varieties with 80–90 days duration, and early genotypes (91–105 days), created a new strategy to escape flood by growing them before and after flooding to give more rice seasons in the Mekong Delta. Rice cropping areas have increased from 2.2 million ha in the 1990s to the current 3.9 million ha/1.7 million ha of cultivated areas by using short duration genotypes. Vietnamese farmers are hard working, skilful, and respond well to new technology once they are convinced that the new technology is appropriate for their social and economic conditions. Their main emphasis is on new varieties of rice. However, poor seed quality has been a perennial problem and improving seed technology should be part of future development plans.

Impact of irrigation

Vietnam has a relative advantage in having highly irrigated areas for rice production. In the 1980s the irrigated area expanded by 2.9% annually and, during the 1990s, this growth rate increased to 4.6% annually. During the 1990s investment in irrigation increased from 1538 billion VND to 2506 billion VND. It was estimated that irrigated rice land increased from 40% to 90%. The Red River Delta has the highest irrigation rate (90%). For the Mekong Delta, the rate is around 70% while the lowest belongs to the High Plateau and north-eastern south.

Except for the severely acid sulfate soils located in Plain of Reeds, Long Xuyen Quadrangle and Ca Mau peninsula, some acid peats and mountainous rock outcrops, the soils of the Delta pose no major constraints to agriculture. Permanently saline soils form a narrow fringe along the coast. Further inland along the coast of the South China Sea, an area of temporary saline soils is planted to paddy in the wet season. With improved irrigation and drainage, it could also be put to agricultural use in the dry season. Slight to moderate acid-sulfate soils can be used for agriculture, provided good water management is established and development is carefully monitored. Development of the more severely acid sulfate soil areas may lead to serious environmental problems. Exposure to air of potentially acid material leads to large quantities of soluble acids being generated in the surface water and to the soil becoming permanently acidified. Drought, which often occurs during the early wet season in the Mekong Delta, currently creates rice-production problems such as salt intrusion.

Approach and methodology

The use of land and water must be optimised within each scenario to:

- bring out the comparative advantages of development options
- provide the framework for the development plan and for the formulation of strategies that could direct government action in water resource development
- provide a background against which projects can be assessed.

Unpredictable drought is the single most important factor affecting world food security and the catalyst of the great famines of the past. Rice is a voracious consumer of water with 5000 litres of water being needed to produce 1 kg of grain (Gale 2002). At present, an unsustainable 70% of the world's water is used for agriculture. More than 400,000 ha in Vietnam are suffering from severe drought in highland and mountainous regions. Drought and erratic rain during the early rainy season in the Mekong Delta has caused salt intrusion.

About 90% of the annual rainfall falls during the rainy season (six months), and 10% during the dry season (six months).

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Table 1. Annual rainfall at three main stations in the Mekong Delta (LeSam 2003).

Annual rainfall	Can Tho	Rach Gia	Soc Trang
Max. (mm)	1787	2747	2611
Min. (mm)	1257	1013	1160
Av. rainy days/year	131	132	135

Floods in the Mekong Delta are influenced by upstream hydrology, tides in the China Sea and Thailand Gulf, and rainfall, and are of a typical stagnant wetland type. The extra early rice varieties with 80–90 days duration, and early genotypes (91–105 days) created a new strategy to escape flood by growing them before and after flooding to increase the number of rice seasons in the Mekong Delta.

The dry season is generally from December to June, and salt intrusion influence is considered as the most serious problem at that time. It varies in duration from one to eight months and affects various parts of a susceptible 2.1 million ha. The dynamics of the China Sea tide is considered to be a key factor influencing the Mekong river flow in the dry season, roughly 2000 $m^3 s^{-1}$ (LeSam 2003).

Acid sulfate soils, which occupy the largest areas (Table 3), are mainly in Dong Thap Muoi, Long Xuyen quadrangle and the Ca Mau peninsula. Water management in these areas is also considered to be the key to reducing the toxicity of aluminium, iron, acidity, and to preventing the capillary effect of sulfate compounds.

Saline soils, which are strongly influenced by the tidal system, especially in the dry season account for 19% of the natural areas in the delta (Table 4). In the coastal areas from Long An to Kien Giang, salt intrudes at times varies from 10 to 25 g/L in the dry season.

Improvement in rice productivity

We are currently interested in the controllable factors of:

- rate and time of applying nitrogen and phosphorus
- weed control
- pest and disease control
- crop genotype.

A broad understanding of the agro-chemical characteristics of the soils in the area has been developed. However, it takes intense and lengthy research to fully understand these important relationships.

To get an optimum rice yield from saline and acid sulfate soils, we have studied land preparation, field design (especially drainage channels), seed rate,

Table 2. Annual rainfall distribution (mm) through multilocations and years (LeSam 2003).

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Av.
C.Doc	6.5	4.5	25.0	80.0	157.7	114.2	134.2	146.8	160.3	252.1	135.3	46.9	1246
L.Xuyen	8.3	2.6	11.7	66.5	147.2	151.6	209.4	174.4	213.8	260.3	130.7	41.8	1418
C.Tho	8.9	2.3	9.7	42.8	170.1	195.2	211.7	209.1	250.5	271.4	146.0	32.3	1550
D.Ngai	4.0	5.2	6.6	38.7	199.5	319.4	218.6	337.8	307.8	257.0	133.9	20.5	1849
P.Hiep	1.4	2.5	3.7	44.9	183.2	198.9	229.0	257.8	306.4	263.4	114.2	14.1	1620
XeoRo	4.0	0.8	36.9	60.2	253.3	283.6	214.5	400.9	334.3	224.7	137.2	20.7	1971
P.Long	5.6	7.6	17.5	72.2	223.2	267.3	215.8	320.5	271.9	265.5	145.8	28.4	1841
CaMau	16.4	7.6	34.1	101.2	270.1	323.3	323.6	365.4	349.2	330.8	190.3	63.6	2376
G.Hao	0.9	0.0	3.8	34.1	187.3	297.3	233.2	294.0	254.7	296.6	196.2	27.5	1826
T.Chau	11.3	7.2	7.8	65.9	110.4	96.0	140.2	112.8	160.3	253.1	202.8	20.0	1188
C.Moi	10.9	1.1	13.3	51.1	163.7	137.8	137.3	189.3	209.1	269.1	181.8	26.5	1391
MyTho	5.0	2.5	4.5	38.5	148.6	187.8	185.7	170.8	233.0	267.0	103.6	35.1	1382
T.Vinh	1.0	0.1	7.4	29.2	172.7	193.0	226.5	212.8	253.1	236.4	115.4	15.7	1463
TanAn	6.9	2.3	7.2	35.6	187.1	222.2	203.9	187.2	245.5	260.8	136.5	40.3	1536
B.Luc	3.0	1.0	4.7	59.2	170.8	236.2	207.8	177.7	264.2	304.8	128.0	14.2	1572
M.Hoa	13.0	4.2	14.1	48.2	187.7	181.6	184.4	168.1	268.7	312.1	150.3	39.9	1572

sowing date, fertiliser application, plant protection, irrigation, sowing time in dry and wet seasons, in terms of rice cultivation in salinity and acid sulfate soils. This study aims at improving rice genotypes adapted to saline areas at seedling stage.

The salt intrusion distance is longest at the end of March or in early April when rainfall is the lowest (Table 4). Accordingly, rice varieties tolerant to salt in the seedling stage need to be developed.

The uncontrollable factors of rice production are mainly erratic rainfall and global climate change. Their consequences such as salt intrusion and flooding should be given more attention.

Table 3. Soils in the Mekong Delta (Buu et al. 1995).

	ha	%
Sandy soils	43,318	1.10
Saline soils	744,547	18.93
Acid sulfate soils	1,600,263	40.69
Alluvial soils	1,184,857	30.13
Peat soils	24,027	0.61
Grey soils	134,656	3.42
Red yellow soils	2,420	0.06
Laterite soils	8,787	0.22
Rivers, canals	190,257	4.84
Total	3,933,132	100.00

Table 4. Salt intrusion level by km per month at main rivers (LeSam 2003).

River	4 g/l				1 g/l			
	Feb	Mar	April	May	Feb	Mar	April	May
Cua Tieu	23	32	37	32	43	51	59	58
Ham Luong	23	30	34	26	46	51	57	54
Co Chien	22	31	35	27	44	58	55	51
Bassac	25	32	33	26	44	54	58	51

Identification of rice germplasm

The nature of gene action for some agronomic traits in rice was studied to develop salt-tolerant and high-yielding rice varieties (Buu and Tao 1993). Heterosis was recorded in grain yield, panicle per hill, and plant height. It was due to dispersed dominant and interacting genes, and genes with dominance and epistatic properties that were in linkage disequilibrium.

Under saline conditions, filled grains per panicle had the largest direct effect on yield (Buu and Truong 1988). Filled grains per panicle and sterility percentage appear to be the most reliable indices for selection under the conditions.

The existence of non-additive gene effects for yield components was noticed, except for 1000-grain weight (Tao et al.1992). There were at least five groups of genes to govern the plant height of deep water rice growing in the coastal areas.

Good combiners for the sink size character were recognised from traditional cultivars: Lua Giau, Ba xe giai, and Bong Huong (Lang 1994).

Salt tolerant varieties have generally been considered as the most economical and effective way to increase crop production in saline soils. Efforts have been made to identify a parameter that could be used as the criterion for mass screening. Parameters generally proposed are leaf injury rate at seedling stage, sterility after heading, and Na^+/K^+ ratio in the shoots under saline conditions (Buu et al. 1995). Selection efficiency for salinity tolerance under field conditions remains low because of stress heterogeneity and the presence of other soil-related stresses. Two or more genes (quantitative) govern salt tolerance that significantly interact with the environment. Recent advances in DNA marker technology have triggered the molecular dissection of complex traits. RFLP linkage maps have also been developed for rice (Kurata et al. 1994, McCouch et al. 1998).

Considerable genetic variation has been reported in salinity tolerance among rice varieties. The salt tolerance of Nona Bokra is greatest at the seedling and vegetative stages with Pokkali being more tolerant at the reproductive stage and less sensitive to photoperiod (Senadhira 1987). Doc Do and Doc Phung were considered to be salt tolerant donors in Vietnam (Buu et al. 1995). Among 418 local rice accessions screened under salt stress of 6–12dS/m, there were 44 tolerant accessions including Nang Co do, Soc Nau (Buu et al. 1995), Doc Do, Doc Phung, Trai May and Ca Dung trang (Buu et al. 2000)

QTL analysis for salt tolerance in rice

One hundred and eight F_8 recombinant inbred lines (RILs) derived from the cross between Tesanai 2/CB were evaluated. Recombinant inbred lines were evaluated for seedling survival day (SD), dry root weight, dry shoot weight, Na^+ and K^+ concentration and Na^+/K^+ ratio in culture solution (EC= 12 dS/m). RFLP and a microsatellite map of this population were used with 108 markers to detect the linkage to target traits. A linkage map was constructed from 12-linkage groups based on the population. The map covers 2340.50 centiMorgans (cM) with an average interval of 21.68 cM between marker loci. Markers associated with salt tolerance were located mostly on chromosomes 1, 2, 3, 9, 11, and 12. Quantitative trait loci (QTL) mapping was used to determine effects of QTLs associated with salt tolerance traits.

We also mapped QTLs for morphological attributes and ion accumulation of salt tolerance. Chi-square tests (χ^2), single maker analysis (SMA), interval mapping (IM) were combined in the QTL analysis procedure. All approaches gave similar results to the QTL detection one. Four QTLs were identified for SD, one for dry shoot weight, two for dry root weight, one for Na^+ absorption, one for K^+ absorption and four for Na^+/K^+ ratio. The proportion of phenotypic variation explained by each QTL ranged from 5.2% to 11.6% for SD, and 4.80 to 14.38% for morphological characters and Na^+, K^+ accumulation. Common QTLs were observed in chromosome 3 and 9 for quantitative traits (SD and root weight and SD and Na^+/K^+). Common QTLs were also detected on chromosome 12 for (Na^+/K^+ and K^+). The result explains much of the transgressive variation for the most traits observed in this population (Lang et al. 2000, 2001a, 2001b and 2001c).

An advanced backcross population, BC_2F_2, was developed with the parents including OM1706, Type3, Cheng Hui 448, FR13A, Almol 3 and Madhadar as donors of salt tolerance, and IR64, IR68552-55-3-2, Teqing as recurrent parents with good quality traits. Molecular markers associated with both qualitative and quantitative salt tolerance were identified by using 150 microsatellite markers. IR64/ChengHui 448, IR68552-55-3-2/Type 3, and IR64/FR13A derived alleles located close to RM315, associated with salt stress tolerance at seedling stage at a distance of 21.2 cM, 1.9 cM, and 0.0 cM in chromosome 1, respectively. In IR68552-55-3-2/OM1706, the alleles controlling salt stress tolerance were linked with RM223 in chromosome 8 at a distance of 7.2 cM. Microsatellite markers in chromosome 1 may be used efficiently in rice-breeding, marker-assisted selection (Lang et al. 2001c).

Rice breeding for salt tolerance

Rice varieties needed to exploit the full potential of the ecosystem must be adapted to many constraints including saline soils. The coastal rainfed lowland rice areas need varieties adapted to a water depth of 30–50 m, with growth duration of 120–140 or 90–105 days, drought tolerance at seedling stage, and tolerance to salt intrusion before the wet season (EC = 4–6 dS/m). Two tolerant varieties, CSR10 and CSR13, were used to investigate biochemical changes under saline conditions. Salinity caused a drastic decrease in potassium content of salt-sensitive varieties. Polyamine, putrescine, spermidine and spermine concentrations are also reported in terms of osmotic shock and desiccation symptoms. A population of 257 segregants from F_3 family was developed from a cross between IR28 and Doc Phung. Phenotypes were evaluated by visual score of salt tolerance at vegetative and reproductive stages under saline stress of EC 10 = dS/m in the phytotron (Table 5). QTL mapping was also conducted with microsatellite markers on this population. Some mid-duration genotypes were well developed such as IR42, OM723-11, A69-1, OM861, OM922, Tep Hanh mutant, OM1346, OM1348 and OM1849. Some early duration genotypes such as OM1314, OM1490, OM2031 were noticed to be suitable under saline conditions.

Marker RM223 was used to facilitate marker-assisted selection (MAS) to identify target genotypes that tolerate salt stress (Lang et al. 2001b, 2001c).

In the coastal areas affected by salt intrusion in the Mekong Delta, IR42 has been stably developed since the early 1980s. A69-1 was also suitable but not well developed because of its poor grain quality. One introduced variety, IR29723-143-3-2, was acceptable although it was susceptible to bacterial leaf blight. Some promising inbred lines of mid-duration genotypes were:

OM344	Mahsuri/IR42
OM723	A69-1/NN6A
OM861	Ba Thiet/IR42
OM916	BG380/A69-1
OM924	IR29723-143-3-2/OM80
OM1571	A69-1/OM87-9

Recently, the following early duration genotypes have also been developed in the target areas:

Ham Trau (OM576)	Hungari/IR48	115–120 days
OM1314	OM80/OM576	105–110
OM1490	OM606/IR44592-62-1-3-3	90–105
OM2031	Thai Lan/Bong Huong	90–105

Mid-duration genotypes should be recommended as followed:

OM1346	IR42/OM739-7-2-2-1	120–130 days
OM1348	IR42/OM736-8-1-1	125–130
OM1849	OM723–11/KSB54	130–135
Tep Hanh mutant	Tep Hanh (traditional cultivar)	130–135

Salt screening studies (Table 6) showed that salt-tolerant lines at the seedling stage should be recommended as compared to Pokkali; and to Doc Do as tolerant and IR28 as sensitive checks.

Table 5. Standard evaluation score (SES) of visual salt injury at vegetative and reproductive stages.

Score	Observation	Tolerance
1	Normal growth, no leaf symptoms	Highly tolerant
3	Nearly normal growth, but leaf tips or few leaves whitish and rolled	Tolerant
5	Growth severely retarded; most leaves rolled, only a few are elongating	Moderately tolerant
7	Complete cessation of growth; most leaves dry; some plants dying	Susceptible
9	Almost all plants dead or dying	Highly susceptible

Some of the coastal salinity in the delta associated with flooding due to tidal fluctuation should be considered with submergence tolerance. Breeding for salinity tolerance is highly feasible because there is no antagonism between high yield and salt tolerance (Akbar et al. 1985). Attention should be paid to introgress from the wild gene pool including *Oryza rufipogon* and *Oryza officinalis* recently collected from mangroves of the coastal areas, and traditional cultivars such as Doc Do, Doc Phung and Soc Nau. Recombination frequency will be enhanced by duplicated backcrossing to obtain desirable phenotypes among segregants through this strategy.

