Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico

Proceedings of a workshop held in Griffith, NSW, Australia, 1–3 March 2005

Editors: C.H. Roth, R.A. Fischer and C.A. Meisner

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Foreword

In recent years permanent raised bed cropping systems have been adopted in a wide range of irrigated and dryland farming systems. Early work on permanent raised beds began in Mexico, initiated by CIMMYT. Subsequently, research has been carried out by international centres such as CIMMYT and IRRI in collaboration with national research institutions in Mexico, Central Asia, South Asia, China, Indonesia and the Philippines. While most of this work has been on irrigated permanent raised beds in irrigated conditions, research on raised bed systems in Australia has been directed towards dryland systems.

ACIAR has supported research into permanent raised bed systems suited for a range of cropping situations across Asia and Australia. At the same time, other funding bodies in Australia have also been supporting research into various forms of raised bed technology.

In an attempt to bring the learnings from all these initiatives together ACIAR organised a workshop in March 2005. The workshop, which was co-sponsored by CSIRO Land and Water in Griffith, NSW DPRI, the Cooperative Research Centre for Irrigation Futures, the Cooperative Research Centre for Sustainable Rice Production and the Grains Research and Development Corporation, provided an opportunity to take stock of what has been achieved to date, what has been learnt from the work originating from the various projects, to discuss some of the unresolved problems and, most importantly, the best strategies to achieve the highest possible level of adoption.

The papers contained in this proceedings bring together the work that was presented at the Griffith workshop and provide a valuable resource for researchers and practitioners of permanent raised bed cropping systems.

Peter Core.

Peter Core
Director
Australian Centre for International Agricultural Research

The effect of raised bed planting on irrigated wheat yield as influenced by variety and row spacing

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Abstract

Experiments were conducted under full irrigation and high fertility in northwestern Mexico during the period 1988 to 2005 to study the response of a range of current cultivars of bread and durum wheat and of triticale to raised bed planting. Results suggested that in this environment the main consideration was the ability of the cultivar to capture the solar radiation falling in the gap between the beds, and that the common gap of 44 cm could be compensated for in most cultivars, but not all. Those losing 10% of yield with such a gap tended to be short cultivars, as in two-gene dwarf bread wheat varieties. There was good evidence that varieties and advanced lines released after the late 1980s showed no yield loss with such a gap, and some could tolerate an even larger gap (up to 55 cm). The results, which, it is stressed, apply to favourable low-latitude wheat growing conditions like those of northwestern Mexico, are discussed in depth.

Introduction

Farmers in the Yaqui Valley of northwestern Mexico (lat 27°N) plant approximately 150,000 ha of spring-type wheat each winter–spring growing season (November to April). Seasonal rainfall is low and all wheat is irrigated; mean temperatures are mild in the winter, rising to warm to hot in the spring. Wheat under these conditions is representative of much of the 40 million ha of irrigated wheat grown in the developing world. This fact has helped CIMMYT, which has worked in the Yaqui Valley since its inception, to develop wheat varieties and technologies suited to many developing countries.

Traditionally, wheat in the Yaqui Valley was planted in flat basins (called *melgas* in Spanish) which were flooded for irrigation. During the 1970s the technique of planting on narrow raised beds *(camas)*, with irrigation water confined to furrows between the beds, was imported into the valley, probably from Arizona. Data from regular surveys of the Yaqui Valley run by CIMMYT's Economics program shows that by 1991 some 65% of the valley's wheat was planted on narrow beds (60–80 cm furrow to furrow), and by 2001 this figure had reached 84%. The system of planting on raised beds is favoured by farmers for many reasons, as discussed by Sayre et al in this volume.

A feature of the bed planting system which initially always arouses concern from farmers and researchers alike is the apparent waste of resources represented by the unplanted space, known here as the gap, between the beds. The gap comprises the unplanted shoulder of a bed, the furrow itself and the shoulder of the adjacent bed. Depending on tractor wheel widths and bed planter configurations, the gap can be between 40 and 60 cm wide, ie from the last row of plants on one bed to the first row on the adjacent bed (dimension 'b' in Figure 1), and cumulatively can appear to occupy half of the land area. In some instances farmers' perceptions about yield loss due to such wide gaps are a key impediment to the uptake of raised bed technology. In other cases farmers even plant wheat in the furrows (33% of those using beds, according to the Yaqui Valley survey of 2001), but to little apparent advantage as judged by the limited growth and tillering of the furrow plants. The wheat plants in the outside rows on the beds normally tiller well and appear to spread into the gap.

CIMMYT itself moved in the late 1980s to plant increasing amounts of its breeding and agronomic experiments on beds. It was therefore deemed

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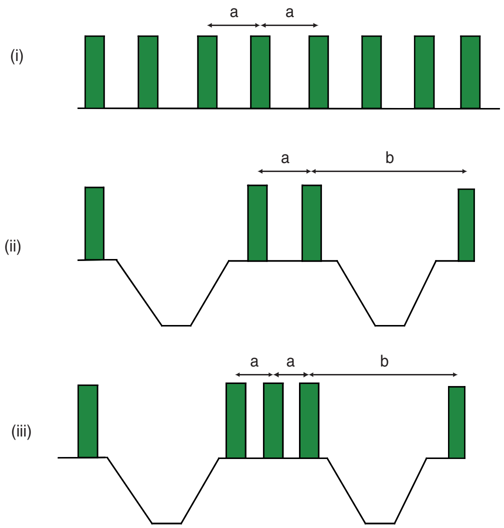

Figure 1. Diagram showing the key dimensions for plantings: (i) flat planting row spacing of a cm; designated 'a, a'; (ii) bed planting with two rows on bed spaced a cm apart, furrow gap b cm; designated 'a, b' (iii) bed planting with three rows on beds spaced a cm apart, furrow gap b cm; designated 'a, a, b'.

important to understand the effect of the gap, and the related questions of bed size and rows per bed, on performance. It was also necessary to know whether certain varieties, in particular short, erect, early and/or low tillering ones, suffered in beds due to a lower ability to compensate for the gap. Prior to this there had been some experiments in the region suggesting that this was the case (O.T. Moreno Ramos, unpublished). Results of probably the first experiment in the valley (1970–71) showed no effect of bed planting (20,55 – see 'Methods' section below) on yield in trials of the bread wheat variety Nuri 70 and the triticale variety Armadillo, but a 9% yield loss with the short bread wheat variety Yecora 70 (T. Fischer, unpublished). New experiments in the Yaqui Valley relating to the issue of bed by variety interactions were carried out over the period 1988–2005, but particularly between 1989 and 1994, and the hitherto unpublished data are summarised in this paper. Varieties of bread wheat (*Triticum aestivum* L.) were the main target of the work but some experiments compared varieties of durum wheat (*Triticum turgidum* L.) and triticale (*X Tritosecale* Wittmack).

Putting aside for the moment the possible effects of raised beds on irrigation water reaching the base of the wheat plants (eg less temporary anoxia during irrigation, lower bulk density in fresh beds due to less slumping), the wheat planting configuration on beds is essentially a problem of row spacing. There is a large literature on this, much summarised in Fischer et al (1976). Under the favourable growing conditions of the Yaqui Valley, grain yields of semi-dwarf wheat varieties of the 1960s and early 1970s were unaffected by row spacings between 10 and 45 cm, or by seeding densities between 40 and 100 kg/ha (plant densities of 80–200/m^2). Interactions with variety were slight, except where differential lodging arose. Subsequently, these results were confirmed in many experiments in the region by O.H. Ramos Moreno; indeed, this body of work suggested that yield was generally unaffected by row spacings as wide as 60 cm, or densities as low as 10 kg/ha seed or 15 plants/m^2 (see also Moreno Ramos et al 1993; Moreno Ramos et al 2004). It was hypothesised in Fischer et al (1976) that the ability of wheat to give full yield from densities as low as 40 plants/m^2 and spacings as wide as 45 cm can be related to vigorous early crop growth. If this growth is sufficient to build a green canopy which can achieve full light interception (generally defined as >95% of incident photosynthetically active radiation) before the onset of accumulation of dry matter in the growing spikes some 30 days before anthesis (ie maximizing crop growth rate), then spike weight at anthesis, grains/m^2 and yield are maximised (Fischer 1985). Nothing has appeared in the published literature on management of irrigated low-latitude wheat since this report to challenge these physiological conclusions, which unfortunately did not extend to row spacings wider than 45 cm.