Drought and salinity are now considered as more important than flood damage to rice productivity in the Mekong Delta, due to the flood escaping strategy using short duration genotypes before and after flooding. Therefore, attention is being paid to rice breeding to improve rice productivity under salt stress and drought at the seedling stage.

Abiotic stress with an emphasis on water shortage is a major constraint to rice production in the Mekong Delta although water availability is considered better than other regions. Considerable collaborative work is under way for the major crop in the Delta (*Oryza sativa* L.). However, the various projects are being carried out in relative isolation so that rice breeding for salt stress and drought stress tolerance is progressing slowly. It needs breeders, physiologists, water resource scientists, soil scientists and others to set up an appropriate research strategy. Most farmers in the target areas are poor so that high input technologies are largely inappropriate. Varietal improvement is considered the most economical approach but it cannot be the only one.

Table 6. Salt screening at the vegetative stage under stress conditions of 6 dS/m and 12 dS/m in Yoshida solution.

Designation	Leaf injury at 6dS/m	Leaf injury at 12dS/m
AS996	3	9
OM1490	3	5
AS1007	5	7
OM1838	3	7
OM2031	3	9
OM2401	3	9
OM1346	3	7
OM1348	3	9
OM1849-5	7	9
A69-1	3	7
OM723-7	3	7
IR28 (susc. check)	5	9
Pokkali (tol. check)	1	3
Doc Do (tol. check)	1	1

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Drought response index for identifying drought resistant genotypes for rainfed lowland rice in Cambodia

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Abstract

Drought is a major problem for rice producers in the rainfed lowlands with losses in grain yield estimated at 11–58%. To be effective the appropriate drought tolerance traits for the environments and their genotypic variation need to be identified routinely and reliably. Experiments with main plots of controlled water conditions—of well-watered and managed drought and with a range of genotypes including local collections, exotic materials and breeding lines—were conducted at two sites, for four years, in Cambodia. The genotypes were evaluated for their interactive performance in yield under the different water conditions and for the drought adaptive traits of phenology, flower delay (under drought) and yield potential.

A technique to routinely provide a managed drought environment in Cambodia was developed where the drought intensity ranged from 12–46%, which is similar to that in the target environments. The drought occurred mainly as a reproductive drought, again consistent with the target environments. There were significant interactions for yield among the genotype grown under the well watered and drought conditions.

Early flowering was found to be a good mechanism for escaping drought and yield potential was an indicator of performance under medium drought conditions (up to a drought intensity of 30% yield reduction). High yield potential was found mostly in the intermediate flowering genotypes. To avoid these confounding effects of maturity and yield potential we measured drought response index (DRI). There was a significant difference among the genotypes in DRI, which ranged from –0.79 to 0.58 and there was a level of genotypic consistency of the trait based on pattern analysis across seven environments. DRI was significantly associated with yield under drought ($R^2 = 0.40^{**}$). A routine approach for selecting drought tolerance in rainfed lowland rice in Cambodia, based on these findings, is discussed.

Introduction

MANY of the world's poor farm in rainfed systems where the water supply is unpredictable and droughts are common. For example, in Asia, about 50% of all rice land is rainfed with yield losses from drought being estimated at 11–58%. In contrast to irrigated rice system, gains from crop improvement of rainfed rice have been modest, in part because there has been little effort to breed and select for drought tolerance in these target environments.

Various studies have examined the complex processes, mechanisms and traits of rice that provide drought tolerance and better adaptation to these variable rainfall environments. Fukai and Cooper (2001) have summarised this complexity and focus on three broad mechanisms—yield potential, appropriate phenology and drought tolerance—that influence yield depending on the severity and predictability of

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the drought. The relationship among these three components in different types of drought is shown in Figure 1. The figure shows that at medium levels of drought stress (where yield is reduced less than 50%), yield potential is an important mechanism for yield in the target environment. With more severe stress, a mechanism for drought escape or tolerance is needed. If the drought is severe, predictable and terminal, then yield is maintained by escaping the drought through the use of earlier maturing varieties. If the drought is severe, mid-season and unpredictable, a mechanism for drought tolerance is required. Thus Fukai et al. (1999) indicated that only phenology, high potential yield and ability to maintain high LWP were associated directly with higher grain yield (GY) in the target drought environments.

Plant breeders rely on direct selection for GY in the target environments as the main criterion for selection. There is growing evidence for other crops (Bidinger et al. 1987a,b) that varieties can be developed for improved yield under drought stress yet respond to well-watered conditions (i.e. the good years) if there is early selection for yield under both drought and well-watered conditions. However, the progress could be enhanced by the judicious choice of parents that provide the genetic materials for the three components of yield under drought, viz yield potential, appropriate phenology and drought tolerance. In practice, breeders often use parents from exotic material for improved yield potential and phenology and local materials to maintain or enhance drought tolerance. While many putative and specific traits for drought tolerance such as osmotic regulation, root length, and root penetration have been suggested for selection for drought tolerance, there is as yet no clear evidence of their contribution to improved yield under drought. A more practical approach is to compare an index of the relative performance of genotypes under stress to that under well-watered conditions as a measure of the complex of traits that provide drought tolerance. Bidinger et al. (1987a,b) developed such a drought response index (DRI) to identify lines tolerant or susceptible to drought in a pearl millet [*Pennisetum americanum* (L.) Leeke]. Pantuwan et al. (2002b) successfully adapted this method for rainfed lowland rice in Thailand. They found that genotypes differed in DRI, but that the estimate of the DRI was inconsistent across different drought stress trials (and presumably under different durations and intensity of water stress).

There is no information on the variation in drought tolerance among the rice materials used in the breeding program in Cambodia. This study aimed to measure the genotypic variation for drought tolerance, measured as DRI, of rainfed lowland rice genotypes in Cambodia and to determine if DRI was consistent across different water stress conditions as a result of drought at different sites and years. The study was conducted in two stages. The first (experiment 1) examined a relatively large number of genotypes at two sites and for two years. The second (experiment 2) examined fewer genotypes but at more sites and for more years

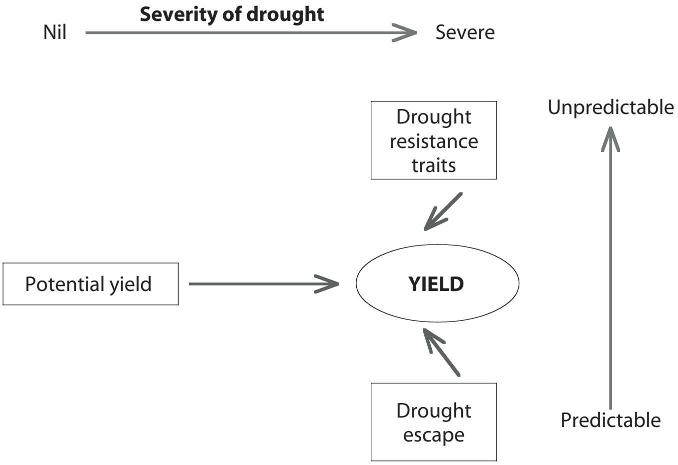

Figure 1. Schematic presentation of medium levels of drought stress in which the potential yield is an important mechanism.

Materials and methods

Experiment 1

The experiment was conducted at two sites: CARDI (Cambodian Agricultural Research and Development Institute) with latitude 11° 28’ 36” N and longitude 104° 48’ 27” E and Prey Veng province, latitude 11° 33’ 39.5” N, longitude 105° 32’ 42.1” E. Soils at both sites are of the Prateah Lang soil group (White et al. 1997).

Water treatments: There were two water treatments: flooded field (well-watered treatment = WW) and drained field (water-stress treatment = WS). The WW treatment relied on rainfall supplemented with irrigation to provide non-stress conditions. In the WS treatment, the field was drained about 20 days before flowering and onward to simulate drought. In addition, small channels about 10 cm deep were dug throughout the fields to collect water into a well 50 cm deep dug in the corner of the fields. The water was pumped from the field during the drained period. The level of the watertable was recorded weekly using PVC tubes placed in each corner of the main water-treatment plots.

Rice genotypes: Twenty-five genotypes were selected from an initial trial using 80 genotypes grown at one site over one year. The 80 genotypes were a mixture of random selections from released varieties, advanced breeding lines (including some from outside Cambodia) and traditional varieties used in the Cambodian breeding program. The set of 25 genotypes represented the range in performance under drought (1.2–1.7 t/ha) and maturity (97–133 days) among the 80 lines previously tested (Table 1). The genotypes also were previously characterised for photoperiod sensitivity index (PSI)[1]

Design: The experiments at each location and each year had two water treatments as the main-plot, and genotypes (25) as the sub-plot. There were three replications. The sub-plots were 1.2 x 3 m in size (six rows) with no space between them. The main-plots (water treatment) were in separate but adjacent fields separated by a bund.

Cultural practices: Seeds were sown in a nursery at about the time for normal planting in Cambodia and the nursery well watered. Thirty day-old seedlings were transplanted by hand with three seedlings placed in each hill with a 20 cm spacing between hills and rows. After 10 days any missing hills were transplanted. Irrigation was applied at transplanting to maintain a water level of 3–5 cm in all treatments, and continued at both sites until about 20 days before flowering in the WS treatment, and until harvest in the WW treatment. In the WW treatment, the water depth fluctuated within the range 3–15 cm (Prey Veng) and 3–20 cm (CARDI).

The fields were fertilised with 60–30–30 kg/ha of N–P_2O_5–K_2O. N was applied as urea (46% N) three times (1/3 at transplanting as a basal, at 30 days, and at 60 days after transplanting), while the P_2O_5 as triple super phosphate (48% P_2O_5) and K_2O as potassium chloride (60% K_2O) were applied once as a basal application. Weeds were controlled three and four times by hand in the WW and WS fields respectively. The fourth weeding in the WS field was 10 days after draining the water. No pesticide was used.

Data Collection: DTF (days-to-flower) was measured as the time taken for 50% of the plants in the two centre rows of each plot to flower. At maturity, plants from an area of 1.04 m^2 were harvested at ground level from the two centre rows leaving one hill at each end of the row as a border. The harvested plants were sun-dried for several days and the grain threshed and then weighed. Sub-samples of 150 g were taken and dried in an oven at 70°C for two days. The oven-dried samples were re-weighed to determine the water content to calculate GY as dry-weight.

Data analysis:

a) An analysis of variance was conducted on the DTF data and grain yield (GY) using a residual maximum likelihood (REML) program (Robinson et al. 1982). It was assumed that the genotypes represented a random sample of rainfed lowland rice genotypes and that the sites and years were a random sample of those used by the breeding program. The water treatment was a fixed variable. Therefore, treatment means for all random variables were computed as best linear unbiased predictors (BLUPs).

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[1] A preliminary experiment was conducted at CARDI in 1999 where the 25 genotypes were seeded on two dates; the first on 18 June and the second on 19 August. Dates of 50% flowering were recorded for both seeding times and the PSI was determined, using the following formula (Immark *et al*. 1997). PSI = 1 – (F2 – F1)/(SD2 – SD1), Where: F1 = date of 50% flowering of the first seeding, F2 = date of 50% flowering of the second seeding, SD1 = date of the first seeding, and SD2 = date of the second seeding. Genotypes with a PSI = 0 are completely insensitive, whereas those with a PSI = 1 are strongly sensitive.

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Table 1. The 25 genotypes used in experiment 1 and a measure of their days-to-flower (DTF), grain yield (GY), and photoperiod sensitivity (PSI) from earlier experiments at Prey Veng in 1998 (for GY and DTF) and at CARDI in 1999 (for PSI).

Gen.No.	Designation	DTF (day)	GY (t/ha)	PSI	Origin
1	IR46331-PMI-32-2-1-1 (P1) (38)	102	1.244	0.45	Thai-ACIAR
2	IR57514-PMI-5-B-1-2 (40)	109	1.585	0.24	Thai-ACIAR
3	IR66327-KKN-10-P1-3R-0 (11)	115	1.695	0.55	Thai-ACIAR
4	IR66327-KKN-12-P1-3R-0 (2)	117	1.587	0.77	Thai-ACIAR
5	IR66327-KKN-25-P1-3R-0 (5)	106	1.691	0.64	Thai-ACIAR
6	IR66327-KKN-33-P1-3R-0 (14)	105	1.477	1.00	Thai-ACIAR
7	IR66327-KKN-47-P1-3R-0 (15)	97	1.423	0.53	Thai-ACIAR
8	IR66327-KKN-54-P1-3R-0 (16)	107	1.658	0.53	Thai-ACIAR
9	IR66327-KKN-75-P2-3R-0 (18)	111	1.275	0.60	Thai-ACIAR
10	IR66327-KKN-8-P1-3R-0 (10)	110	1.662	0.48	Thai-ACIAR
11	IR66368-CPA-48-P1-3R-0 (35)	103	1.554	0.78	Thai-ACIAR
12	IR66368-CPA-6-P1-3R-0 (19)	98	1.482	0.27	Thai-ACIAR
13	IR66368-CPA-84-P1-3R-0 (26)	105	1.380	0.76	Thai-ACIAR
14	IR66368-CPA-91-P1-3R-0 (28)	99	1.267	0.47	Thai-ACIAR
15	Bang Kuy (acc. 2865) (56)	113	1.618	0.71	Cambodia
16	CAR 4 (77)	130	1.374	0.73	Cambodia
17	CAR 6 (79)	128	1.283	0.73	Cambodia
18	CIR158-B-B-SB-8-3-2 (62)	123	1.468	0.30	Cambodia
19	Damnoeub Khlanh (acc. 3172) (60)	119	1.295	0.65	Cambodia
20	Damnoeub Khmao (acc. 3390) (61)	115	1.381	0.73	Cambodia
21	DJM1-B-B-SB-SB-3-1-1 (69)	128	1.594	0.30	Cambodia
22	Kpor Daung (45)	133	1.235	0.81	Cambodia
23	Santepheap 3 (73)	118	1.546	0.26	Cambodia
24	Somaly (50)	100	1.415	0.77	Cambodia
25	KDML105 (51)	101	1.491	0.77	Thailand

REML software (Robinson et al. 1982) was used to calculate the BLUPs. Two main analyses were done. The first was a combined analysis over both water treatments to detect the effects of water, and genotype and how they interacted at each site. In the second analysis, a combined analysis over sites or years was done to detect the effects of site or year, water and genotype and their interactive effects.

b) The drought response index (DRI) was calculated using the equation proposed by Bidinger et al. (1987b) as follows:

$$\mathrm{DRI} = (Y_{act} - Y_{est})/\mathrm{S.E.\ of\ } Y_{est}, \qquad (1)$$

where Y_{act} is the actual grain yield under the WS treatment for each genotype, Y_{est} is the estimated GY for each genotype under the WS treatment, and SE of Y_{est} is the standard error of estimated GY of all genotypes. Estimated GY (Y_{est}) was derived from a multiple regression analysis as follows:

(a) when the relationship between GY in the WS treatment (Y_{act}) and DTF in the WW treatment (FL) is not quadratic:

$$Y_{est} = a + b(Y_p)_i + c(\mathrm{FL})_i \qquad (2)$$

(b) when the relationship between GY in the WS treatment (Y_{act}) and DTF in the WW treatment (FL) is quadratic:

$$Y_{est} = a + b(Y_p)_i + c(\mathrm{FL})_i + d(\mathrm{FL})^2{}_i \quad (3)$$

where $(Y_p)_i$ is the potential GY as measured under the WW treatment for genotype i, i = 1,…,g; $(\mathrm{FL})_i$ is the DTF under the WW treatment for genotype i, $i = 1,\ldots,g$; $(FL)^2_i$ is the square of FL for genotype i, $i = 1,\ldots,g$; and a, b, c and d are regression parameters estimated by least square methods.

Bidinger et al. (1987b) computed a DRI for a genotype from the mean GY of the genotype across replicates in the drought trial and the mean GY and DTF of the genotype in the well-watered trial. We modified this method slightly to estimate variance statistics of the DRI. In this study a mean value for GY and DTF of the genotype in the WW treatment was computed and used to calculate the DRI separately for each replicate in the WS treatment. The resulting experimental error for the DRI is a combined error of the genotype mean error from the WW treatment and the single replicate error from the WS treatment.[2]

Experiment 2

Five more trials were conducted from 1998 to 2001 at the two sites described earlier (Prey Veng and CARDI) to assess the adaptation of rice genotypes and determine the reliability of the DRI.