Methods

All experiments were conducted at the CIANO experiment station near Ciudad Obregon, Sonora, Mexico (lat 27°33´ N, long 109°09´ W and 38 m above sea level). The soil type was a coarse, sandy clay (mixed montmorillonitic Typic Calciorthid). The climate in the wheat growing season (December to April) can be described as very favourable, being mild (January mean 15°C) grading to hot (April mean 21°C), with little rainfall (44 mm) and abundant clear skies (see Fischer et al (1976) for more deta ils).

Experimental details are similar to those described in Tripathi et al (2005). Most experiments followed summer leguminous green manure, after which the soil was prepared for wheat by cultivation to about 20 cm depth and incorporation of broadcast fertiliser (around 100 kg/ha N as urea and 20 kg/ha P as triple superphosphate). Where there were beds, they were made just ahead of seeding with a bed former (= fresh beds) to give a flat topped bed with a bed height of around 20 cm and furrow width (bed edge to bed edge) of around 40 cm, so as to fit the narrow tyres of the tractor used. Usually two or three rows of wheat were planted by drill on the top of each bed (Figure 1). Thus, a 15,15,50 (a,a,b) system refers to 3 rows per bed, 15 cm apart on the bed, separated by a 50-cm gap across the furrow to give an 80-cm-wide bed/furrow system, which is called an 80 cm bed for convenience. Control plantings on the flat were all conducted at 20 cm row spacings (20,20 system). Bed plots (or subplots if genotypes were being compared, as was usually the case) comprised two or three adjacent beds, while flat plots (subplots) were usually 8 rows wide. Some experiments looked at 'simulated' beds, referring to wheat planted on the flat but having the row configuration and seeding density of bed plantings in order to test only the effect of row configuration. All plots were oriented north–south unless otherwise stated. Seeding density was around 100 kg/ha for beds and 150 kg/ha for flats, aiming to give around 50 plants/m along each row, except where this was varied experimentally.

Crops were usually sown dry and irrigated in late November or early December, the optimal date for planting. Subsequent irrigations followed when available water in the top 60 cm fell to 50% as determined using gravimetric sampling, and were given to beds and flats on the same date. Water was supplied to the plots long enough to refill the profile (around 3 hours), after which excess water was drained off; the raised beds were never 'over topped ' by irrigation water. A few experiments were run with reduced irrigation, and one with no weed control, as weeds were normally fully controlled by management and herbicides. Generally, diseases were at such low levels as to not need control. However, in experiments with historic varieties fungicide treatments were applied so that rust susceptibility did not complicate variety comparisons. Wheat crops usually received another 200 kg/ha N, topdressed as urea at the first node stage, immediately followed by irrigation. As a result, soil fertility levels were very high but probably no higher than in farmers' fields, where the average N application rate is 275 kg/ha (Flores & Aquino 2001).

Plant populations were counted soon after seedling emergence and are reported where relevant in the 'Results and discussion' section below. Sometimes crop growth (above-ground dry matter in g/m^2) was measured by cutting small areas of crop, and at maturity grain yield was determined by cutting several square meters per plot. All cuts avoided border rows and took special care to sample each row with equal intensity. A random subsample of around 100 spike-bearing shoots was taken from the maturity cut for the determination of harvest index and yield per spike. The remainder was threshed for grain yield, from which spike number and total dry weight (biomass) were calculated. The weight of 100 grains was determined on two subsamples, and kernel weight was used to calculate grains/m^2.

In some experiments photosynthetically active radiation (PAR) interception was measured with a linear PAR sensor randomly placed beneath the canopy. At least three random locations per plot were sampled, always across the exact full bed width in order to properly sample the gap as well as the planted area. Sometimes leaf chlorophyll measurements were taken with a Minolta SPAD meter. Anthesis and maturity dates were observed, and lodging noted (score = % plot lodged divided by angle of lodging to vertical/90). Sometimes lodging (inevitably post-anthesis) was so variable as to defy interpretation of the experimental yields, and such experiments were excluded. Experiments were laid out as randomised complete block (RCB) or split plot experiments with 2–4 replications. Spatial variability was very low under the soil and crop management techniques adopted (CV for yield usually <5%), so that simple RCB or split plot analyses of experimental variables were deemed adequate to test treatment effects and interactions. Often, mean results (as a percentage of check) of many experiments across years were considered; if the year interaction appeared small, a simple standard deviation of the mean was calculated for comparison purposes.

Results and discussion

Density, row spacing and row orientation effects on the flat

Results are shown in Figure 2 from a series of experiments in which crops were hand sown on the flat and thinned to give the rectangular grid point spacings between plants and the plant densities as shown. Maximum yields (and grains/m^2) were achieved at low densities (around 30 plants/m^2), but note that even with the grid planting at 32 plants/m^2 the largest distance or gap between plants was only 25 cm. Lower yields at the highest density appear to have been associated with post-anthesis lodging and lower kernel weights.

The performance of the very low plant density crops matches the results of Moreno Ramos et al (1993) and Moreno Ramos et al (2004) and is much better than results in Fischer et al (1976), where densities of over 100 plants/m^2 were needed for maximum yield. This difference is probably explained by the fact that Fischer et al (1976) used 20-cm rows and random within-row plant spacing, as is normal with drill sowing, whereas in the study reported in Figure 2 and in Moreno Ramos et al (2004) plants were arranged on square or close-to-square grids. PAR interception measurements in 1991–92 showed that >95% interception was reached at

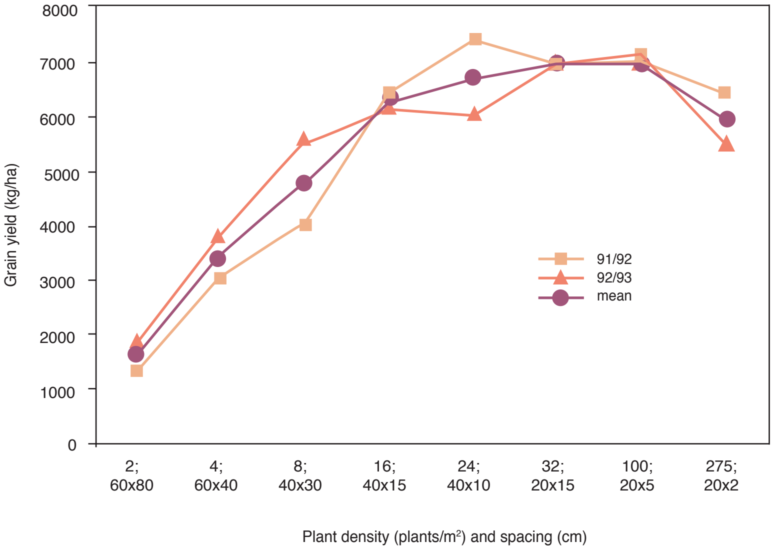

Figure 2. Grain yield response to plant density and spacing for 2 years (mean of bread wheat varieties Oasis 86 and Rayon 89) sown on the flat.

about 55 days after emergence with 250 plants/m^2, but it took another 30 days to reach this amount of cover with 24 plants/m^2; anthesis was at 78 days with the higher density and only a day later at the lower density. This appears to contradict the hypothesis regarding full PAR interception (>95%) before 30 days pre-anthesis for full yield enunciated above (see 'Introduction' section), because the thin crops appeared to lose significant amounts of radiation in the critical period yet they did not lose yield. There is no obvious explanation for this, but the thinner crops possibly had higher radiation use efficiencies (RUE). This would be consistent with higher leaf N contents because SPAD meter readings (at 68 days after emergence) declined from 51 units (2 plants/m^2) to 43 (250/m^2); RUE increases with percentage of leaf N (Fischer 1993).

The performance of these wheat crops planted with regular spacing at very low densities appears to mimic that of rice grown under SRI (Sisteme Riziculture Intensive), and is a reminder of the remarkable ability of cereals to compensate for low density via tillering, provided there is no weed competition and

Table 1. Effect of row spacing and configuration on grain yield of bread wheat varieties planted on the flat.

	Grain yield (% of control, 20,20 and kg/ha)				
Year	90–91	91–92	91–92	92–93	Mean
Cultivars	4	4	1	4	
Row arrangement (cm)					
20,20	100 (7169)	100 (5970)	100 (6260)	100 (6686)	100
40,40	85	100		97	94
50,50			87	95	91
60,60	67	93		85	82
80,80	61	84		75	73
20,60	76	97	90	91	89
20,80	72	90		82	83
Spacing × cv interaction[a]	*	*	na	*	

[a] * = significant at P<0.05.

Table 2. The effect of simulated beds on grain yield of bread wheat.

Year	1989–90		1990–91		1988–94	1992–95[a]
Cultivars	12		8		Many	Many
	Yield (kg/ha)	% control	Yield (kg/ha)	% control	% control	% control
Planting system:						
20,20 flat	7607	100.0	7240	100.0	100.0	100.0
20,55 flat	7211	98.0	6549	90.0	89.1	90.5
20,55 raised bed	7057	95.0	6461	89.0	90.9	95.3
LSD ($P<0.05$)	345 **		326 **		4.6 ns	4.7 ns
System × cultivar	ns		ns		na	na

[a] The bed configuration in these experiments was three rows per bed: 18,18,54.

soil fertility is favourable. The wheat crops with 2–4 plants/m^2 had more than 50 spikes per plant, and at 30 plants/m^2 there were 15 spikes per plant.

Table 1 summarises 4 years of experiments in which wide row spacings are compared with standard 20-cm spacing. Since these experiments were all drill sown, the within-row spacing of plants was random. On average, there were clear yield depressions for row spacings equal to or greater than 50 cm, and in one year (1990–91) there was a substantial depression at 40 cm spacing. The last two rows of the table refer to simulated bed configurations (20,60 and 20,80): compared to a 20,20 configuration the yield depressions are at least as great as would be predicted by the uniformly spaced 60,60 and 80,80 arrangements. It is not clear why yield depressions varied between years. The genotype by spacing interaction was significant each year and relates particularly to the contrasting varieties Oasis 86 and Rayon 89 (to be discussed later).

The effects of row spacing on wheat yield as reported in the literature, even when restricted to those from low-latitude irrigated conditions, are quite variable. South Asian papers, when the experimental conditions are properly described, often show no effect on yield with modern cultivars up to at least 45 cm spacing (eg Jat & Singhi 2003; Sheikh et al 1985); and those which show yield declines may have suffered late sowing or poor fertility. Under irrigation at Griffith, Stapper and Fischer (1990) showed a significant yield loss (10%) at 45 cm relative to 30 cm spacing. In summary, the common gap in bed plantings (around 50 cm) appears to be at the limit of being so large that yield may be reduced due to the loss of interception of available light, other factors remaining equal.

Row orientation was tested across two cultivars in plantings on the flat in 1989–90 and 1990–91, both in 20,20 and 20,55 arrangements, but there were clearly no differences in grain yield. At the latitude of CIANO (27°N), solar elevation is low during most of the wheat season and after 50 or so days following emergence little direct sunlight is intercepted. However, there is usually a brief period (a few minutes) around solar noon when sunshine reaches the ground in the furrow with wide north–south rows.

Raised beds compared to simulated beds

Two experiments conducted in 1989–90 and 1990–91 compared beds and simulated beds (Table 2). Although both bed row configurations reduced yield, there was clearly no difference in yield between the simulated bed (on the flat) and the actual raised beds. This result is reinforced in the final two columns of the table, which summarise a number of experiments across several common years. Adjacent experiments used simulated beds and actual beds of the same dimensions growing similar bread wheat cultivars. Raised beds are known to reduce the incidence of lodging (Tripathi et al 2005), but there were no lodging differences in these experiments. The results suggest that comparison of wheat on beds and on the flat under the soil and irrigation conditions at CIANO is a comparison of the effects of spatial arrangement. Thus, the raised beds appeared to offer no advantage in terms of, for example, reduced anoxia associated with the irrigation event due to non-flooding of the plant bases.

Effect of raised bed planting on yield

As shown in Table 2, there are small yield losses with some raised bed planting configurations, namely the 2-row 20,55 and 3-row 18,18,54 beds. A balanced comparison of these two bed types is shown in the top rows of Table 3, where the 18,18,54 arrangement is seen to be slightly superior. This may relate to the

Table 3. The effect of raised bed configuration on grain yield of bread wheat.

Years	No. expt.s	No. cvs	Mean control yield (kg/ha)	Bed configuration	Grain yield as % of 20,20 flat control planting	
					Expt mean	Mean of six common vars
91–92 to 93–94	6	1–16	7057	20,55	89.8	
				18,18,54	93.8	
94–95 to 95–96	2	8,48	6764	18,18,54	94.5	
				18,1 8,44	93.0	
96–97	2	14,23	8406	18,18,44	95.0	91.5
97–98	2	14,14	8925	18,18,44	95.5	93.4
98–99	2	16,16	9357	18,18,44	100.2	103.0
99–00	1	16	8436	18,18,44	98.6	96.5
00–01	1	16	9439	18,18,44	101.2	103.5
01–02	1	16	7867	18,18,44	101.5	103.0
03–04[a]	1	32	5836	18,18,44	108.8	103.0
04–05	1	32	7067	18,18,44	99.8	94.2

[a] There were no experiments in 02–03.

effect of competition from the extra central row stimulating the outer rows to spread more into the gap (see later discussion). This idea was not, however, supported by a 1992–93 experiment involving two bread wheats in simulated beds. When comparing a 30,50 configuration with a 15,15,50, and a 40,50 configuration with a 20,20,50, the 2-row systems had the same relative yield as the 3-row ones (91.0% vs 91.5%). Nevertheless, the notion of stimulated spreading into the gap by a third row was supported in one experiment in 1993–94 in which the mechanically difficult 10,10,55 configuration was tried: across 16 bread wheats it yielded significantly better than the 20,55 one, namely 97.5% vs 91.3%.

PAR interception data is available for a 1991–92 experiment with 20,50 beds (simulated in this case) compared to flat planting. Data was averaged over two common bread wheat cultivars (Opata 85 and Bacanora 88), for which grain yield was depressed 12% in the simulated beds. The 20,20 crops reached 95% interception at around 30 days before anthesis (Figure 3) while the 20,50 ones did not reach this level of cover until almost anthesis, although for the last 20 days only a few percentage points separated the planting methods. Averaged over the 30 days, the 20,20 crops had a mean interception of 97.1% compared to 90.6% for those in simulated beds. The relative difference was approximately equal to that in grain yield, supporting the idea that lost PAR was the reason for the yield loss in beds under these experimental conditions (in contrast with the earlier-mentioned PAR results from differing plant densities).

In 1994–95 a potentially more efficient 3-row bed configuration, namely 18,18,44, was introduced. Although it had a smaller gap, yield results over 2 years of comparison with 18,18,54 beds were no better (Table 3). However, research continued with this more convenient configuration and after 1997–98 (Table 3) yields from 18,18,44 beds, relative to the 20,20 control, rose to close to 100% (with an unusual 109% in 2003–04 for which there is no explanation).