Water treatments: There were two water treatments including well watered (WW) and a controlled drought (WS), which was imposed in a similar manner to that described in Experiment 1.

Genotypes used: The number of genotypes in each trial varied but there were 15 genotypes in common in these 5 trials and in experiment 1. Of the 15 lines, six are Cambodian varieties, one is a Cambodian breeding line, seven are Thai–ACIAR breeding lines, and one is a popular variety from the North-east Thailand region (KDML105 Table 2). Three of the genotypes are photoperiod insensitive, four are mildly photoperiod sensitive and the others are strongly photoperiod sensitive. Somaly and KDML105 are aromatic rice varieties (Table 2).

Data collected and methods of analysis: Data was collected and analysed as in experiment 1. In addition a two-way cluster analysis of the DRI values for the genotypes was done with truncation at the three-group level of genotypes and at the three-group level of the environments. This truncation retained 75% of the G × E variance for DRI.

Results

The water environments and types of drought

The weekly rainfall and water levels under the WW and the WS treatments in all sites for experiments 1 and 2 are shown in Figure 2. The draining technique was successful in providing drought conditions. The WS treatment reduced yield by as much as 46% in 1999 at the Prey Veng site and, on average, over all trials by 28%. The range of drought conditions can be described as 'severe, prolonged drought from booting stage' at Prey Veng to 'mild, short drought during the grain filling' at CARDI 2000 (Table 3). These droughts are reasonably representative of the target environments of the rainfed lowlands in Cambodia.

The combined analysis for CARDI and Prey Veng in 1999 shows significant effects of site (S), G and G × water treatment (W), and G × S interactions on GY. The size of the variance component of the G x E interaction ($\sigma^2_{G\times E}$) was similar to that of the genotype component (σ^2_g). The G × W component of variance was about half the size of the genotype component but large relative to the other interaction components. The combined analysis over two years (1998 and 1999) at Prey Veng highlights no significant effect of year (Y) and its interaction effects on GY. There was a significant effect of G and the interaction effect of G × W on GY. The G × E component of variance was slightly smaller than the genotype component ($\sigma^2_{G\times E}/\sigma^2_g = 0.8$). The G × W component of variance was about 0.4 that of the genotype component but larger than the other interaction components.

There was a significant difference among the genotypes for DRI (P<0.01) with mean values ranging from –0.91 for IR66327-KKN-33-P-1-3R-0 to 0.89 for Bang Kuy (Table 4). There was no significant relationship between DRI and either GY or DTF under the WW treatment.

The combined analysis over the two sites and years indicates significant differences among the genotypes for DRI with the values ranging from –0.79 for genotype IR66368-CPA-6 PI-3R-0, to 0.58 for genotype IR66327-KKN-47-PI-3R-0. The relationship between the DRI estimated at Prey Veng and the DRI estimated at CARDI was positive and significant (R^2=0.23).

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[2] An advantage of this method for computing the DRI for individual replicates in the WS treatment is that with replicate measurements in the WS treatment the DRI could be more fully analysed by ANOVA to study the consistency of the DRI values in different environments.

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3.2 Experiment 2

There was a significant effect of the genotype (G) on DRI in five of the seven trials. The heritability of DRI in the different environments varied from 0.23 to 0.74 (Table 5). There was also a significant difference in the mean DRI across the years/locations. The mean DRI varied from –0.68 for CAR4 to 0.47 for IR57514 and the mean heritability was 0.44. The effect of the G × E for DRI was significant ($P<0.01$) and the G x E interaction component of variance was 4.2 times that of the genotype component.

The two-way cluster analysis of the genotype DRI values was truncated at the three-group level of genotypes (GGD = genotype group for DRI) (Figure 3) and at the three-group level of drought environments (EGD = environmental group for DRI) (Figure 4). The GGD1 comprised two genotypes IR46331-PMI-32-2-1-1 and CAR4 with the lowest mean DRI values of –0.63. The GGD2 comprised eight genotypes and had a mean DRI value of –0.02. The GGD3 comprised five genotypes with a highest mean value of 0.29. The Environmental Group 1 comprised CARDI 1999 and Prey Veng 2001. These two environments

Table 2. Genotype information (including the source and photoperiod sensitivity index (PSI)), and environment information (including the tested sites and in what year), seeding date (SD), water treatment, and site-year-water treatment code (experiment 2).

Gen.No.	Genotype	Source	PSI	Site	Year	SD	Water	Code
1	IR46331-PMI-32-2-1-1(P1)	Thai-ACIAR	0.45	Prey Veng	1998	11-Jul	WW	PV98WW
2	IR57514-PMI-5-B-1-2	Thai-ACIAR	0.24	Prey Veng	1998	11-Jul	WS	PV98WS
3	IR66327-KKN-10-P1-3R-0	Thai-ACIAR	0.55	Prey Veng	1999	5-Jul	WW	PV99WW
5	IR66327-KKN-25-P1-3R-0	Thai-ACIAR	0.24	Prey Veng	1999	5-Jul	WS	PV99WS
8	IR66327-KKN-54-P1-3R-0	Thai-ACIAR	0.53	Prey Veng	2000	18-Jul	WW	PV00WW
10	IR66327-KKN-8-P1-3R-0	Thai-ACIAR	0.48	Prey Veng	2000	18-Jul	WS	PV00WS
13	IR66368-CPA-84-P1-3R-0	Thai-ACIAR	0.76	Prey Veng	2001	4-Jun	WW	PV01WW
15	Bang Kuy (acc. 2865)	Cambodia	0.71	Prey Veng	2001	4-Jun	WS	PV01WS
16	CAR4	Cambodia	0.73	CARDI	1999	2-Jul	WW	CA99WW
17	CAR6	Cambodia	0.73	CARDI	1999	2-Jul	WS	CA99WS
18	CIR158-B-B-SB-8-3-2	Cambodia	0.30	CARDI	2000	31-Jul	WW	CA00WW
22	Khpor Daung	Cambodia	0.81	CARDI	2000	31-Jul	WS	CA00WS
24	Somaly	Cambodia	0.77	CARDI	2001	4-Jun	WW	CA01WW
25	KDML105	Thailand	0.77	CARDI	2001	4-Jun	WS	CA01WS
26	CAR3	Cambodia	0.73					

WW = well-watered treatment, WS = water-stressed treatment.

Table 3. Mean grain yield (t/ha) at Prey Veng (PV) and CARDI (CA) under the well-watered (WW) and water-stress (WS) treatments, relative grain yield reduction (GYR), severity of drought (SoD) and period of drought (PoD) for experiments 1 and 2.

	PV1998		PV1999		PV2000		PV2001		CA1999		CA2000		CA2001	
	WW	WS	WW	WS	WW	WS	WW	WS	WW	WS	WW	WS	WW	WS
MGY	1.93	1.52	1.98	1.08	1.49	1.17	2.46	1.71	2.72	2.07	2.42	2.13	2.63	1.47
GYR (%)	21		46		21		30		24		12		44	
SoD	Mild		Severe		Mild		Moderate		Mild		Mild		Severe	
PoD	Grain filling		From booting stage		From flowering stage		From vegetative stage		From booting stage		Short grain filling		From vegetative stage	

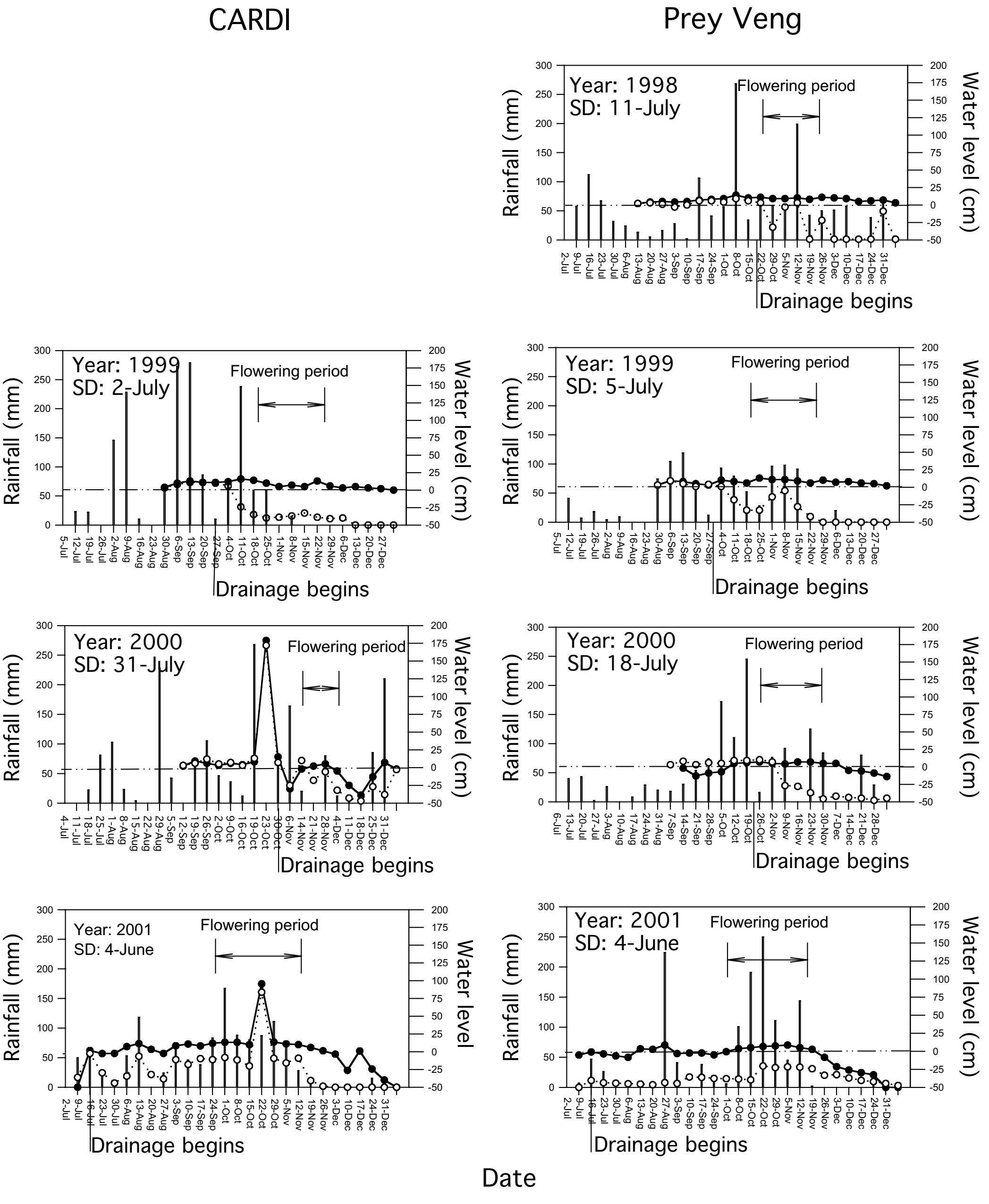

Figure 2. Rainfall (bars) and water levels under the well-watered (solid lines) and the water-stress (dotted lines) treatments at CARDI and Prey Veng from 1998–2001. Dash-dot-dotted lines refer to the ground level within an experiment.

are characterised by mild, prolonged drought from booting stage and moderate, prolonged drought from vegetative stage, respectively. Mean yield was reduced by 27% in this cluster of environments. The EGD2 comprised CARDI 2000 (mild, short drought at the grain filling stage) and Prey Veng 1998 (mild drought at the grain filling stage) and mean yield was reduced by 15.5%. The EGD3 comprised CARDI 2001 (severe, prolonged drought from vegetative stage), Prey Veng 1999 (severe, prolonged drought from booting stage) and Prey Veng 2000 (mild, prolonged drought from flowering stage) and mean yield was reduced by 37%.

The mean DRI values of each of the three-genotype groups at the three drought environmental groups are shown in Table 6. The GGD3 had high and consistent values of DRI (i.e. drought tolerant) across the three groups of drought. The GGD1 had the lowest DRI values (i.e. drought susceptible) particularly at the EGD1, causing most of the G × E interaction effect.

Table 4. The mean values (best linear unbiased prediction) of drought response index for 25 genotypes grown at CARDI and Prey Veng in 1999 and their mean. Genotypes are ranked based on the mean values over both sites.

Gen.No.	Designation	CARDI	Prey Veng	Mean
7	IR66327-KKN-47-P1-3R-0	0.47	0.68	0.58
4	IR66327-KKN-12-P1-3R-0	0.80	0.30	0.55
15	Bang Kuy (acc. 2865)	0.89	0.18	0.54
24	Somaly	0.30	0.48	0.39
2	IR57514-PMI-5-B-1-2	0.49	0.27	0.38
8	IR66327-KKN-54-P1-3R-0	–0.04	0.57	0.27
3	IR66327-KKN-10-P1-3R-0	0.51	–0.04	0.24
23	Santepheap 3	0.28	0.12	0.20
18	CIR158-B-B-SB-8-3-2	0.19	0.20	0.19
25	KDML105	0.49	–0.15	0.17
22	Kpor Daung	0.12	0.22	0.17
5	IR66327-KKN-25-P1-3R-0	–0.09	0.39	0.15
11	IR66368-CPA-48-P1-3R-0	–0.19	0.41	0.11
21	DJM1-B-B-SB-SB-3-1-1	0.60	–0.38	0.11
17	CAR 6	0.48	–0.30	0.09
9	IR66327-KKN-75-P2-3R-0	–0.04	0.10	0.03
13	IR66368-CPA-84-P1-3R-0	0.00	0.01	0.01
20	Damnoeub Khmao (acc. 3390)	0.08	–0.43	–0.18
14	IR66368-CPA-91-P1-3R-0	–0.12	–0.61	–0.37
10	IR66327-KKN-8-P1-3R-0	–0.53	–0.26	–0.40
6	IR66327-KKN-33-P1-3R-0	–0.91	–0.02	–0.46
1	IR46331-PMI-32-2-1-1 (P1)	–0.73	–0.44	–0.59
19	Damnoeub Khlanh (acc. 3172)	–0.70	–0.63	–0.66
16	CAR 4	–0.87	–0.56	–0.71
12	IR66368-CPA-6-P1-3R-0	–0.57	–1.02	–0.79
	5% LSD genotype (G)	0.93**	0.99*	0.68**

** = significant at $P<0.01$, * = significant at $P<0.05$

Table 5. The drought response index (DRI) of 15 rice genotypes, the LSD 5% values, and the genotype mean heritability (*h*²) when grown at two locations and for a number of years in rainfed lowlands in Cambodia.