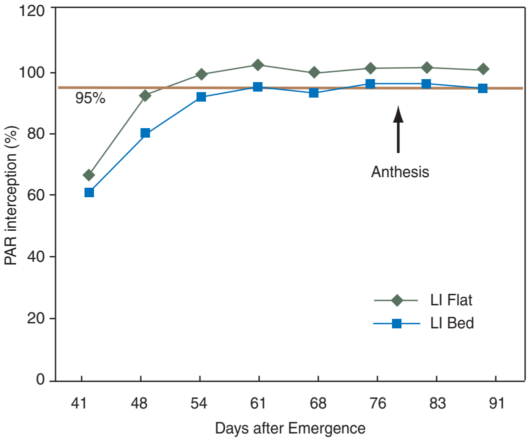

Figure 3. Percentage of intercepted photosynthetically active radiation (PAR) (LI) against days after crop emergence for flat (20,20) and bed (20,55) planting in 1991–92; average of Opata 85 and Bacanora 88 cultivars.

From 1996–97 onwards the comparisons in Table 3 were between a control treatment which had effective lodging protection (nets) and beds without protection; if anything this should have favoured the control and reduced relative yields on beds (but lodging in the beds was slight). These experiments with 16 cultivars comprised 6 recurrent checks (released varieties) and 10 promising lines from the breeders. The final column in Table 3 shows the mean relative yield of the recurrent checks, which indicates a similar year-to-year variation as did the experiment means. Importantly, they also show a tendency to increase yield over the years (except for 2004–05), suggesting that bed agronomy has somehow improved with time. Data from parallel durum wheat experiments show a similar increase with time in the relative yield of the five recurrent checks used. But it must also be considered likely that experiment mean relative yields were rising because the advanced lines included were steadily becoming better adapted to beds (see later discussion).

With respect to the key components of grain yield (Table 4), in a 1989–90 experiment which showed a significant effect of beds on grain yield (reduction of 7.2%), there was significantly less biomass and fewer grains/m^2 with the beds. There were also fewer spikes/m^2, and this was only partly compensated for by more grains per spike. In 1998–99 there was no effect of beds on yield and no effect on yield components (Table 4, second column), except again there were lower spikes/m^2 and higher grains per spike. The final column summarises responses for the bread wheat variety Oasis, which lost on average 12% of yield on beds. Again, biomass and grains/m^2 explained the yield loss, and spike number and size responded as before. The pattern was consistent throughout: biomass and spikes/m^2 were reduced in beds where there was yield loss, while harvest index and kernel weight generally were unaffected by planting method. This suggests that beds reduce pre-anthesis crop growth enough to reduce yield in some instances.

There are few published data on bed performance in countries with irrigated wheat under conditions similar to northwestern Mexico. The greatest amount of unpublished work is from northwestern India, where a 20,47 bed system is most common, fitting the 134-cm wheelbase of the local tractors. Generally, yields were somewhat lower than those reported in this paper, and were similar or slightly higher in beds compared to conventional flat plantings (K.D. Sayre & R.K. Gupta, pers comm); other examples are quoted later in this volume. The difference between the Indian experience and the early results with beds in northwestern Mexico is probably explained by the different varieties involved (see below).

Effect of species and cultivar on relative yield with raised beds

In Table 3 in most years the cultivar by planting method interaction was significant at the 5% level. However, it is also useful to look at species effects on the response of grain yield to raised bed planting. Over the period 1988–89 to 2004–05 there were 9 years when balanced comparisons between beds and the flat were possible. The results were as follows:

- bread wheats: mean relative yield 97.1%, range 88–102%, SE mean 1.5%
- durum wheats: mean relative yield 96.3%, range 88–102%, SE mean 1.5%
- triticales: mean relative yield 97.4%, range 87–103%, SE mean 2.1%.

Obviously the main effect of species was not significant. The interaction of this effect with year was not tested but appeared to be small.

Despite the triticales appearing to be generally taller and more spreading, and the durums more erect, than bread wheats, the absence of a species effect is puzzling in view of the cultivar by planting method

Table 4. Bread wheat grain yield and key yield components in raised beds expressed as a percentage of the corresponding values in flat planting.

	Source of comparison[a]		
Variable	89–90	98–99	5 years
No. cultivars	12	16	Oasis 86
Grain yield	92.8*	100.9	88.0**
Biomass	92.6*	98.7	85.6**
Harvest index	98.9	101.8	103.0
Spikes/m^2	86.0**	91.0**	69.0**
Kernels/spike	104.7	110.3*	133.2*
Kernels/m^2	90.5**	100.6	89.4*
Kernel weight	102.1	100.6	98.7

[a] Different from 100.0 at P<0.05 (*) or P<0.01 (**)

interactions within bread wheats (and durums and triticales as well). In general, the cultivar interactions seemed related to a few cultivars not performing well in beds.

In ten experiments over 9 years the most contrasting varieties, Oasis 86 and Baviacora 92, were both included. Oasis 96 is short (76 cm) although heavy-tillering and somewhat spreading, while Baviacora 92 is tall (107 cm), low-tillering and non-erect; both have a similar time to anthesis (around 85–90 days after emergence). The yields in beds relative to the flat control averaged 91.0% and 104.0%, respectively, and were highly significantly different. Eight experiments over 6 years compared Oasis 86 to Rayon 89, also taller (98 cm) and more spreading than Oasis; the relative yields were 85.8% and 96.4%, respectively, again being significantly different. The equally short and somewhat earlier sister variety of Oasis 86, namely Yecora 70, also had a low relative yield in beds (91% in 1970–71, 85% across 1990–95). Two contrasting durum varieties, Altar 84 and Aconchi 89, were grown together in seven experiments over 7 years. Altar is slightly taller (91 cm) and semi-erect, Aconchi is shorter (86 cm) and extremely erect; the average relative yields were 101.5% and 94.7%, respectively, and were significantly different. Another durum variety which generally did less well in beds was the early variety, Mexicali 75; across 8 years it averaged 94.9% compared to 101.2% for Altar 84.

These examples show that even in the absence of lodging, some varieties yield as well on beds as on flats while others don't, and suggest that the poorer performance on beds may be related to shorter, more erect and/or earlier plant types. Moreno Ramos (1987, pers comm) reported that the short bread wheat variety Torim 73 performed relatively poorly in beds, especially when sown late, conditions in which other bread wheat varieties also yielded less in beds. Ortiz Monasterio (1993, pers comm), in summarising 3 years' work on the issue, concluded that there were at that time (early 1990s) three types of wheat variety, those whose yield was unaffected on beds (eg Baviacora 92, Altar 84), those whose yield suffered but by no more than 10% (eg Rayon 89, Aconchi 89), and those which suffered more than a 10% yield loss (eg Oasis 86). The last group comprises entirely short (two gene dwarf) bread wheats.

Attempts were made to relate significant genotype by planting method interactions for grain yield to plant type characteristics, as suggested above. In the 1989–90 bread wheat experiments with 16 cultivars, the absolute yield difference between flat planting and raised beds across cultivars (in the range 1295 kg/ha to –61 kg/ha) was correlated with height (–0.66, P<0.01) and days to anthesis (+0.56, P<0.05), and weakly correlated with % PAR interception in beds before flowering (–0.48). In this experiment cultivar extremes were represented by Oasis 86 (relative yield 84.5%, interception 48.8%) and Rayon 89 (relative yield 100.8%, interception 80.5%). In a parallel experiment in the same year with 16 durum cultivars there were no significant correlations between plant traits and relative yield (range 80–98%). In 1990–91 in a detailed pairwise comparison between Oasis 86 and Rayon 89, it was confirmed that the difference in relative yield between these two cultivars was indeed qualitatively associated with lower light interception at critical stages in Oasis 86.

It is also interesting to ask whether there is clear evidence of improved adaptation of more recent CIMMYT material to bed planting, as might be expected since breeders moved to doing most of their yield testing on beds in the early 1990s. Even before then, very short double-dwarf bread wheat material (eg Yecora 70 and Oasis 86) had generally fallen out of favour, and Oasis 86 was the last such release of a double-dwarf variety. Excluding Oasis 86, seven historic bread wheat varieties spanning the period 1966–2003 were tested in both planting systems in 2003–04 and 2004–05. They were low yielding years (see Table 3) but the correlation between relative yield and year of release was significant (r = 0.78, P<0.05, Figure 4). The latest releases (Tucapeto 2001 and Kronstad 2003) seem to be yielding even better in beds than on the flat. Curiously, in the case of durum varieties there was no evidence in the 2003–04 and 2004–05 experiments that the latest releases (Atil 2001, Jupare 2001) were especially adapted to beds. However, even the 1970 varieties (Cocorit 71, Mexicali 75 and Yavaros 79) of this species had an average relative yield on beds (98.5%) close to 100%.

The relative performance described here could of course change whenever there is substantial lodging,

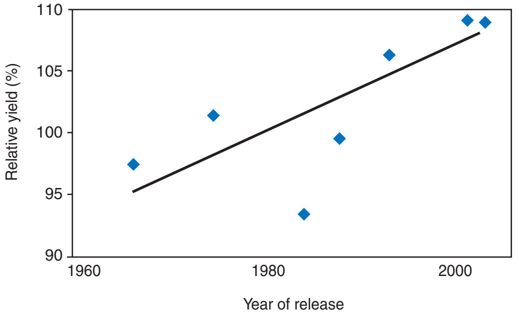

Figure 4. Yield in beds relative to that on the flat (%) of bread wheat varieties against year of release in northwestern Mexico; mean of experiments in 2003–04 and 2004–05.

because lodging varies considerably between cultivars and was usually observed to be less on beds (eg Tripathi et al 2005).

Effect of beds in the presence of water stress and weeds

One experiment across 14 bread wheats in 1992–93 looked at the interaction between bed planting and weed control. Yield loss without weed control was 39% in the 20,20 planting, significantly higher at 57% in the 20,55 beds, but not so high in the 18,18,54 beds at 42%. Many reports have shown that narrowed rows somewhat reduce the yield losses due to weeds, which could be considered a disadvantage of a large gap in bed systems. However, in reality this is countered by the fact that beds facilitate field entry for control of weeds by hand, directed spraying or interrow cultivation, and in rain-free environments fewer weeds germinate on the dry bed surface.

Several experiments between 1992–93 and 1996–97 looked at performance in beds with and without full irrigation. With early water stress the yield in beds was similar to the yield in a flat system with the same irrigation regime, but with late water stress the yield in beds exceeded that in the flat by 33% (1993–94) and 26% (1996–97). This yield increase is probably due to the reduced early crop growth on beds conserving scarce moisture for grain filling, and can be likened to the skip row system used for cotton and sorghum when planted on limited stored soil moisture. It should not be taken to imply that beds are always more efficient where water is limited.

General discussion and conclusion

For comparison purposes, we would like to urge researchers to report the geometry of the raised beds which they use, along the lines suggested in Figure 1. Too many papers do not describe unambiguously the systems they are comparing. As can be seen from the plant density studies, it is also important to report exact plant arrangements at low densities, and to be aware of the possible difference of a random arrangement of plants in the row compared to a regular one (as becomes very important in crops with larger plants like maize or sunflower). In addition, it is useful to note mature plant height and horizontal spread of the cultivars being compared.

These studies were undertaken to examine the potential yield loss due to the gap (ie the unseeded furrow) between raised beds apparently not being utilised. The plant density studies reported here did not provide an answer to this question. However, they did show the extent to which wheat can compensate for low planting density by tillering, and somewhat extending the spike growth period due to the later order tillers flowering significantly later than the first two or three on the plant (Fischer et al 1976). Maximising the utilisation of space by planting on a regular grid assisted in this compensation, something already well known to crop physiologists, who sometimes refer to this as minimising interplant competition. With mechanical plantings of beds, however, plants are more likely to be spaced at random in the rows. Although there was no evidence of planting method × plant density interactions, it would seem that beds should have 25–50 plants/m along the row, and bed *versus* flat comparisons should aim for similar lineal plant densities (ie the seed rate per hectare for 20,55 and 18,18,44 beds should therefore be 53% and 75%, respectively, of that for 20,20 flat plantings, other things being equal).

There was no definitive answer on the size of gap which could be tolerated: it depended on wheat genotype and to some extent on conditions. For the most sensitive cultivars 10% of yield was consistently lost with a 45–55 cm gap, but for the least sensitive there was no yield loss; and above a 60 cm gap most cultivars would be expected to lose yield. There was good evidence that the CIMMYT bread wheat breeding program has moved towards using a greater proportion of advanced lines which are in the least sensitive category. This is not surprising since later generation observation and yield testing in their Mexico program prompted a move to bed plantings in the early 1990s. Other breeding programs need to be aware of the need to use cultivars adapted to beds if bed planting is likely to be adopted because of its management advantages. The basis of the adaptation to beds seems to be related to more complete light capture over the gap during the critical pre-anthesis period (thereby favouring taller, later and less erect types). However, this connection has not been proved convincingly and needs more work (see also below). It also raises the question as to whether yield potential on the flat in, say, 20-cm rows, is being limited by the move away from an ideotype (short, erect, even moderate tillering) which does not do well on beds but which some physiologists (eg Donald 1968) argue offers the greatest potential in solid stands on the flat. The possibility exists that new cultivars that perform well on beds may suffer yield loss with conventional planting; there is little evidence for this to date but it needs to be borne in mind.

Throughout this paper it has been assumed that in irrigated wheat the question of utilisation of the gap is one of light capture; equal yields for simulated and actual raised beds supported this. Fischer (1985) argued that yield is proportional to grain number/m^2, and that this is proportional to both PAR captured and crop growth rate in the month or so leading up to flowering. If the wheat in beds covers the gap to the extent that all the light is captured before this critical spike growth period, there would be no yield loss. Comparisons showed here and elsewhere (eg Fischer et al 1976) that all the extra vegetative growth and tillering on an area basis that is so evident in the first weeks of crops sown at higher plant density (>200/m^2) and narrow row spacings (<30 cm) was of no advantage to yield. The general effects of beds on the components of yield (lower spike number, higher kernels per spike, and no change in kernel weight or harvest index) also support this notion. However, the performance of the low density spaced plantings and the associated PAR interception data remain an enigma for further study.

Comparison of simulated and actual raised beds suggests that there are no other major factors affecting bed performance under these conditions and in the absence of lodging (which can be less on beds). This does not mean that there may not be additional important differences or advantages for yield with raised beds in other environments (see, eg, Wang Fahong et al, this volume), but light capture is likely to remain a key factor everywhere in tolerance of the gap and absence of yield loss. When accelerated growth relative to the rate of development (time to flowering) is required, high soil fertility and good water supply are obviously important. Short days and relatively cool temperatures of low-latitude winters may also help in boosting growth ahead of development. Conversely, for later than normal sowing dates, and for cultivars sown in the spring at high latitudes, where development is accelerated relative to growth, yield may be more sensitive to the gap size.

There is one interesting observation relating to intercepting all the available light across a gap. Not only does fully occupying the gap obviously depend on there being sufficiently vigorous plant growth, but evidence from the experiment with a 10,10,55 arrangement suggests that the presence of a middle row close to the edge row (which is the case when there are two or more rows on a bed) could also somehow force the edge row to spread more rapidly into the gap than in the case when there was no middle row and a similar gap. This could result from light ‘foraging’ photomorphogenetic responses, effects arising because plants can sense the presence of neighbours (Ballaré et al 1997), and could help in compensatng for the gap.