Gen. No.	Genotype	PV98	PV99	PV00	PV01	CA00	CA99	CA01	Mean
2	IR57514-PMI-5-B-1-2	0.76	–0.33	**1.35**	–0.20	0.94	0.39	0.39	0.47
26	CAR3	0.32	0.14	0.43	–0.14	–0.48	0.14	**1.71**	0.30
3	IR66327-KKN-10-P1-3R-0	0.01	–0.58	0.41	0.63	**1.34**	0.04	0.05	0.27
17	CAR6	–0.68	–0.04	0.89	0.14	0.46	0.79	0.32	0.27
5	IR66327-KKN-25-P1-3R-0	0.30	**1.24**	0.98	–0.16	–0.39	–0.53	0.41	0.27
10	IR66327-KKN-8-P1-3R-0	0.66	–0.36	–0.77	**1.09**	0.42	–0.03	–0.09	0.13
22	Khpor Daung	0.25	**1.25**	–0.93	–0.62	0.14	0.21	–0.17	0.02
24	Somaly	–0.06	–0.20	–0.21	0.57	–0.43	0.38	0.00	0.01
18	CIR158-B-B-SB-8-3-2	–0.39	–0.07	0.16	0.41	0.34	0.12	–0.70	–0.02
8	IR66327-KKN-54-P1-3R-0	–0.55	0.52	0.02	–0.41	0.59	–0.17	–0.45	–0.06
25	KDML105	–0.35	0.51	–0.86	0.47	–0.49	0.10	0.15	–0.07
13	IR66368-CPA-84-P1-3R-0	0.02	–0.42	–0.81	0.45	–0.32	0.41	–0.31	–0.14
15	Bang Kuy (acc. 2865)	–0.21	0.15	–0.13	0.26	–0.87	0.76	–1.27	–0.18
1	IR46331-PMI-32-2-1-1(P1)	0.29	–0.70	0.19	–2.12	–0.03	–1.05	–0.03	–0.58
16	CAR4	0.21	–1.07	–0.74	–0.37	–1.21	–1.54	–0.01	–0.68
	LSD 5%	ns	0.94	0.95	0.95	0.98	0.90	ns	0.40
	Heritability (h²)	0.23	0.58	0.72	0.74	0.60	0.57	0.50	0.44

ns = not significant. Bold and shading indicates higher than 1 and lower than –1, respectively

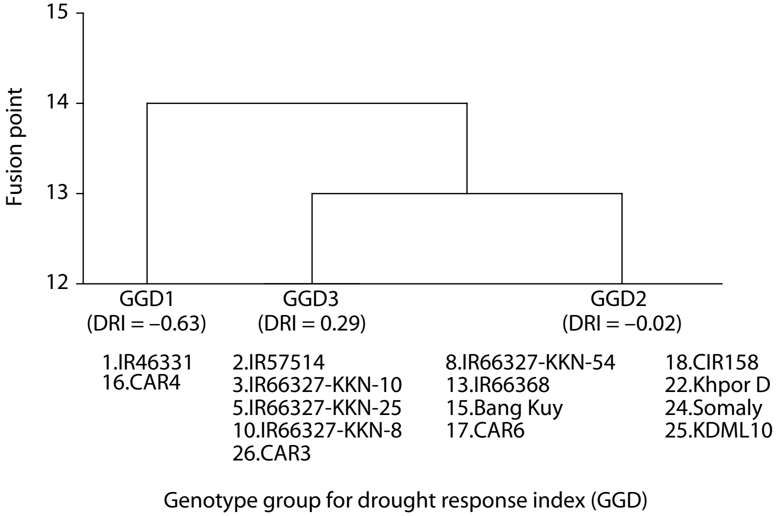

Figure 3. Dendogram, truncated at the three-group level, for the hierarchical clustering of 15 rice genotypes, based on the matrix of standardised drought response index (DRI), best linear unbiased predictors (BLUPs) for seven drought environments in Cambodia. The mean DRI values are shown for each group.

Table 6. Group mean drought response index (DRI) values for three groups of rice genotypes (GGD) and three groups of environments (EGD) in Cambodia as shown in Figures 3 and 4 and the mean values over environmental groups.

Genotype group	Environmental Group for drought response index (EGD)			Mean
	EGD1	EGD2	EGD3	
GGD1	–1.07	–0.33	–0.53	–0.63
GGD2	0.19	–0.16	–0.07	–0.02
GGD3	0.13	0.39	0.32	0.29

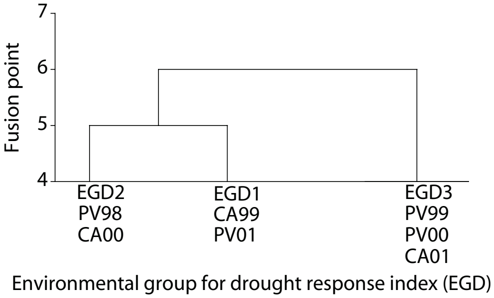

Figure 4. Dendogram, truncated at the three-group level, for hierarchical clustering of seven environments—based on the matrix of standardised estimated drought response index (DRI) best linear unbiased predictors (BLUPs) for the 15 genotypes tested at PreyVeng and at CARDI from 1999 to 2001 in Cambodia.

Discussion

A major issue for rainfed lowland rice plant breeding programs is how to identify and manipulate environments for drought screening that represent the target population of environments of the framers (Fukai and Cooper, 1995). While the historical rainfall pattern may be used to explain yearly variation in GY, the water level in the paddies is a more direct measure of water available to the current rice crop (Jearakongman et al. 1995). In this study, drought environments were established successfully by draining paddies at different crop-growth stages so different types of drought environments were available for screening genotypes. The types of drought varied in timing, with crop development from prolonged drought being affected from the vegetative stage or being restricted to a short duration in the grain filling stage. They also varied in intensity from mild to severe drought. However, the actual stress mainly developed late in the season and as such represents the target environments. The drought effect ranged from a 12–46% reduction in GY (only one site was 12%, the others were greater than 20%). In similar environments in Thailand, Wonprasaid et al. (1996) obtained a 40% reduction in GY by draining the paddies about one month before flowering, while Pantuwan et al. (2002a) obtained reductions from 19% to 80%. The values obtained by manipulating water in the experiments here are in keeping with the estimated losses in the farmer fields in Cambodia.

In experiment 1 there was a significant difference among the genotypes for DRI and no significant interactive effect of year or site, suggesting some level of consistency in DRI across growing conditions. For example, 23% of the variation in DRI among the 25 genotypes grown under the WS treatment at CARDI was predicted by the DRI under the WS treatment at Prey Veng. In experiment 2, which used more environments, there was a significant interaction of DRI and the environment, and the G × E component of variance was 4.2 times that of the genotype component. This finding is consistent with that of Pantuwan et al. (2002b) who suggested that the timing and severity of the drought would influence the DRI value. However, the high DRI group (drought tolerant) in the study here was consistently high in all environmental groups indicating that the DRI of some genotypes is stable and can be used as a reliable measure of drought tolerance.

The effective use of the DRI in a breeding program relies on its:

- ability to predict yield performance under drought in the target environments
- being independent of, or not negatively associated with, yield (and other important adaptive traits).

The DRI calculated for each drought environment was not confounded by DTF (data not shown) or GY under the WW treatment, indicating that DRI can be used in selection without untoward effects on yield potential and maturity.

The ability of DRI to predict yield in the target population is shown in Table 7. Grain yield (GY) was used to form the clusters truncated at the four-group level for genotypes and at the three-group level for environments (data not shown) and the DRI values of these groups analysed. There was a significant difference in the DRI values among the genotype (groups based on GY) which ranged in GY from 1.35 to 2.64 t/ha. This suggests that the DRI can, to some extent, explain the clustering of genotypes based on GY in the drought environments and it is possible to select for the high DRI genotypes with the superior GY at all sites.

Table 7. The mean drought response index (DRI) for rice genotypes and environments based on the two-way cluster analysis for grain yield[a] of rice grown at one site in 1998 and at two sites in 1999–2001 either under rainfed or imposed drought conditions in Cambodia.

Genotype	EG1	EG2	EG3	Mean
GG1	-0.41	0.01	-0.05	-0.06
GG2	0.21	0.13	-0.04	0.11
GG3	-0.16	-0.31	0.03	-0.24
GG4	0.25	0.18	0.04	0.17
5% LSD for GG	ns	0.36	ns	0.31

[a] Clustering analysis based on grain yield not shown.
Genotype (GG) and environmental (EG) groups are based on grain yield.

Of the five genotypes in the high DRI group found to be stable across all environments, one of the released lines in this group (IR57514-PMI-5-B-1-2) had the highest DRI value and it was also found to have drought tolerance by Jearakongman et al. (1995). This line also performed well under diverse rainfed lowland environments in North-east Thailand (Romyen et al. 1998) and in Lao PDR (Inthapanya et al. 2001). This result suggests that it is possible to use IR57514-PMI-5-B-1-2 either directly as a drought-tolerant genotype or indirectly as a parent in a rainfed lowland breeding program to develop drought-tolerant varieties.

Bidinger et al. (1987b) proposed a method to estimate DRI by comparing the mean values over replications in the WS and WW treatments that uses threshold values for the upper and lower 10% of the normal distribution ($Z = +1.3$ and -1.3) to identify the drought-tolerant (DRI >1.3) and susceptible (DRI<–1.3) genotypes. This method identifies the extreme genotypes but has the disadvantage of selecting only the upper and lower genotypes. The method used in the present study estimates DRI for each replication and hence allows a comparison of all of the genotypes based on significant variation for DRI among genotypes. Researchers can use this test to judge the level of consistency of DRI among the genotypes growing under different environments and from that identify genotypes with high and consistent DRI values for use as parents in a crossing program.

This study did not attempt to understand the underlying mechanisms and traits that contribute to the variation in DRI. Jearakongman et al. (1995) found that the high DRI line IR57514-PMI-5-B-1-2 had greater green leaf retention under the prolonged drought. The value of DRI as a measure of drought tolerance will be enhanced once the mechanisms for the variation in DRI are better understood in terms of our knowledge of drought tolerance in rice. However, for now, plant breeders can screen and use DRI along with yield potential and appropriate maturity to identify parents to improve the performance of rainfed lowland rice under variable moisture environments.

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Progress in drought avoidance of rainfed lowland rice

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Abstract

Rainfed lowland rice is grown in bunded fields covering more than 36 million hectares of South and South-east Asia. Drought stress is common, with yields averaging only 2.3 t ha^{-1}. The ecosystem is characterised by fluctuating water, with soil hydrology ranging from flooded and anaerobic to droughted and aerobic. Root systems have to cope with too much and too little water at different growth stages. Drought stress may be encountered during panicle development, and especially during grain filling. These patterns vary in intensity with location, season, soil type and topographic position.

Our previous research has demonstrated that cultivars differed in their patterns of adaptation to various types of rainfed environments, and this was associated in part with patterns of root behaviour during droughts. In simulated rainfed lowland conditions in the greenhouse, cultivars differed in the extent to which they could proliferate roots in, and extract water from, deeper soil layers as drought progressed. In the field, cultivars differed in the ability of their roots to penetrate hardpans and proliferate in deeper soil layers.

Our most recent experiments have demonstrated that cultivars differed in the amounts of water extracted from deeper soil layers during drought. Greenhouse and field experiments have now indicated that root signals are strong in rainfed lowland rice, and are associated with increasing levels of abscisic acid in leaves as drought progresses. Cultivars varied in stomatal closure as drought progressed, with implications for rate and extent of water loss. Molecular studies have identified consistent responses in protein regulation during drought and after rewatering. In the field, the soil water from above and below the hardpan has been shown to differ in hydrogen isotope composition, raising the prospect that analysis of xylem water could be used to identify lines with a greater capacity to extract water from deeper soil layers, without destructive measurements of the root system. The implications of these results for the selection of cultivars with more efficient water use and their agronomic requirements for producing higher and more stable yields in rainfed lowland conditions are discussed.

Introduction

THE rainfed lowlands support about 700 million people who derive about 50% of their calories from rice (Dawe 2000). Farmers are poor and often lack access to credit. The rainfed lowlands have level to slightly sloping bunded fields with non-continuous flooding of variable depth and duration (Zeigler and Puckridge 1995). Rice (*Oryza sativa*, L.) is the major crop, with yields averaging 2.3 t ha^{-1} over 36 million hectares, mainly in South and South-east Asia (IRRI, 1997) with drought being recognised as the major

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constraint to rice performance (Widawsky and O'Toole, 1990). Depending on the surrounding landscape, however, the hydrology of the rainfed lowlands differs greatly (Wade et al. 1999b). Paddies in a high position lose water readily through surface runoff and seepage, while those in a low position may intercept that water. Such lateral water movement results in different depths and durations of ponded water, and different exposures to drought stress later in the growing season, at different topographic positions (Fukai et al. 2001). Soil texture (Nesbitt and Phaloeun 1997), soil fertility (Mazid et al. 1998) and soil-water holding capacity (Samson et al. 2004) also vary across the landscape, with implications for the timing of agronomic events and for crop performance and stability in different topographic positions (Samson et al. 2004).

The rainfed lowlands are characterised by fluctuating water, with soil hydrology ranging from flooded and anaerobic to droughted and aerobic (Wade et al. 1998). Root systems have to cope with contrasting stresses. In direct seeding, there may be a short period in which soils are aerobic before inundation occurs. A period with ponded water follows, with water depth and duration varying. In extreme cases, the crop may be fully submerged more than once. Later in the season, drought stress may be encountered during panicle development, and especially during grain filling. Reviews have concluded that deep root systems would be beneficial in upland conditions, where drought stress is common in the continuously aerobic soils (O'Toole 1982; Yoshida and Hasegawa 1982). It has been argued that deep roots would also be beneficial in other rainfed rice systems.

But roots are generally shallow in the rainfed lowland (Pantuwan et al. 1997; Samson et al. 2002). At issue is the capacity of roots to penetrate deeply and extract water from deeper layers as the drought progresses. Many questions such as the following arise (Wade et al. 1998):

- Is the initial shallow rooting caused by lack of oxygen, as roots are developed in the flooded conditions encountered before drought stress.
- Can a deeper, constitutive root system developed before water stress provide an advantage?
- Can roots penetrate the hardpans often present at about 20 cm, or soil transitions such as acid subsoils?
- Does poor nutrition, especially at depth, inhibit root development?
- Given the anaerobic–aerobic transitions, is high root turnover important, and is a different set of root traits needed for different conditions?
- Since there are many root tips in drying soil of the surface layers, are root signals important in rainfed lowland rice?
- Are these additional traits mandatory, in order for deep roots to be expressed and to function effectively in rainfed lowland?
- Further, is the issue solely the capture of additional resources, or are metering of resource use, efficiency of conversion to dry matter, and its partitioning to yield also of critical importance?

A research program was set up to address these issues at various levels of integration. Genotypes were grown across environments to examine patterns of adaptation, to identify reference lines for the breeding program, and help the breeding program with trait combinations likely to be of benefit in different target environments (Wade et al. 1999c). Target environments were characterised (Wade et al. 1999b), and their nutrient requirements identified in relation to fluctuating water supply (Wade et al. 1999a). Physiological studies were done in greenhouses (Wade et al. 2000; Azhiri-Sigari et al. 2000; Kamoshita et al. 2000) and the field (Samson et al. 2002) to understand plant response to drought. Genetic studies, including phenotyping and QTL (quantitative trait loci) identification (Kamoshita et al. 2002a,b; Chandra Babu et al. 2003), and proteomic and functional genomic studies (Salekdeh et al. 2002a,b), were added recently, to help determine the underlying basis of improved adaptation, and help develop better genotypes. This research has demonstrated that cultivars differed in their patterns of adaptation to various types of rainfed environments, and this was associated in part with patterns of root behaviour under drought. In simulated rainfed lowland conditions in the greenhouse, cultivars differed in the extent to which they could proliferate roots in, and extract water from, deeper soil layers as drought progressed. In the field, cultivars differed in the ability of their roots to penetrate hardpans and to proliferate in deeper soil layers.

Based on these findings, there was a need to examine the following questions:

- Does an improved root system at depth result in greater extraction of water from deeper soil layers in the field as drought progresses?

- Is a capacity for osmotic adjustment advantageous in maintaining leaf water potential and biomass production under drought?
- At the molecular level, are there consistent responses in protein regulation during drought and after rewatering?
- Are root signals important in rainfed lowland rice, and are they associated with levels of abscisic acid in leaves?
- Does soil water from above and below the hardpan differ in hydrogen isotope composition, raising the prospect that analysis of xylem water could be used to identify lines with a greater capacity to extract water from deeper soil layers.

This paper provides evidence from recent research on these questions, and discusses the implications for selection and management.

Water extraction from deeper soil layers under drought

Our previous greenhouse research indicated a relationship between the extent of root proliferation in deeper soil layers as drought progressed and the extent of water extraction there (Wade et al. 2000; Azhiri-Sigari et al. 2000; Kamoshita et al. 2000). In the field at Rajshahi in Bangladesh, Samson et al. (2002) showed that cultivars differed in the capacity of their roots to penetrate hardpans and to proliferate in deeper soil layers. Experiments were then conducted at Rajshahi in 2000 and 2001 to examine the relationship with water extraction. Both seasons encountered severe terminal drought stress. Penetration resistance at 25 cm soil depth increased from 1.0 to about 3.0 megapascals (MPa) as drought progressed during grain filling, while volumetric soil-water content declined from 0.30 to 0.18 in 2000 and to 0.22 in 2001 (Table 1). Cultivars differed in the extent of water extraction from the soil profile (Table 2), although the relationship between water extraction and root length density in a soil layer was less clear than in the greenhouse (Samson et al. in preparation).

Osmotic adjustment for maintenance of LWP and biomass under drought

The experimental system developed by Wade et al. (2000) was used to further examine changes in osmotic adjustment, leaf water potential and biomass during short and prolonged drought periods in the greenhouse (Kamoshita et al. 2001). Averaged over a range of cultivars, osmotic adjustment generally increased as leaf water potential became more negative (Table 3). Osmotic adjustment ranged from 0.38–0.47 MPa and 0.71–0.81 MPa in the shorter and longer drought periods respectively over the set of six cultivars (not shown). While there was no clear relationship between osmotic adjustment and biomass production during drought, there was one between plant water status and recovery from prolonged drought on rewatering (Kamoshita et al. in review). Nevertheless, recovery on rewatering was more strongly associated with plant size and leaf area at the end of the drought period, which was consistent with Mitchell et al. (1998) and Wade et al. (2000).