The measurements of PAR interception supported the general notion that some cultivars sensitive to the gap intercepted less radiation at the critical time. However, the data was not sufficient to show that the critical gap by cultivar interaction always corresponded to those cultivars not suffering yield loss as a result of reaching full light interception before the onset of the critical period. Interception would need to have been measured and integrated throughout the daylight hours more thoroughly in order to test this idea. One piece of evidence, however, suggests that it may not represent the whole picture. It can be readily observed that bed crops are darker green (which could be another response to the extra light from the side), and this was confirmed on at least one occasion with the SPAD meter (Wang et al 2004). Since SPAD measurements correlate closely with leaf N% and radiation use efficiency (RUE) increases as the %N in the canopy increases (eg Fischer 1993), this could be another mechanism by which crops compensate for the gap. Analysis of light penetration into the bed canopy may reveal further favourable differences for total canopy photosynthesis, RUE and crop growth. Such research needs to be done.

The research here has focused on understanding an effect which is quite subtle in the overall scheme of things: a 5–10% yield difference in the field, with no confounding due to lodging or other differences between beds and flats, is not easy to create and measure accurately, let alone understand. The issue should continue to be investigated by crop physiologists, as breeders need to know what to target in their selection, and farmers need reassurance regarding the likely amount of yield loss to expect due to the interbed gap, especially as larger gaps have certain cost-saving management advantages. For the moment it seems safe to conclude that under irrigated, high fertility and climatic conditions similar to those in northwestern Mexico, most modern cultivars will tolerate a gap of 50 cm without yield loss arising because of lack of light interception.

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Experiences with permanent bed planting systems CIMMYT, Mexico

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Abstract

The use of planting practices that permit tillage reductions and retention of crop residues on the soil surface for surface/gravity irrigated wheat-based production systems is very rare in both developed and developing countries. But over the past 25 years more than 95% of the farmers in the Yaqui Valley in north-western Mexico have changed from the previous practice of planting most crops (especially wheat) on the flat with flood/basin irrigation to the establishment of all their crops (including wheat) on tilled freshly raised beds using furrow irrigation. These crops are planted in rows on top of the beds, which normally measure 70–100 cm wide between bed centres.

CIMMYT agronomists, working with farmers in the Yaqui Valley, began to look closely at this bed planting system, adding reduced tillage and retention of crop residues, and thereby introducing permanent raised beds. In 1992 a long-term trial was initiated to compare the farmer practice of tilling to destroy the beds after the harvest of each crop with a new approach. In this alternative method new raised beds are made following a final cycle of tillage, after which these beds are maintained permanently with only occasional reshaping as needed after harvest and before planting the next crop. By the 2003–04 winter crop season, 12 wheat crops during the winter cycle and 4 soybean plus 7 maize crops during the summer cycle (a total of 23 crops) have been successfully produced in this long-term trial, including treatments where no tillage (except bed reshaping) or no crop residue removal has been practised.

Significant yield differences between the tillage/residue management treatments have been observed for wheat, with major differences starting with the sixth wheat crop. More stable, higher wheat yields have been obtained with permanent beds combined with residue retention, whereas permanent beds combined with residue burning have resulted in markedly lower wheat yields. These yield differences appear to be associated with gradual changes in soil physical, chemical and biological parameters that are related to tillage and residue management practices.

Permanent beds have also been tested in the non-irrigated moderate and high rainfall environments of CIMMYT's experiment stations in central Mexico and have shown similar promise for both maize and wheat, especially when crop residue is at least partially retained in the moderate rainfall environment.

Introduction

Two general themes related to bed planting in Mexico are described in this paper. The first is a brief account of the farm-level condition of bed planting in Mexico. This account of the farmer experience is then used to introduce the second theme — the strategic bed planting research activities with which CIMMYT has been engaged over the past 15 years in Mexico. Together these two discussions will outline the evolution of permanent bed planting technologies that are relevant to Mexican farmers. These technologies have served as the 'platform' for extending permanent bed planting as a form of conservation agriculture (CA) to CIMMYT's national agricultural research systems (NARS) program partners in developing countries. This diffusion of information has involved visits by NARS scientists to see the strategic research activities in Mexico, and to participate in our twice-yearly in-service training courses that emphasise permanent bed planting CA. In addition, both regionally based and Mexican-based CIMMYT staff have provided

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continued in-country support to these NARS scientists on return to their home countries.

The focus for both discussions will be mainly centered on the irrigated production systems found in the southern part of the state of Sonora (located in northwestern Mexico), especially in the Yaqui Valley where over 95% of the farmers have adopted furrow-irrigated bed planting systems for nearly all crops (alfalfa being the only major exception) over the past 30 years (Meisner et al 1992; Sayre & Moreno Ramos 1997). This location is where CIMMYT's main wheat research station is located. CIMMYT's strategic work with bed planting systems in the Yaqui Valley, and the allied training of NARS scientists, has resulted in the extension of CIMMYT/Mexico bed planting technologies to many other areas with similar cropping systems, including irrigated areas in northwestern India, Pakistan, the eastern Gangetic Plains, the Yellow River Basin in China, central and western Asia, the Caucasus, North Africa and South America.

Farmer experience in the Yaqui Valley

Until about 35 years ago farmers in the Yaqui Valley (a cultivated area of nearly 350,000 ha) practised basin/flood irrigation for wheat (the principal crop) as well as for other crops, with extensive use of heavy tillage and burning of crop residues. Occasionally, farmers would 'hill-up' crops like safflower, maize, sorghum, soybeans, sesame and dry beans for subsequent furrow irrigation after these crops had been planted on the flat following a pre-seeding flood irrigation. Cotton, however, has always been routinely planted on a raised bed with furrow irrigation (80–100 cm furrow to furrow), while some farmers drilled solid stand wheat on the flat and then formed furrows for subsequent irrigation (70–80 cm between furrows). Therefore, even though most farmers predominantly used flood irrigation, there was some early local experience with growing crops on raised ridges/beds with furrow irrigation.

In the mid 1970s some farmers began to plant wheat on flat beds raised between irrigation furrows, with the innovation that only 2–4 defined rows were planted on top of each bed (referred to as raised bed or bed planting). Common bed widths ranged from 70 to 90 cm furrow to furrow, with 75 cm as the most common width (Figure 1, left side). Use of wider beds was not possible because of irrigation problems associated with 'wetting across to the middle of the bed' for crops like wheat. Once the move to planting wheat on beds in this fashion was adopted, farmers also began to plant most other crops on similar sized beds, but still continued to use heavy tillage and extensive burning of crop residues before tilling, followed by the formation of new beds for each succeeding crop cycle.

Some of the main reasons given by farmers for their move to bed planting, especially for wheat, have been identified as follows:

- Wheat seed rates could be markedly reduced (down from 200+ kg/ha to 80–150 kg/ha) while maintaining or even increasing yield; this was important since many farmers had begun to specialise in the production of registered and certified wheat and wanted to maximise the seed multiplication rate.
- Less irrigation water was used for all crops (up to 25+% savings as compared to basin/flood irrigation) and labour required for irrigation was also reduced.
- Periodical waterlogging caused by extreme rain events (especially during the summer crop cycle) and/or poorly levelled fields was ameliorated.

Figure 1. Left – Bed planted wheat in the Yaqui Valley, Mexico (2 rows of wheat spaced 35 cm apart on beds 75 cm furrow to furrow); Right – Mechanical weed control for bed planted wheat.

- Less crop lodging occurred, especially for wheat.
- Better fertiliser management options were available for wheat. Beds facilitated incorporation of band placement of N, P and other nutrients, both for basal and post-emerge applications, because the furrow bottoms between the beds controlled implement trafficking and permitted implement access after emergence.
- Perhaps most importantly, this access also permitted weeds in wheat to be controlled mechanically (Figure 1, right side), as was practised for row crops like cotton, since wheat was planted in defined rows on the beds (normally 15–40 cm apart depending on bed width and row number per bed). Weed control in solid seeded wheat planted on the flat was totally dependent on post-emerge selective herbicides.