Table 1. Root length density RLD (cm/cc), soil penetration resistance SPR (MPa), and volumetric water content VWC at 25 cm soil depth at days 82, 108 and 120 at Rajshahin Bangladesh in 2000 and 2001.

		82	108	120
2000	-RLD	0.5	0.5	0.5
	-SPR	1.0	3.3	3.0
	-VWC	0.30	0.20	0.18
2001	-RLD	0.5	0.5	0.5
	-SPR	1.0	1.6	3.0
	-VWC	0.30	0.24	0.22

Table 2. Soil water extraction (mm) from 0–40 cm soil depth by rice lines in rainfed lowland conditions at Rajshahin Bangladesh in 2000 and 2001.

	2000 Cycle 1	2000 Cycle 2	2001
CT9993	32.0	36.7	–
IR62266	26.9	23.5	43.2
DH79	26.3	26.6	33.0
DH77	–	–	33.9
DH102	–	–	38.7

Source: Samson et al. Field Crops Research (in preparation).

Table 3. The relationship between LWP and OA in prolonged drought in the greenhouse over 6 cultivars as drought progressed.

LWP (MPa)	OA (MPa)
–1	0.55
–2	0.65
–3	0.75

Source: Kamoshita et al. Plant Production Science (in review).

Responses to drought at the molecular level

QTLs for root traits and osmotic adjustment have been reported for flooded conditions (Kamoshita et al. 2002a,b), upland drought (Champoux et al. 1995, Courtois et al. 2000; Price et al. 2000; Price and Tomos 1997; Yadav et al. 1997) and rainfed lowland drought (Chandra Babu et al. 2003). No simple picture emerges, despite some QTL positions being consistent between reports (Figure 1). Different QTLs were important in anaerobic and aerobic conditions, and in japonica and indica populations. The QTLs identified were highly subject to the conditions in which the plants were phenotyped, emphasising the need to carefully target conditions likely to be encountered in target environments. The greatest challenge in developing candidate genes and molecular markers is not the genetic analysis, but the complexity in appropriately managing the environments for assessing abiotic stresses and incorrect phenotyping. Research progress is more likely with a balanced team comprising representatives from a number of key disciplines, such as plant breeding, crop physiology, soil science, plant nutrition, plant pathology, and agronomy as well as molecular biology. When this is done correctly, QTLs for drought tolerance and for yield under rainfed lowland drought in the field may be identified (Figure 2).

Our greenhouse and field research revealed that cultivars differed in their strategies of response to drought stress. CT9993 aggressively pursued soil water more deeply as drought progressed via a reliance on a deeply-penetrating root system. In contrast, IR62266 was more conservative, showing an enhanced capacity for osmotic adjustment and a greater stomatal regulation for slower transpirational water loss as drought progressed. Consequently, IR62266 was widely adapted to various drought environments, while CT9993 performed well only in those environments where its deep roots could exploit subsoil moisture reserves as drought progressed (Wade et al. 1999c). We are now studying the

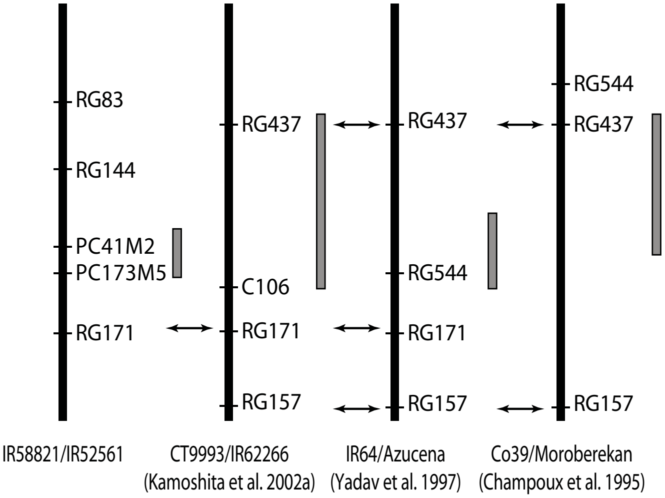

Figure 1. Comparison of common QTL for deep root per tiller on chromosome 2 across mapping populations. The vertical bars beside the markers are the genomic regions associated with the traits. Arrows indicate common markers across mapping populations. Source: Kamoshita et al. (2002a).

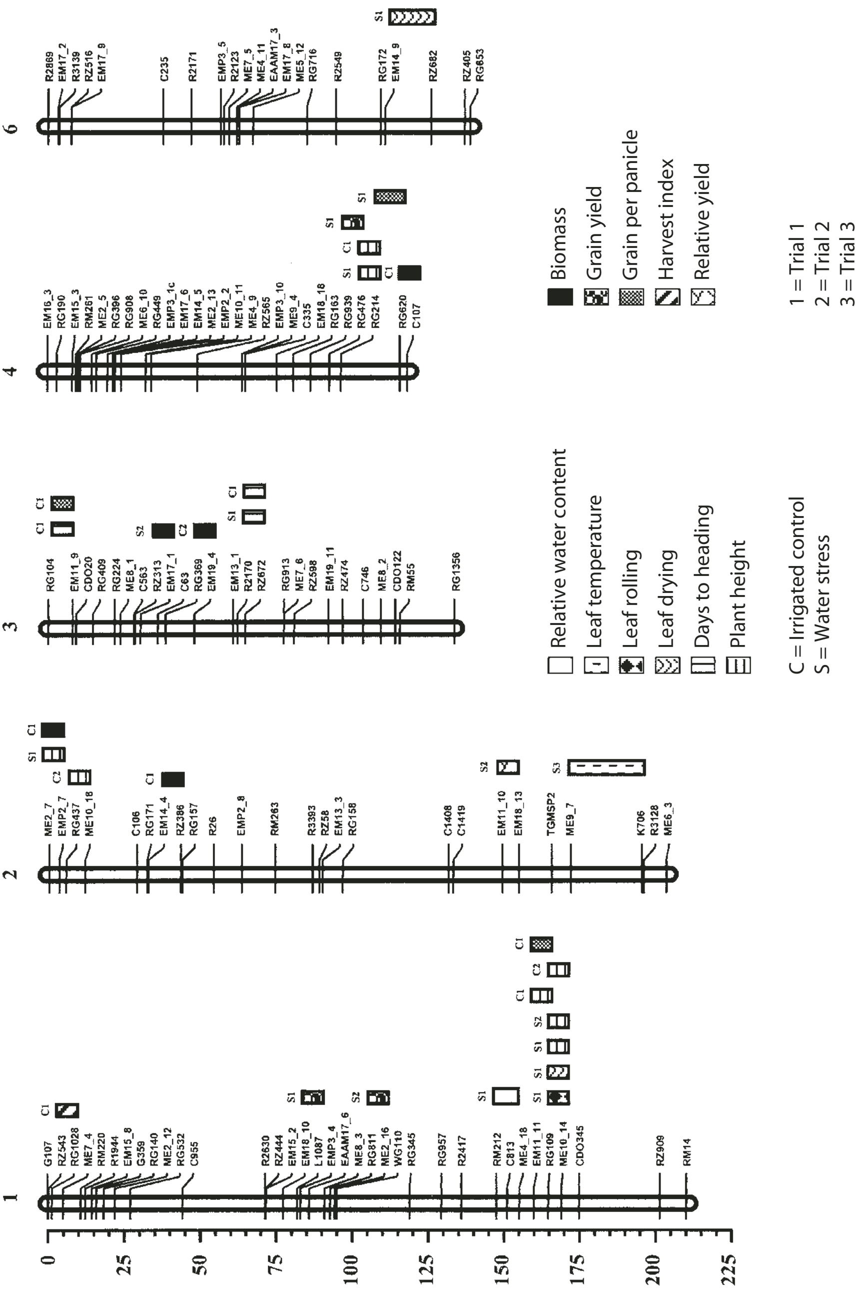

Figure 2. The molecular genetic linkage map of rice based on 154 doubled-haploid lines derived from a cross, CT9993-5-10-1-M × IR62266-42-6-2. Chromosome numbers are indicated above each chromosome. Distances are given in Kosambi centimorgans. The letters before the numbers in the marker names indicate the category of mapped clones as follows: RM, rice microsatellites; EM and ME, AFLPs; other letters, RFLPs. The positions of QTL are indicated by vertical bars besides chromosomes. The bar length is drawn to be equal to the length as detected for the QTL in the QTLMapper software.

basis of these responses more closely, by considering changes at the protein level during progressive drought and rewatering. Samples were taken from our greenhouse and field experiments for this purpose (Salekdeh et al. 2002a,b). Figure 3 shows changes in abundance and position of leaf proteins as drought intensifies and is relieved by rewatering. In Figure 4, protein up-regulation was more common in CT9993 as drought progressed, while down-regulation was more common in IR62266. Our research continues to identify these proteins and to consider their roles in the plant as drought progresses.

Root signals under drought

Root signals were examined in pots by dividing root systems, withholding water from one portion, and in some cases, severing the droughted portion of roots to remove the putative signal (Sekiya 2002). Droughted roots were severed from some droughted plants at day 13 after water was withheld, when leaf water potential was similar between control and droughted plants (not shown). Stomatal conductance was lower in droughted plants, and there was a further decline in the severed treatment due to

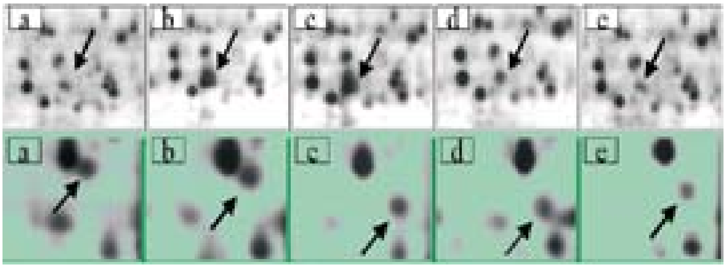

Figure 3. Details of silver -stained 2D gels of leaf proteins of line IR62266 experiencing 18 days drought followed by re-watering. Arrows indicate proteins showing changes in abundance (top panel) or position (bottom panel). Treatments: (a) well-watered, (b) 3 kg water lost, (c) 4 kg water lost, (d) 5 days after re-watering, (e) 10 days after re-watering. Arrows in top panel: actin depolymerization factor. Arrows in bottom panel: unknown protein. Source: Salekdeh et al. (2002) Field Crops Res. 76, 199–219.

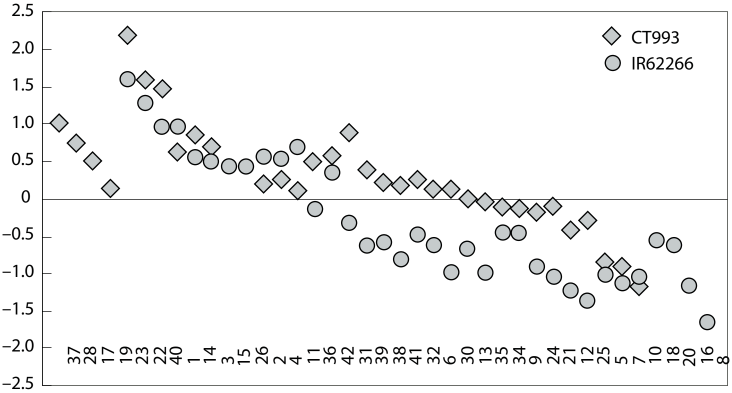

Figure 4. Abundance ratio of 39 individual leaf proteins in drought-stressed and wellwatered plants of cultivars CT9993 and IR62266 at 43 DAS. The ratio is expressed as $\log_2$ (abundance in stressed plants/ abundance in control plants). Source: Salekdeh et al. (2002) Proteomics 2, 1131–1145.

wounding on day 14 (Table 4). However, by day 19, in pots where droughted roots were severed, stomatal conductance had recovered to control levels, while stomatal conductance continued to decline in the intact droughted plants. These responses were associated with increased levels of abscisic acid (ABA) in leaves under drought (Table 5), which differed between cultivars. These results provide powerful evidence of the presence of root signals in rice in rainfed lowland conditions, where many root tips are present in drying soil close to the surface (Siopongco et al. 2003).

Table 4. Stomatal conductance (cm/s) of control, drought, and drought-severed treatments in the greenhouse. Droughtedroots were removed from the drought-severed treatment at day 13 after water was withheld. Data are presented at 9, 14 and 19 days after imposition of drought. For the severed treatment, day 14 shows response to wounding and day 19 the absence of root signal

	9	14	19
Control	1.0	1.3	1.1
Drought	0.5	0.7	0.2
Severed	–	0.4	1.0

Source: Sekiya (2002). MS Thesis, Nagoya University, Japan

Table 5. Plant ABA levels (mg hormone g FW -1) in well-watered and droughted treatments at days 7, 13 and 18 after withholding water in the greenhouse at IRRI.

	7	1 3	1 8
WW -CT9993	trace	trace	trace
-IR62266	trace	trace	trace
Drought -CT9993	trace	0.20	0.06
-IR62266	0.15	0.45	0.15

Source: Siopongco et al. (2003). Japan J. Crop Sci. (in press).

Hydrogen isotope composition of water from different soil layers

Soil-water samples were obtained from above and below the hardpan in our field experiments at Rajshahi in Bangladesh. Hydrogen isotope composition of the soil-water samples was measured (Table 6). Water from above the hardpan had consistently higher values than water from below the hardpan, raising the possibility of using deuterium/hydrogen ratios (D/H) from xylem water as a method for examining the proportion of water being drawn from deeper soil layers as drought progresses (Yano et al. in review).

Table 6. Delta-D values of soil water from above and below the hardpan at Rajshahi, Bangladesh in 2001.

Depth	Sep 21	Sep26	Oct 03
10 cm	5	5	0
40 cm	–2	–2	–10

Yano et al. Plant Production Science (in review).

Discussion

These results provide further understanding of traits associated with alternative strategies of plant response to drought and its implications for adaptation to rainfed lowland conditions. The mechanistic understanding provides a potential basis for selecting improved cultivars that use water more efficiently during drought. Variation in the D/H ratio of xylem water could be used to select cultivars with a greater capacity to extract water from deeper soil layers, without the need for difficult root or soil-water measurements. Likewise, variation in leaf ABA and stomatal conductance could be used to identify cultivars that are more conservative in their use of the extracted water, again without the need for complex measurements of roots or soil water.

Yield under drought may be viewed as the product of the water extracted, the efficiency of its conversion to dry matter, and the proportion of that dry matter allocated to grain. In every situation, the best outcome is an optimisation of all three parameters. Unless all of the available water is extracted from the soil profile, the plant limits its potential yield in that environment. Consequently, an effective and deep root system is needed to capture the resources as drought progresses in rainfed lowland, but to achieve this the plant must be able to cope with the associated conflicts from anaerobic–aerobic transitions, rate of onset of drought, chemical and physical barriers and root signals. Also, the captured water needs to be efficiently converted to biomass, which means having enough leaf nitrogen—which in turn is dependent on nutrient–water interactions in fluctuating water environments. Finally, a high harvest index is desirable, so the dry matter is expressed as yield. To do this, appropriate phenology and plant size are essential relative to growing-season duration and favourability, so sufficient soil water remains for completion of grain filling. In this context, a capacity to meter the transpirational loss of water via appropriate root signals and stomatal regulation is important. The high epidermal conductance of rice is a further hazard needing attention, if we want to control water loss in drought for improved plant performance. Such a combination of traits should result in development of lines with improved performance and stability under drought stress in rainfed lowland conditions.

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Synthesis

Per Pinstrup-Andersen[1]

IN MY OPINION we have had a stimulating interaction with great presentations and discussions during the past four days. It has been a real pleasure to participate. The content of presentations and discussions has been rich and there is no way I can do full justice to it in this short synthesis presentation. Instead, I would like to refer to several highlights from the conference.

Dr Takase reminded us that agricultural development built the foundation for the East Asian miracle. I would add that agricultural development also led economic growth elsewhere in Asia including South Asia. In fact, both historical evidence and many analyses demonstrate the tremendous importance of agricultural development as a driver of general economic growth and poverty eradication in countries where agriculture employs a large share of the population. Virtually every country in the world with the exception of Singapore and Hong Kong has gone, or is going through, a period with agriculture the only or the most viable driver for general economic growth. I believe this evidence provides a very clear lesson to Cambodia and other countries at relatively low income levels. The lesson is, in my opinion, to invest in agricultural and rural development with emphasis on productivity increases in small scale farming. It will pay off handsomely, not only in agricultural, but in economic growth as well.

During the past four days we heard that Asia has less land per capita than most other parts of the world. Yet, Asia is likely to be the only region that will achieve the Millennium Development Goal for Poverty and Hunger Alleviation. The point here is that productivity per unit of land, driven to a large extent by appropriate research and use of fertilisers and plant protection measures, has been critical for Asian agricultural development. The amount of land per capita is only one of the factors to consider.

At the same time as Asia has achieved rapid agricultural and economic growth, it has also experienced serious environmental problems. Degradation of natural resources such as land, water, forests, and biodiversity is widespread and it is of critical importance that sustainability be incorporated into future efforts to promote agricultural growth and development. Increasing productivity on lands that are well suited for agriculture will relieve pressure on land that is less well suited as well as on forests. It is likely to improve biodiversity by leaving more of the natural resources to their natural state.

Conforming to the overall theme, the conference focused on improving water management. The term ‘crop per drop’ was used widely and one of the presenters suggested that we should also look at ‘poverty reduction per drop’. After all, the issue at hand is to help poor people out of poverty and hunger. Agricultural production is clearly an essential tool to achieve this but it is not an end in itself. As water becomes more scarce, the concept of how much poverty can be reduced per unit of water used becomes even more important.

The conference discussed results from analyses of various irrigation schemes. We had interesting discussions about the use of tube wells, drip irrigation, and other household-level irrigation approaches. One of the eye opening issues discussed was how farmers have learned to live with and benefit from natural flooding, for example, that which takes place around the Tonle Sap Lake. While natural flooding is usually seen as a risk, it appears that farmers in some areas have learned to actually benefit from it. This raised a series of issues around the management of risk and the coping with uncertainty that small farmers are faced with. One of the many ways of managing risk

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that was discussed during the conference was the development of drought tolerant crop varieties. We concluded from the various discussions and presentations on water management that location-specific solutions are needed. The most appropriate are likely to be those tailored to local circumstances.

Rice dominated the presentations and discussions. We talked primarily about lowland rain-fed systems, maybe because those are the ones most prevalent in Cambodia. We discussed the economics of double cropping but it appears that the results from double cropping vary widely among locations. Notwithstanding the emphasis on lowland rain-fed systems, there were several calls for more emphasis on agricultural systems in upland areas where many of the low income people live. As part of this discussion, we approached the question of diversification and the role that government should play. Results from research in a number of locations indicate that the role of government should be one of facilitating farmers' choice for diversification instead of governments deciding on which kind of diversification should take place. The facilitating role that governments can play would include investment in rural infrastructure and access to appropriate technology and markets for the various products that could enter into a diversified agricultural system.

Much of the conference was dedicated to discussing sustainability and agriculture. The disaster around the Aral Sea was presented and discussed and potential disasters, such as seawater intrusion, were identified as serious. We were told that during the dry season, sea water has been found to intrude as much as 60 km up the Mekong River in Vietnam. We also briefly discussed the intrusion of sea water into ground water on the East coast of China. Sustainable management of soils was discussed widely. We heard a presentation of a production system that could yield up to 23 tons of rice without the use of chemical fertilisers. We recognised that it would be difficult or impossible to replace the plant nutrients removed simply by using the small amount of compost available. We also heard a presentation on what appears to be excessive use of nitrogen fertilisers. Specifically, we were told that in some of these production systems, as much 600 kg of nitrogen were used per hectare per year with a crop utilisation rate of about 25%. These are examples of situations in which there has been either too little or too great an amount of plant nutrients applied.

Various research and technology issues emerged in the presentations and discussions. However, participants largely agreed that we need interdisciplinary approaches in the research required to help the development of sustainable and profitable farming systems in Asia. The research and development must be relevant to farmers' problems and farmers should participate in setting priorities and designing research programs. I would even argue that relevant applied agricultural research should begin and end with farmers. I would also add that consideration has to be given to the market and to future consumer demand. It is important that the priority setting in agricultural research in Asia pays due attention to what the consumers want and what they are likely to oppose. The time has passed when agricultural research would be successful if it only met the expectations of the farmers. We need only to look at what is happening in Europe to confirm that hypothesis.

There is clearly a need to develop public goods type technology for small farmers in Asia. This kind of technology is unlikely to be developed by the private sector because exclusive intellectual property rights cannot be taken out on public goods. Therefore, there is a need for continued public investment in agricultural research for Asia, although I would expect an increasing share of the agricultural research, namely that which can be subjected to exclusive property rights, will be taken over by the private sector. Molecular biology-based research is used widely in Asian agricultural research but genetic engineering is not yet widespread. Marker-assisted plant breeding, tissue culture, and other molecular biology-based research methods have not experienced any serious opposition. Genetic engineering, on the other hand, has been promoted only in a few countries such as China, India, and the Philippines.

Returning to the question of interdisciplinary approaches, I believe it is critically important that all the disciplines be represented from the outset of the research and be involved in designing the research and setting priorities. In particular, the socioeconomic components of such interdisciplinary approaches should not be brought in towards the end of the research but rather at the beginning. One concern that we briefly discussed is related to the biodiversity convention which was recently put into effect. I am referring to the possible barriers to continued sharing of germ plasm across countries. Past research in Asia that led to the green revolution depended very much on free international movement of germ plasm and it would be extremely unfortunate if countries were to put up barriers to such free flow of germ plasm in the future. Asian agricultural research has also benefited greatly from international sharing of knowledge and it is important that further efforts be made to strengthen international networks and partnerships, both among public research institutions, and with the private sector and the CGIAR.

Let me now turn to the future. Even though there was much discussion about diversification, we should recognise the critical importance of rice in Asian agriculture and among Asian consumers in the future. However, Asian agricultural development should pay close attention to future market prospects for other commodities such as livestock, livestock feed, fish from agriculture, and a number of high value commodities including some fruits and vegetables. While the demand for rice will continue to be high, there will be strong increases in the demand for these other commodities. The lesson for Asian agriculture is to move ahead more aggressively on the development of production systems for these other commodities. One of the questions that Asia needs to face is who will produce the livestock feed for the increasing number of Asian livestock. Will Asia increase its production of livestock feed or will most of the increasing demand be met by imports from the USA, Brazil, or Argentina. A related question, of course, is to what extent Asia will meet the rapidly increasing demand for livestock products from production in the region rather than from imports.

Irrespective of the relative commodity priorities, this conference has underlined the need for Asia to pursue the five objectives of:

- pursuing increasing agricultural productivity from water, land, and labour
- managing nutrients for Asian agriculture better
- managing Asia’s natural resources so that more emphasis is given to enhanced sustainability
- having Asian governments emphasise assistance to farmers who are faced with additional risks and uncertainties associated with weather and market fluctuations as well as risks associated with changing production systems
- Asian agriculture taking into account future market prospects for the various commodities and inputs.

In the above, I have tried to cover what I believe is only a small part of the tip of the iceberg. The rest of the iceberg, meaning the full picture of the conference, will emerge in the chapters of the Proceedings.

Increasing productivity through genetic improvement for tolerance to drought and excess-moisture stress in maize (*Zea mays* L.)

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Abstract

Both too much and too little water are major causes of crop yield losses around the world, and in the major food systems of the tropics. Significant yield losses due to drought and/or excess-moisture (waterlogging) conditions occur one out of every three to four years, and climate change caused by global warming is expected to add to the uncertainty of weather patterns and contribute to an increase in the occurrence of such stresses. Genetic studies showed that yield components and morpho-physiological traits involved in water-stress tolerance in maize are regulated by several genes. Therefore, development of germplasm with stress-adaptive genes needs to be conducted in a systematic manner. At the International Center for Maize and Wheat Improvement (CIMMYT), various approaches to improving drought tolerance in maize have been explored. About three decades of work on drought tolerance in maize has resulted in improved source populations and useful open-pollinated and hybrid products that perform well under drought stress. Results from recent studies show the usefulness of this germplasm under severe drought-stress conditions. Furthermore, improvement in mid-season drought tolerance appears to impart tolerance to various other stresses, such as low-nitrogen soil fertility. Under the Indian Council of Agriculture Research–CIMMYT collaborative program, a large number of materials, including inbred lines from CIMMYT and the Indian national program, were screened for excess-moisture (waterlogging) tolerance in maize at sites managed by the Directorate for Maize Research, India. Promising tolerant lines were identified and further improved toward developing waterlogging-tolerant cultivars for waterlogging-prone areas in India. Secondary traits, such as anthesis–silking interval, early and increased brace-root development, and high root porosity were found to be associated with excess-moisture tolerance.

Introduction

Among various abiotic stresses, extremes of water availability, including drought and excessive soil moisture, are the major limiting factors for maize production and productivity in the tropics. In the Asian region, the maize crop is exposed to excessive moisture during the ‘knee-high’ stage of plant development and to drought at the flowering/grain-filling stage. Most of the time, mean rainfall during the crop season appears suitable, but weekly precipitation levels are highly variable. The result is that a crop can have both too much and too little water at critical stages of growth during the one cropping season (Figure 1). The average yield loss due to drought in lowland tropical environments (<1000 m above sea level) alone was estimated at 15.0 million t/year (Edmeades et al. 1992). Such losses represent 17% of the well-watered environment and it can be as high as 60% (Rosen and Scott 1992) in severely drought-affected regions such as in southern Africa during 1991–92, and again in 1994–95. In Southeast Asia, about 15% of total maize-growing areas are affected by floods and waterlogging problems, causing losses in maize production of 25–30% almost every year (Rathore et al. 1998). The normal inter-seasonal fluctuations in rainfall have been found to be associated

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closely with variations in average national maize yields across quite large production regions in the tropics (Rotter 1993; Edmeades et al. 1995), suggesting that water stress is the pervasive cause of yield instability in maize-based cropping systems in most years in the tropics. Since most modern, high-yielding cultivars are usually developed under favourable environments and optimal input conditions, it is not surprising to observe their poor performance under marginal and less favourable conditions. Although some spillover with selection for high-yield potential under optimal input conditions is realised under stress conditions, this holds good only under mild stress. Under severe stress conditions, germplasm with stress-adaptive genes is required (Blum 1996).

Maize is thought to be comparatively more susceptible to drought at the flowering stage because of its unusual floral structure, i.e. physical separation of male and female flowers by about 1 m, and non-synchronous development of florets on a single ear, borne on a single stem (Bolanos and Edmeades 1993). A reduction in the grain number per plant under drought occurs within the first two weeks after pollination (Grant et al. 1989). A characteristic of maize under drought and waterlogging (and most other abiotic stresses that reduce a plant's photosynthesis) is an increase in the anthesis–silking interval (ASI) and a concomitant increase in the number of barren plants (DuPlessis and Dijkhuis 1967; Bolanos and Edmeades 1993; Zaidi and Singh 2001; Zaidi et al. 2003a). Pollen shortage is rarely the reason for this type of barrenness under water stress (Westgate and Bassetti 1991; Zaidi et al. 2003a). A short ASI is considered to be an indication of the diversion of an increased fraction of the plant's current photosynthetic output to the ear, since it is associated with rapid ear growth (Zaidi et al. 2003c). When late-emerging silks on water-stressed plants are pollinated, fertilisation usually takes place, but grain development is arrested shortly afterwards (Bassetti and Westgate 1993), giving rise to patchy grain formation, unfilled ear tips or complete barrenness. Abortion of fertilised kernels shortly after pollination seems to be due to reduced flux of assimilates to the developing kernel (Schussler and Westgate 1995; Zinselmeier et al. 1995). The newly fertilised ovules have been found to be a weak sink with poor capacity to attract assimilate reserves from the stem and other plant parts. Drought at flowering also affects the carbohydrate metabolism of the developing ovule, further reducing sucrose flux to the newly formed seed (Schussler and Westgate 1995). A long ASI under drought or waterlogging conditions is, therefore, an indicator of reduced assimilate flux to the developing ovule.

In this paper, we use the results of four studies to review the current progress in developing water-stress tolerance in maize at the Center for Maize and Wheat Improvement (CIMMYT) in Mexico and at

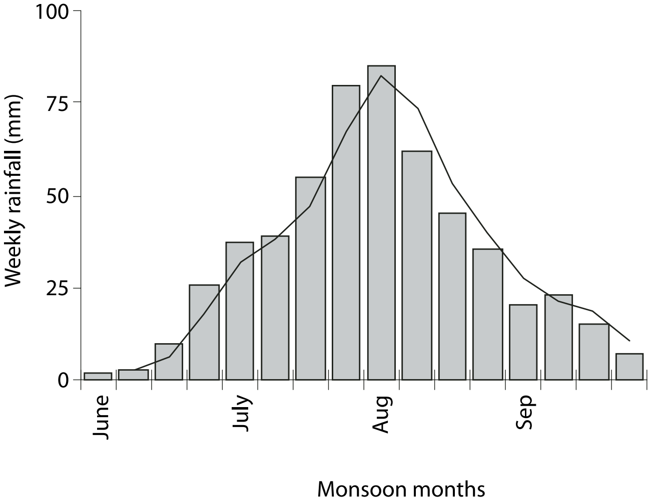

Figure 1. Rainfall (mm) distribution pattern during the *kharif* season in the northern states of India (1997–2001).

the Directorate for Maize Research (DMR), India, using yield and secondary traits associated with the stresses of the target domain. We also discuss the importance of improved maize germplasm in increasing maize productivity with stability across stressed and unstressed environments in Asia.

Study 1: gains from breeding for drought tolerance in CIMMYT germplasm

Drought tolerance was selected for using two maize populations, La Posta Sequia (LPS) and a drought tolerant population (DTP), with progress estimated after eight or nine selection cycles, respectively. A cycle of selection experiments was conducted during the rain-free winter season in 2002–2003 (November–April) at Tlaltizapan, Morelos, Mexico under two moisture regimes — well-watered (WW) and drought (DR). The materials consisted of 12 entries replicated three times. The 12 entries comprised four cycles of selection from LPS (C0, C3, C6, C8) and Population 43 C9 (a source LPS population which was not improved for drought tolerance), six cycles of selection from DTP (DTP-2 C0, C3, C5, C6 and DTP C9 W and DTP C9 Y) and Tuxpeno Sequia C8 (a drought-tolerant population). The plot size was four 5 m rows planted 0.75 m apart. Data were collected from the two middle rows to avoid any border effect. The same set of materials was also evaluated under low-nitrogen (low-N) conditions (data not reported in this paper). These base populations have been evaluated in previous years in the Asian region and have been found to be well adapted to the tropical environments of Asia.

Background of the materials

The LPS population was developed through S_1 selection as described by Edmeades et al. (1995). Within each selection cycle, 500–600 S_1 families were pre-screened under drought and heat conditions at Sonara Desert, Obregon, north-western Mexico. The superior 200–220 families thus identified were grown at CIMMYT's sub-tropical experimental station in Tlaltizapan, Morelos, Mexico (18°N, 940 m above sea level) during the winter cycle using remnant seed under three water regimes: well-watered (WW); intermediate stress (IS, water withdrawn during late flowering and throughout grain filling); and severe stress (SS, no water applied from three weeks before silking onwards). The best 50 S_1 families selected for performance under these treatments were recombined to form the subsequent cycle of selection.

The DTP population was constituted during the mid-1980s using 25 putative drought-tolerant sources, including CIMMYT's drought-tolerant population Tuxpeno Sequia C8, Latente, Michoacan 21, Suwan 1, crosses of CIMMYT populations 22, 32, 62, 64 and 66, landraces, corn-belt hybrids, and germplasm from Thailand, Brazil and South Africa. The sources were selected on the basis of their *per se* performance under water-deficit conditions and a wide array of drought-adaptive traits. The population was formed in 1986 and named DTP-1. In 1990, a second population was developed, including 58% of DTP-1 with the remaining introgression of new, drought-tolerant sources from lowland tropical (27%), subtropical (7%) and temperate germplasm (8%), and named DTP-2. During 1995, these two populations were separated on the basis of grain colour, and named DTP–white and DTP–yellow. The populations were improved for drought tolerance in Tlaltizapan, Morelos, Mexico using half-sib recurrent selection up to C4, followed by S_1 recurrent selection up to the recent cycle (C9).