Much evidence suggests that the main stimulus for the adoption of bed planting of wheat by Mexican farmers was the effect of the oil embargo during the mid 1970s, which led to dramatic increases in the costs of imported herbicides into Mexico. Most farmers were dependent on these herbicides for routine weed control in the flat-planted, flood-irrigated wheat. As a consequence of the embargo, many sought less expensive mechanical weed control options provided by wheat bed planting with defined rows on top of the beds. At present, selective herbicides are applied on less than 10% of the wheat area in the Yaqui and Mayo valleys.

Over the past 10 years there has been a substantial reduction in tillage operations when compared to the previous widespread practice of deep subsoiling on a regular basis combined with disc ploughing, followed by several passes of the disc harrow and then superficial levelling before each crop cycle. Now, few farmers are using the plough and the number of passes with the disc harrow has been markedly reduced. Similarly, there has been a marked reduction in the burning of crop residues, with more farmers chopping residues either with combine harvester-mounted choppers or by tractor-drawn field choppers.

Very few farmers, however, have adopted permanent bed planting, although some have taken the first true step towards use of permanent beds, especially in the main cropping systems that involve wheat or barley in the autumn/winter cycle followed by maize, sorghum or soybean in the spring/summer cycle. Land is still tilled and new beds made for the autumn-sown wheat or barley, but these same beds are reshaped if needed and reused for the succeeding summer crop of soybean, maize or sorghum. Because of the lack of appropriate planters to seed summer crops on untilled beds with retention of the wheat/barley straw on the soil surface, most farmers tend to either burn the straw, or cut the stubble close to the ground with the combine harvester and bale the loose straw, before planting the summer crop. In the autumn after harvesting the summer crops, the beds are destroyed by tillage and new beds re-established for the following small grain crop. Thus, the principal reason that farmers use this 'hybrid tillage system' is the lack of suitable small grain seeders that can readily and reliably plant 2–3 rows of wheat or barley on the untilled top of the permanent beds, especially in the presence of high levels of surface-retained maize or sorghum straw.

Similarly, almost no technical advice has been made available to farmers about how to manage weeds, fertiliser and irrigation for the new permanent bed planting practice since little or no formal research effort to generate this information has been carried out in Mexico. The realisation of this knowledge gap, combined with a firm belief that permanent bed planting offers the best alternative for ensuring farmer adoption of sound, sustainable CA technologies for surface irrigated cropping systems, has provided a foundation for CIMMYT to initiate research in, and extension of, permanent bed planting systems.

Permanent bed research in Mexico

The main motivation for initiating this work on permanent bed planting systems has been to develop crop production technologies that can offer marked reductions in production costs. An additional goal was ensuring that these new technologies were compatible with resource-conserving and sustainable CA norms which are characterised by:

- marked reductions in tillage, with the ultimate goal of direct seeding without tillage
- rational surface retention of adequate levels of crop residues (predicated by the rule of thumb that CA will not function in most situations in the long term unless adequate levels of surface residues are maintained)
- use of rational and economically feasible diversified crop rotations.

As mentioned above, the main focus in Mexico has been towards gravity irrigated, upland crop production systems (wheat, barley, maize, cotton, safflower, soybean, sorghum, chickpea, canola and a variety of vegetables). Flooded rice has not been considered, although there have been some farmer experiences in rice production on tilled beds in the neighboring state of Sinaloa.

Given the absence of knowledge and lack of experience in managing permanent beds with retention of surface crop residues in irrigated systems, both worldwide and especially in Mexico 15 years ago when we initiated our activities, we have focused most of our efforts on the following crop management aspects:

- fertiliser management with emphasis on N
- weed control issues
- irrigation management
- proper crop residue management – the evolution of practices that can manage full residue retention but that also identify the minimum levels of residue that need to be retained for ensuring system sustainability while allowing removal of some residues if there is economic demand for it
- characterisation of tillage/planting system/residue management by genotype interactions (especially for wheat) to ensure that appropriate crop genotypes are identified for permanent bed planting systems
- development of prototype implements for seeding and managing permanent beds.

In many ways the last-mentioned point has been the most important issue to confront, ie the development of prototype implements for seeding on permanent beds with retained residues, including band application of fertilisers and maintaining the shape of the beds. Without doubt, the main factor that has limited extension and adoption of permanent beds (and essentially most other relevant CA technologies), particularly for small grain crops such as wheat, by small- to medium-scale farmers in developing countries has been this complete lack of appropriate implements, especially seeding equipment. Our philosophy has been to develop multi-crop/multi-use implements that can be simply reconfigured for bed reshaping, band application of basal or post-emerge fertiliser, and easy and rapid seeding of both small- and large-seeded crops (Figure 2).

We are developing implements with fertiliser and seed tanks with appropriate distribution mechanisms that can seed both small- and large-seeded crops with an acceptable level of precision. These implements use a multiple toolbar arrangement to mount all needed attachments (eg fertiliser/seed tanks and their distribution systems, seed and fertiliser openers, residue management tools like discs or trash whippers, and shovels or discs for bed reshaping) using adjustable clamp systems.

For small- and medium-scale farmers, we visualise a single implement capable of being easily and rapidly reconfigured to perform most seeding, fertilising and permanent bed management activities for the suite of crops grown by these farmers. This implement would markedly reduce machinery costs as farmers convert from conventional, flat planting systems to permanent beds.

We have continued to use raised bed sizes (70–80 cm furrow to furrow) for permanent beds that are similar to the bed widths routinely used by farmers for tilled beds. These bed sizes can be made compatible with the various common crops used in production systems in Mexico by varying the row number per bed (2–3 rows for wheat, triticale and barley; 1–2 rows for chickpea and canola; and 1 row for crops like cotton, maize, sorghum, safflower, soybeans and dry beans). By maintaining the same bed widths that farmers are already using for tilled beds, it has been easier, whenever feasible, to modify existing implements for use with permanent beds as well as eliminate the need to alter tractor wheel spacings already in use. In addition, we find that this range of bed widths (70–80 cm furrow to furrow), when compared with beds 1.2 m or wider:

- is much more amenable and flexible for use by small-scale farmers who may only have adequate tractor horsepower (2-wheel walking tractors or small 4-wheel tractors) to manage one or two narrow beds at a time
- achieves more efficient irrigation water use
- facilitates inter-row and inter-bed management activities.

Our crop residue management strategy for permanent beds has been to ensure that the implements

Figure 2. Left – Multi-crop/multi-use implement configured for reshaping permanent beds and applying basal fertiliser; Right – The same implement configured for bed reshaping, fertilising and maize planting.

and other management features can handle seeding with full or partial residue retention. If there are clear alternate and economical uses for crop residue, then the focus has been to identify the minimum levels of residue that must be retained to provide adequate groundcover and contribute effectively to the improvement of soil chemical, physical and biological properties. This can be achieved by removing the cut, loose residue and leaving the standing stubble, especially with crops like wheat and sorghum; or, alternatively, by rotational removal of residues (ie keeping all winter-planted wheat straw prior to planting summer crops like maize, while removing the maize straw prior to planting wheat). A clear understanding of how to achieve rational implementation of strategies that allow adequate, partial residue retention will be crucial in those (most) developing countries where the use of residues for fodder in mixed crop/livestock enterprises is of great importance or where residues are used for other purposes like fuel, thatching or paper production. Otherwise, opportunities for implementation of new technologies like permanent bed planting will be markedly diminished.

Our goal has been to attempt to use permanent beds continuously for as long as feasible. We now have irrigated permanent beds that have supported up to 26 consecutive crops of wheat, maize and soybean and are still functional, and in many ways the soil quality parameters are improving over time. Following harvest of each crop, the beds are scrutinised and a decision is made whether reshaping is needed or whether it can wait another cycle. Experience has shown that when in doubt, it is better to reshape. We try to 'piggy back' various management operations such as reshaping, banding basal fertiliser and seeding in one operation whenever possible (see Figure 2).