Progress with recurrent selection for mid-season drought

Preliminary results from this trial evaluated in one season under two water-stress environments are presented below. Yield gains in the LPS and DTP populations averaged 218 and 239 kg/ha/cycle under drought, and 55 and 41 kg/ha/cycle under well-watered conditions, respectively (Table 1). The yield improvement under drought was associated with an increase in ears per plant and in harvest index, and with a decrease in the ASI. Gain per cycle for ears per plant was highly significant (0.42**) in DTP.

The Population 43 C9 was developed by conventional selection for yield in international progeny-evaluation trials grown mainly at well-watered sites. The nine cycles of selection did not increase drought tolerance and the Population 43 matured later by about 1 day/cycle. In previous studies involving cycles of selection from Population 43, gains for yield were observed only under well-watered conditions (Byrne et al. 1995). Principal component analysis of yields in 10 different environments showed that well-watered and drought environments were generally orthogonal (Chapman et al. 1997), indi-

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cating that selection under well-watered environments is unlikely to give improvements in yields under drought. They concluded from these and other analyses that selection for drought tolerance has improved broad adaptation, as well as specific adaptation to dry environments.

Study 2: performance of hybrids derived from drought-tolerant populations and from routine breeding in multiple environments

A set of top-cross hybrids was developed using lines derived from DTPs to examine their performance under drought-stress conditions across multiple environments. The top crosses were made by initially selecting the best hybrids involving S_2 lines from DTP-1 and DTP-2 populations that were grown under drought-stress and low-N conditions and a well-watered control. The parental lines (S_2) of these hybrids were advanced to S_3 and top-crossed with two tropical testers, one of white (CML 449) and the other of yellow (CML 451) grain type. A set of high-yielding normal (non-DTP) single-cross hybrids (hereafter referred to as NSC hybrids) that were not subjected to selection for drought was also included for comparison purposes in this study. The lines involved in the development of the NSC hybrids were from advanced generations of inbreeding (S_5–S_8) derived from CIMMYT's tropical maize populations improved for over 15 cycles for various agronomic traits, biotic stresses, combining ability; with major emphasis on yield under optimal input conditions.

Four trials were planted under three different stress levels: drought; low-N; and optimum conditions of moisture and fertility. The DTP–white hybrid trial comprised 80 S_3 × tester (DTW C9 S_3 × CML 449) progenies replicated two times and planted in one row plot of 5 m long, spaced 0.25 m between plants. The corresponding NCS–white hybrid trial had 49 single-cross hybrids, replicated twice with similar plot size. The DTP–yellow hybrid trial comprised 80 S_3 × tester (DTY C9 S_3 × CML 451) progenies replicated twice and the corresponding NSC–yellow hybrid trial comprised 36 single-cross hybrids. All the trials were grown during the 2001–2002 winter cycle in Tlaltizapan, Morelos, Mexico.

Table 1. Grain yield (t/ha) and other traits of various cycles of selection for drought-tolerance and the gains per cycle in the maize populations La Posta Sequia (LPS) and drought tolerant population-2 (DTP-2) when grown under well-watered (WW) and drought (DR) conditions at Tlaltizapan, Mexico (2002–2003).

Germplasm	Yield (t/ha)		Days to anthesis	ASI (days)	Ears per plant (EPP)	Harvest index (HI)
	DR	WW	DR	DR	DR	DR
LPS C0	1.87	8.24	84.3	6.40	0.77	0.10
LPS C3	2.43	8.26	83.4	4.40	0.85	0.18
LPS C6	2.55	8.39	82.2	3.90	0.92	0.17
LPS C8	2.62	8.42	82.9	3.30	0.99	0.19
Population 43 C9	1.74	8.00	86.1	7.00	0.79	0.09
DTP-2 C0	2.32	7.83	80.2	3.80	0.91	0.22
DTP-2 C3	2.36	7.88	80.1	3.33	0.92	0.23
DTP-2 C5	2.48	8.03	80.2	3.07	0.95	0.24
DTP-2 C6	2.43	7.90	81.2	2.82	0.97	0.22
DTP C9 W	2.62	8.34	81.6	2.73	1.01	0.24
DTP C9 Y	2.53	8.24	81.0	2.71	1.00	0.23
Tuxpeno Seq. C8	2.29	7.76	80.0	3.90	0.93	0.22
Gains/cycle						
LPS	0.218**	0.055^{ns}	–0.57**	–1.09**	0.10**	0.05**
DTP	0.239**	0.041**	–0.49**	–0.94**	0.42**	0.03**

Note: ** and * indicate that gains were significantly different at $P < 0.01$ and $P < 0.05$, respectively; ns = not statistically significant.

The yield performance of five best and five worst top crosses is shown in Figure 2 for DTP–white, DTP–yellow, NSC–white and NSC–yellow. The performance of the NSC hybrids was slightly better, but not statistically significantly so, than DTP top crosses under unstressed conditions. However, under drought-stress conditions, the average yield of DTP–white top crosses ranged from 1.5–4.3 t/ha compared with NSC–white hybrids with yields of 0.1–1.9 t/ha and with several hybrids barren under severe moisture stress during flowering. A similar trend was seen in the DTP–yellow top crosses. Similar, but less dramatic, advantages of DTP hybrids over NSC hybrids were exhibited under low-N stress as well (Figure 2). The NSC hybrids yielded only 3.3–4.8% under drought and 34.8–36.2% under low-N, compared with the normal unstressed conditions, while hybrid progenies of DTPs yielded up to 31.8–42.4% under drought and 48.9–63.6% under low-N (Figure 2).

Gains from selection for mid-season drought stress in DTPs were remarkable for drought (89.6%), and for low-N stress (39.3%). In an earlier report on this work, Zaidi et al. 2003b showed that the improved performance of the DTP hybrids across the environments was related to improvements in various secondary traits under stress conditions, such as reduced ASI, increased ears per plant, delayed senescence, and relatively high leaf chlorophyll during the late grain-filling stage. We also observed that the grain yield under drought and low-N stress was highly correlated when the germplasm was improved for mid-season drought tolerance. However, the relationship was not significant with germplasm improved for yield *per se* under optimal conditions. The data showed strong linear relationships between yield under drought and low-N in both DTP–white ($r^2 = 0.45^*$) and DTP–yellow ($r^2 = 0.42^*$). Correlations between yields of the two stress environments were also strong and significant for both

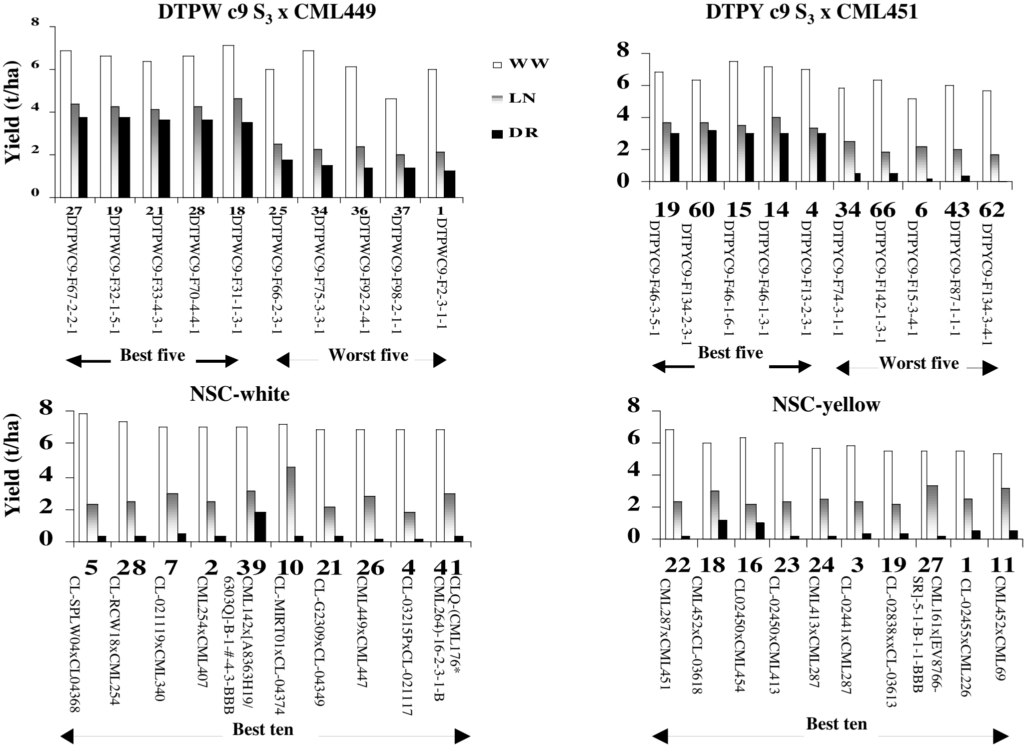

Figure 2. Performance of the best and worst five entries of drought-resistant population (DTP) white (W) and yellow (Y) top crosses, selected on the basis of performance across the environments using a multi-traits selection index, and the best 10 hybrids from each white and yellow group of normal single-cross (NSC) hybrids selected on the basis of performance multi-location evaluation under optimal conditions (WW = well-watered, LN = low nitrogen, DR = drought stress).

DTP–white ($r = 0.56^*$) and DTP–yellow ($r = 0.52^*$). However, with NSC hybrids, both linear regression and correlation between drought and low-N stress were not significant.

An additive main and multiplicative interaction (AMMI) analysis for the effect of genotype and genotype × environment interaction (GGE) highlights the importance of environment in discriminating between genotypes (Figure 3). In the case of DTP top crosses, drought was the best environment for discriminating between genotypes, followed by optimal conditions. However, with NSC hybrids, since most of the genotypes were highly susceptible to drought stress, drought showed very poor efficiency for genotype discrimination; rather, low-N stress was the most effective environment, followed by optimal conditions.

Study 3: performance of CIMMYT-derived drought-tolerant germplasm in Asia

CIMMYT's improved drought-tolerant germplasm has been evaluated in multi-location trials around the world and has been found to have excellent potential for yield under drought-stressed conditions (CIMMYT 2000). Thirty tropical, late-maturing cultivars, including hybrids of S_5 lines from LPS C3 and S_4 lines from Tuxpeno Sequia C6 crossed to two testers (CML 247 or CML 254), were evaluated in 13 locations in Africa, Asia and Latin America. The best hybrid combination, LPSC3-H297-2-1-1-2-1# × CML 254, yielded 4.9 t/ha across locations and had

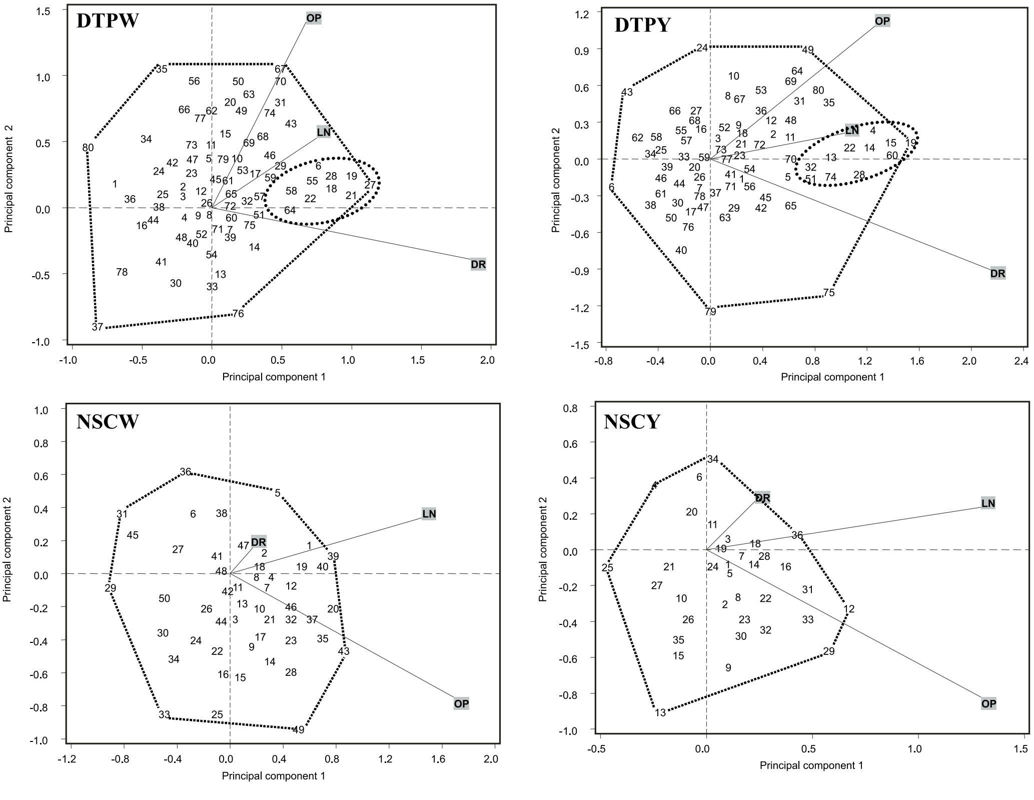

Figure 3. Biplots of effect of genotype and genotype × environment (GGE) of the first and second principal components for grain yield of (a) drought-tolerant population (DTP) white (W) C9 S_3 × CML 449, (b) DTP–yellow (Y) C9 S_3 × CML 451, (c) normal single-cross (NSC)–white (W), and (d) NSC–yellow (Y) hybrids. Encircled entries indicate the best genotypes across the environments. Lines drawn to environments (OP = optimal conditions, LN = low nitrogen, DR = drought stress) indicate the direction of increasing performance in that environment.

an ASI of 1.4 days. In Maros, Indonesia and Nakhon Sawan, Thailand, this hybrid yielded 4.9 t/ha and 6.8 t/ha, respectively, surpassing the local check by 22% and 28% (CIMMYT 2000). A synthetic derived from Tuxpeno Sequia is being released by the Indonesian national program as a drought-tolerant, open-pollinated variety in 2004. In a trial involving 25 early-maturing lowland tropical cultivars evaluated in 12 locations in Asia, Population 31 was found to be promising. Variety Dholi 9331 was the best entry, yielding 4.3 t/ha across all locations and 6.9 t/ha in Nakhon Sawan, Thailand. In Bontobili, Indonesia, variety CMU-Bukidnon 9331 top-yielded with 2.2 t/ha, 29% higher than the best check in an environment severely affected by drought stress. In another trial, 10 early- and extra-early-maturing maize varieties were tested in 12 environments. Pool 17E C6 and Pop. 101 Syn were the highest yielding entries (3.6 t/ha) across environments. In Maros, Indonesia, these two varieties yielded 6.0 and 5.7 t/ha, respectively, out-yielding the local check by more than 25% and earlier than the checks by 12 days to flowering. These results point to the utility of CIMMYT-derived drought-tolerant germplasm both under drought-stressed as well as normal conditions.

Study 4: breeding for excess-moisture (waterlogging) tolerance in maize — research at DMR, India

Research on screening for waterlogging tolerance in maize was launched during the mid-1990s under a collaborative program between the Indian Council of Agricultural Research (ICAR) and CIMMYT. Initially the work was undertaken by the All India Coordinated Project Center at Govind Ballabh (GB) Pant University, Pantnagar, and Uttar Pradesh, India. During 1998, this work was moved to DMR, New Delhi.

The objectives of the project were to:

- identify the crop stage most susceptible to excess moisture
- develop suitable screening techniques
- determine secondary traits associated with the stress tolerance
- generate tolerant sources of germplasm.

The progress and achievements of the project are presented below.

Identification of the crop stage most susceptible to excess-moisture stress

In order to identify the most susceptible growth stage(s), an experiment was conducted during the summer rainy season of 1999, and repeated again during 2000 at the maize research farm, DMR, New Delhi, India. Fifty-two tropical/sub-tropical advance-generation elite inbred lines were planted in flat fields with three replicates. A waterlogging treatment (described below) was applied for 10 days with a ponding depth of about 10.0 ± 0.5 cm at four different physiological stages: (a) V2 stage (early vegetative stage) at 10–19 days after sowing (DAS); (b) V7 stage (knee-high stage) at 30–39 DAS; (c) VT stage (tasseling stage) at 52–61 DAS; and (d) R1 stage (silk-emergence stage) at 62–71 DAS.

In an earlier report of this work, Zaidi et al. 2002 showed that the excess moisture caused severe plant mortality, stunted plant growth, reduced leaf-area growth, and reduced total biomass production at all the physiological stages studied. However, the effect was comparatively more pronounced at the V2 stage followed by V7 stage, although there was some variation in response among the genotypes. The largest numbers of genotypes were found to be susceptible at the V2 and V7 stages (Table 2). There were only two genotypes that were found to be tolerant to waterlogging during all the stages. The frequency distribution of the genotypes showed that 50 genotypes were susceptible at the V2 stage, followed by 48 at the V7 stage, 12 at the VT stage, and only 4 at the R1 stage (Table 2). The crop susceptibility index was highest at the V2 stage followed by the V7 stage (Figure 4). Susceptibility to excess-moisture stress declined with advancing crop growth stage, highlighting that younger maize plants are much more susceptible to waterlogging than older ones.

Developing a screening technique

Preliminary screening was done using the ‘cup method’ originally developed by Porto (1997), with certain modifications to make it suitable for large-scale screening under our conditions. The detailed methodology involved in the screening technique is described elsewhere (Zaidi et al. 2003a). In brief, the plant materials were grown in disposable plastic cups (250 cm^3) with four 5.0 mm diameter holes in the base. Cups were filled to 220 cm^3 with soil and placed in plastic trays (50 × 30 × 10 cm) containing water which was maintained at 5.0 cm throughout the experiment. Before sowing, the soil was fully saturated with water entering from the holes in the base of the cups through capillary action. After 24 h, one seed per cup was sown and seedlings grown for 20 days. After 20 days, all the successfully growing genotypes were transplanted to the field. The same set of materials was planted directly in the field during the next summer rainy season to evaluate the performance of genotypes observed during the cup screening. At 14 days after transplanting, i.e. at V6–V7 growth stage, a waterlogging treatment was applied in the field continuously for 10 days with a ponding depth of approximately 10.0 ± 0.5 cm. The ponding depth was maintained at the same level during the stress treatment by maintaining a continuous supply of water from one end of the plots, with an overflow arrangement for excess water (>10 cm depth) at the other end.

Table 2. Frequency distribution of tolerant and susceptible maize genotypes identified after waterlogging treatments were imposed at various developmental stages (Directorate for Maize Research, New Delhi, 1999 *kharif* season).

No. of genotypes	Developmental stage			
	V2 stage	V7 stage	VT stage	R1 stage
4	S	S	S	S
8	S	S	S	T
36	S	S	T	T
2	S	T	T	T
2	T	T	T	T
Total susceptible genotypes	50	48	12	4

Note: S = susceptible; T = tolerant; V2 stage = early vegetative stage, 10–19 days after sowing (DAS); V7 stage = knee-high stage, at 30–39 DAS; VT stage = tasseling stage, 52–61 DAS; R1 stage = silk-emergence stage, at 62–71 DAS.

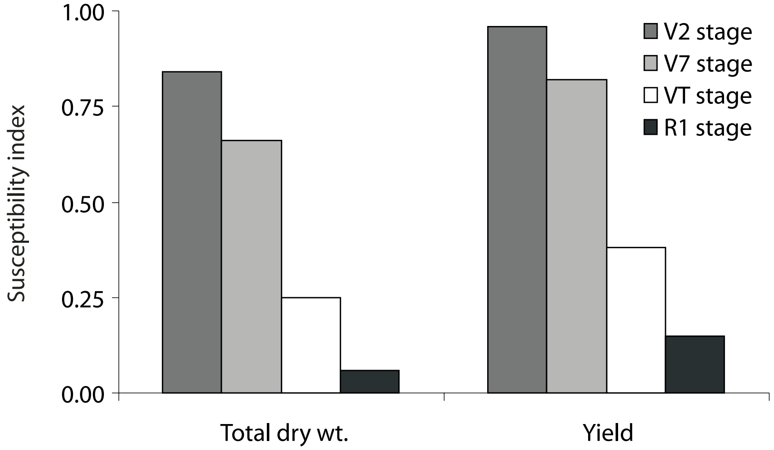

Figure 4. Crop susceptibility index for maize under conditions of excess soil moisture (V2 stage = early vegetative stage, 10–19 days after sowing (DAS); V7 stage = knee-high stage, 30–39 DAS; VT stage = tasseling stage, 52–51 DAS; R1 stage = silk-emergence stage, 62–71 DAS).

Identification of waterlogging-tolerant germplasm and important secondary traits

Some 324 tropical/sub-tropical lines (S_4–S_n) were screened using the screening technique described above during the main monsoon season in 2002. The entries involved in the experiments were obtained from the All India Coordinated Maize Improvement Project, New Delhi, India and CIMMYT. The entries were subjected to three moisture stresses: (a) normal moisture (NM); (b) direct planting and applying excess moisture at the V6–V7 stage (W); (c) excess moisture at germination and early growth in cups and transplanting the seedlings in field followed by excess moisture at the V6–V7 stage (WW). Eight traits were measured for all the treatments: plant mortality (%), leaf area, dry plant weight, total chlorophyll content, stem CHO, alcohol dehydrogenase (ADH) activity, ASI, and grain yield.

There were highly significant differences ($P < 0.01$) among the genotypes for all the traits except leaf area and total chlorophyll, which showed significant differences at 5% probability level (Table 3). There was also significant genotype × water treatment effects, indicating that genotypes differed in their response to the stress levels. Susceptible genotypes, identified during early-stage waterlogging, were again found to be susceptible to the stress at the V6–V7 growth stage, with severe plant mortality, and poor brace-root development, leaf-area growth and dry-matter production (Table 3). Pre-hypoxia/anoxia treatment during cup

Table 3. Means of the traits observed among 52 maize genotypes categorised into different response groups when grown under different moisture conditions at the Directorate for Maize Research, New Delhi, India during the 2002 *kharif* season.

Traits	Moisture condition	Category of genotypes [a]					LSD
		HTL	TL	MTL	SUS	HSUS	
Plant mortality (%)	NM	0.0	0.0	0.0	0.0	0.0	6.82*
	W	7.8	25.6	46.5	80.8	93.2	
	WW	5.9	23.7	40.2	76.9	–[b]	
Leaf area (dm^2/plant)	NM	286.3	301.2	282.1	292.2	287.2	21.3*
	W	210.3	198.3	142.3	122.2	80.2	
	WW	221.6	204.1	150.1	131.3	–	
Dry weight (DW) (g/plant)	NM	48.9	51.2	50.2	50.2	51.4	8.27**
	W	43.1	35.2	26.3	14.3	9.5	
	WW	44.2	37.1	28.2	17.5	–	
Total chlorophyll (mg/g)	NM	1.12	1.16	1.14	1.12	1.15	0.15*
	W	0.92	0.85	0.56	0.42	2.22	
	WW	0.98	0.88	0.65	0.42	–	
Stem CHO (mg/g DW)	NM	70.2	71.6	64.2	52.6	48.2	3.52**
	W	58.6	72.3	32.3	15.2	10.7	
	WW	61.2	48.5	36.8	21.3	–	
ADH-activity (units/mg protein)	NM	37.3	32.6	38.4	32.5	34.6	14.5**
	W	155.3	165.4	168.8	210.5	208.1	
	WW	145.6	156.2	170.2	200.3	–	
ASI (days)	NM	3.6	3.4	4.2	3.7	3.5	1.23**
	W	4.3	5.7	8.7	18.7	25.3	
	WW	4.1	4.6	7.3	15.4	–	
Grain yield (t/ha)	NM	2.86	2.91	2.79	2.12	2.39	0.23**
	W	1.63	1.03	0.89	0.42	0.16	
	WW	1.71	1.21	0.97	0.58	–	

[a] NM = normal moisture, W = direct planting, excess moisture at V6–V7 stage, WW = transplanting, excess moisture at germination and early growth stage and V6–V7 stage; HTL = highly tolerant, TL = tolerant, MTL = moderately tolerant, SUS = susceptible and HSUS = highly susceptible; LSD = least significant difference; ADH = alcohol dehydrogenase; ASI = anthesis–silking interval.

[b] No transplanting because of poor seedling survival at early stage screening.

Note: * and ** indicate significant differences due to growing conditions at $P < 0.05$ and $P < 0.01$, respectively.

screening may have caused favourable physiological/biochemical changes culminating in better performance under excess-moisture stress at later stages.

Wang et al. (1997) suggested that hypoxia pre-treatment might improve waterlogging tolerance through induction of active lactate fermentation. During conditions of excess soil moisture, the most common and immediate symptom was leaf yellowing that initiated from the base and proceeded towards the top of the plants. Qualification of this response in the present study showed that excess moisture inhibited chlorophyll 'a' and 'b' concentrations, both at the early stage and V6–V7 growth stage (Zaidi and Singh 2001). This also affected total carbohydrate content. Data indicate that tolerant genotypes were able to maintain a supply of current photosynthetic products in spite of excess-moisture stress. On the other hand, susceptible lines might have utilised all available CHO quickly through aerobic/anaerobic mechanisms; therefore, they may have faced starvation for CHO, and shown susceptibility. Reduction in CHO concentration under flooding might be related to leakage of the CHO from leaf tissues due to partial loss of membrane integrity (Yan et al. 1995), or increased consumption of stored CHO due to arrested photosynthetic activity (Lizaso and Ritchi 1997). The activity of nicotinamide adenine dinucleotide (NAD^+) – alcohol dehydrogenase (ADH) increased sharply in almost all the genotypes under stress conditions, especially susceptible ones (Figure 5). This might be one of the general responses to anoxia, and not related to stress tolerance.

Liu et al. (1991) suggested that increased alcohol fermentation was a temporary adaptation and a major cause of root injury during flooding, and flooding tolerance was related to low ethanol fermentation. However, in contrast to our findings, Sachs (1993) analysed excess-moisture tolerance in maize and found that increased ADH activity was apparent within 90 minutes and reached its highest level after approximately 5 h of the anoxia treatment, and concluded that variation in the stress tolerance was related to ADH activity.

The impact of the excess-moisture stress and pre-anoxia exposure was apparent in reproductive behaviour. Female flowering was comparatively more susceptible than male flowering. Delayed silking

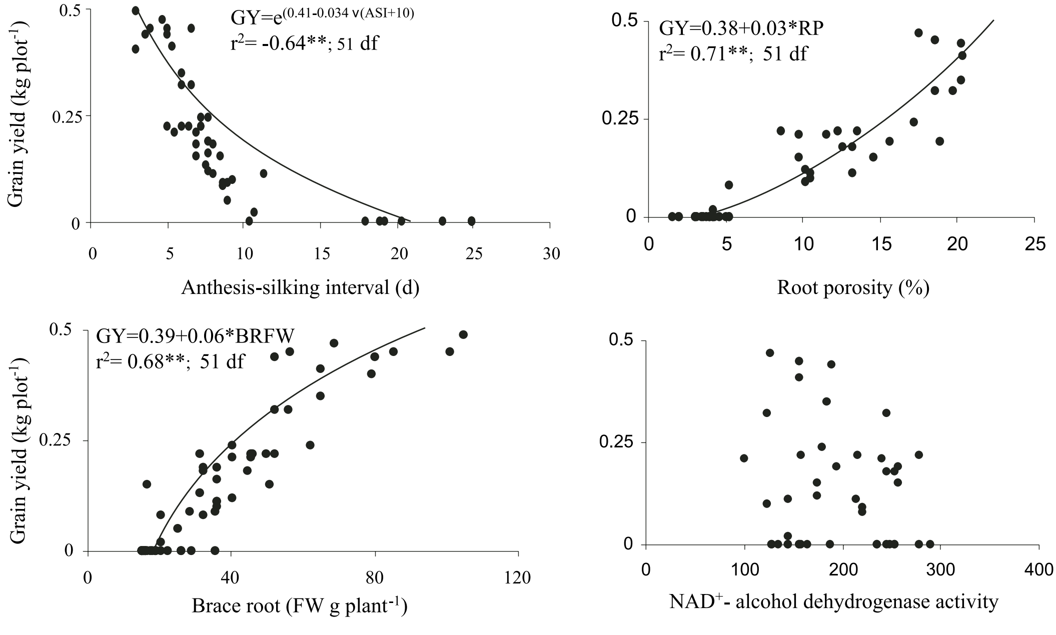

Figure 5. Grain yield as a function of mean anthesis–silking interval (ASI), root porosity, fresh weight of brace roots per plant, and nicotinamide adenine dinucleotide (NAD^+)–alcohol dehydrogenase activity in maize genotypes exposed to waterlogging stress under field conditions at the V6–V7 growth stage.

resulted in a long ASI and severe barrenness in susceptible genotypes (Table 3). However, in tolerant genotypes, ASI was maintained at around five days or less. The process of female flowering reflected in silk emergence was found to be largely dependent on the availability of current photosynthates under drought (Bolanos and Edmeades 1996). Reduced current photosynthesis in susceptible genotypes under excess-moisture stress (Huang et al. 1994) might have resulted in poor availability of assimilates for silk growth and cob development. In our study, ASI showed a strong relationship with grain yield (Figure 5), and this has also been reported for other abiotic stresses, such as drought (Agrama and Moussa 1996; Bolanos and Edmeades 1996), and high population density (Dow et al. 1984).

On the basis of data obtained during cup and field screening, genotypes were grouped into the following five categories using a multi-trait selection index (ALPHA): highly tolerant (HTL), tolerant (TL), moderately tolerant (MTL), susceptible (SUS) and highly susceptible (HSUS). Most of the genotypes were found to be susceptible and grouped under HSUS and SUS categories. However, seven entries, including four from CIMMYT lines and three from the national program, were identified as highly tolerant, and 12 as tolerant (Table 4). The identified promising waterlogging-tolerant lines were further improved and used in breeding for development of waterlogging-tolerant cultivars.

Based on this study, initial screening of large numbers of genotypes in the laboratory using the cup method and later transplanting the tolerant ones to field conditions and applying additional excess-moisture stress at the V6–V7 stage is highly efficient in identifying tolerant genotypes.

Conclusion

Our findings suggest that selection for mid-season drought tolerance resulted in morpho-physiological changes that proved to be advantageous not only under drought but also under low-N stress, without any yield penalties under optimal input conditions. Data indicate that selection and improvement for yield under optimal conditions may be a suitable approach for favourable environments, but not for marginal areas where the abiotic constraints such as drought and low-N are prevalent. Castleberry et al. (1984) examined corn-belt hybrids developed under optimal input conditions from a period of more than 50 years and found very low selection gains under low soil fertility. Similarly, Martinez-Barajas et al. (1992) reported that progress from selection for high yield under well-watered conditions was greatly reduced under water-deficit conditions. These results suggest that spillover effects from selection under optimal conditions to stress conditions may be limited. Duvick (1995) proposed that the major goal of tropical maize improvement programs should be to improve and stabilise yield, and broaden adaptation through increased tolerance to various stresses. However, wide adaptation and stability defined in terms of performance of germplasm in multi-location testing largely under optimal input conditions needs to be more broadly defined by including performance under low input and less favourable conditions as well. While it is possible to have stable but low yield

Table 4. List of tolerant maize genotypes when grown under waterlogging stress at the early seedling and at the knee-high (V6–V7) stage of growth.

Categories	No. of genotypes	Genotype
1. Highly tolerant (HTL)	7	CML 425, CML 226, CML 311, CML 327, CM-105, CM-118, Jaunpur local-5
2. Tolerant (TL)	12	CML 228, CML 338, CM-117, P501c1##-293-2-2-2-1-4-3-B*7, CM-133, CM-300, CM-400, CM-500, CM-501, CM-600, CM-601, PIO-301 1F2-3-5-3-B*6
3. Moderately tolerant (MTL)	35	
4. Susceptible (SUS)	87	
5. Highly susceptible (HSUS)	183	
Total	324	

under drought-prone and low-fertility-prone areas by selecting for early maturity (Edmeades et al. 1995), selection and improvement of germplasm under mid-season drought, and low-N, may prove to be a better approach to achieving stable and improved yield under marginal and less-favourable environments in tropics. Although gains in selection may be comparatively less and progress slow, they may lead to more stable production across a range of environments. Promising germplasm with high levels of drought tolerance that is adapted to Asian conditions has been identified. Improvement for mid-season drought tolerance has significant spillover effect towards low-N tolerance, but not vice versa.

For waterlogging-stress tolerance, our findings suggest that the stress is highly detrimental to maize before tasseling. However, there is considerable genotypic variability in maize, both at the seed germination and early seedling stage, and also at the V6–V7 growth stage. Early and increased adventitious rooting, enhanced root porosity and reduced ASI (<5 days), along with grain yield, can be used in a selection index for identification of waterlogging/excess-moisture tolerant maize genotypes.

Our results suggest that substantial genetic gains have been made for drought tolerance in maize. With a concerted effort, similar progress can be made for excess-moisture tolerance as well.

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