The only tillage on our permanent beds is the use of shovel or disc tools in the furrow bottoms to reshape the beds. We have also looked at the use of miniature subsoiling shanks that operate in the middle of the bed to a depth of about 15–20 cm to shatter potential shallow compaction in the bed that may have developed over time, but without inverting or destroying the permanent beds. So far, in beds with residue retention we have not seen much response in those areas where we have kept machinery wheels, especially those of combine harvesters, off the top of the beds. We try to ensure that all machinery traffics in the furrow bottoms, and we try not to enter the fields when it is too wet. Maintaining this policy has been most difficult with combine harvesters, mainly due to pressure to harvest even under wet field conditions and because most combine harvesters' wheel sizes and distances between wheels do not precisely correspond to the bed widths. However, some farmers have modified their harvesters' axles to have dual, narrow wheels on each side of the machine, thus allowing each wheel to traffic in the furrows between 70–80 cm beds.

Our preferred strategy for fertiliser application has been to band apply and, especially for N fertilisers, to band N through the residues so that the fertilisers and residues are never or only minimally in physical contact. Our evidence indicates that keeping N fertiliser out of contact with residues favorably alters the dynamics of straw decomposition as well as minimising potential N tie-up and release from microbial action in the soil. If irrigation water availability is totally dependable, it would also be possible to band N fertilisers by simply dribbling in the furrows followed by immediate irrigation. However, many farmers, especially in developing countries, face much uncertainty about when irrigation water will actually reach the farm. Dribble application in furrows containing crop residues could be risky if the irrigation water arrives several hours after the dribble application, thus leading to potentially large N volatilisation losses (especially with urea). Other possible application methods to reduce contact between the N fertiliser and the residue include dissolving the N source in the irrigation water or using foliar N applications. However, these methods depend on farmers properly calibrating the application or having adequate spray equipment.

For irrigation of wheat and other crops when 2 or more rows are planted on top of the beds, we normally apply seeding irrigation in each furrow, as well as auxiliary or post-emerge irrigations. However, in some soil types post-seeding irrigations may be applied in every alternate furrow, with each successive irrigation occupying furrows not used in the previous irrigation. For crops planted with 1 row on each bed (eg cotton or maize) we may irrigate either in each furrow or in every alternate furrow for seeding irrigation, but in nearly all cases subsequent irrigations are made in alternate furrows, usually switching furrows for each succeeding irrigation.

It is obvious from the above discussion that we believe the use of narrower beds (70–90 cm) provides a large degree of flexibility for gravity irrigated conditions, ensuring more efficient management options for inter-crop weed control, fertiliser banding, irrigation water application, and handling of high levels of crop residues. By using alternate row irrigation strategies, narrow bed planting allows irrigation opportunities (providing 1.4–1.8 m distances between furrows used for irrigation) similar to those of wider beds for row crops like maize. The biggest advantage, however, lies with irrigation of crops like wheat, where planting of multi-rows on narrow beds markedly reduces the time needed to 'wet across to the middle of the bed'. Because this time is an exponential function of bed width, it can be inordinately long in wide beds on many soil types.

Our research strategy has been to install a small number of long-term trials that focus mainly on comparing permanent bed planting systems against conventional bed planting with tillage. The trials also investigate residue management issues, N management alternatives and rotations. In addition, we have established a series of permanent bed component technology trials that have allowed us to compare potential planting systems according to genotype interactions, contrasting irrigation strategies and additional fertiliser management issues (eg rate, timing, placement). Results from these component trials regularly feed into the long-term trials (eg the more appropriate varieties or more optimum irrigation strategies that are common across the trials).

In addition to the research trials established at the station in the irrigated Yaqui Valley in northwestern Mexico, we have established similar trials at two high-elevation experiment stations: in the moderate rainfall altiplano at El Batan (2000–2500 m above sea level; both irrigated and rainfed conditions with 450–600 mm growing season rainfall); and at the high rainfall site of Toluca (2640 m above sea level; rainfed conditions with 850–1000 mm growing season rainfall). Both sites are in central Mexico at latitude 19°N.

Results of permanent bed research in Mexico

Irrigated conditions in northwestern Mexico

Some aspects of these experiments are also described in Limon-Ortega et al (2000a, b, 2001). Table 1 presents some information about location and soil type at the main research station in the Yaqui Valley. The soil type is a heavy, cracking soil that is difficult to manage if operations are performed outside a rather narrow soil moisture window of opportunity. Permanent beds, with their marked reduction in tillage and field operations, have provided relief from this problem.

Figure 3 presents wheat yield trends at a high N application rate for the main long-term furrow-irrigated permanent bed trial in the Yaqui Valley. The trial was initiated with a maize crop in the summer cycle of 1993 and compares tillage, residue management and N management. Wheat has been planted each winter cycle; soybean was planted in the summer cycles of 1994, 1996 and 2001, and maize in the summer cycle in all other years. The original intent was to alternate soybean and maize in the summer cycle, but in 1995 a new biotype of white fly arrived in the Yaqui Valley, basically rendering soybean uneconomical for farmers. The area under soybean declined from 100,000 ha in the summer of 1994 to zero in 2004. Maize is now essentially the only summer crop that can be economically rotated annually with wheat. There have been large annual changes in wheat yields (Figure 3), with low yields in 1995 and 2004 as a result of extended warm, cloudy periods during the first half of the crop cycles. The key outcome seen in Figure 3 is that there were no significant wheat yield differences between any of the tillage/residue management practices for the first 5 years (10 crop cycles). However, after 5 years the yield of management treatments clearly diverged, with a dramatic overall reduction in the yield for permanent beds, where all residues have been routinely burned from onset of the trial.

This result illustrates the following four points:

- First, for irrigated agriculture systems (at least for tropical, semi-tropical and warmer temperate areas) the application of irrigation water appears to 'hide or postpone' expression of the degradation of many soil properties associated with continuous residue burning until they reach a level that can no longer sustain yield, even with irrigation. As indicated in Table 2, most of the chemical, physical and biological soil parameters measured around 10 years after commencement of the experiment

Table 1. Soil characteristics, CIANO Experiment Station, Ciudad Obregon, Yaqui Valley, Sonora, Mexico.

- Location – 27.33°N; 109.09°W; 38 masl
- Soil type – Coarse sandy clay (mixed, montmorillonitic typic calciorthid)
- Organic matter (0–90 cm) – 0.75%
- C.E.C. (0–60 cm) 36.00 meg/100 g
- pH ($CaCl_2$ 0–30 cm) – 7.5 • E.C. (0–30 cm) 1.9 mS/cm
- Texture:

Depth	% clay	% silt	% sand
0–30 cm	43	24	33
30–60 cm	48	25	27

Table 2. Effect of tillage and crop residue management on soil properties (0–7 cm) in 2002 for a long-term permanent raised bed planted trial initiated in 1993 at CIANO, Ciudad Obregon[a].

Tillage/residue management	% organic matter	Na (ppm)	Soil dry aggregate MWD[b]	Soil wet aggregate	*SMB*[c] *C* ($mg\ kg^{-1}$ soil)	*SMB*[d] *N* ($mg\ kg^{-1}$ soil)
Conventional till beds + incorporate residue	1.23	564	1.32	1.262	464	4.88
Permanent beds + burn residue	1.32	600	0.97	1.12	465	4.46
Permanent beds + partial removal of residue for fodder	1.31	474	1.05	1.41	588	6.92
Permanent beds + retain residue	1.43	448	1.24	1.96	600	9.06
Mean	1.32	513	1.15	1.434	552	6.40
LSD (P=0.05)	0.15	53	0.22	0.33	133	1.60

[a] Samples for wet aggregates were collected in 2004; all others were collected in 2002

[b] Mean weight diameter

[c] Soil microbial biomass – C content

[d] Soil microbial biomass – N content

showed significantly inferior levels for permanent bed management with burning of all residues. The exceptions, interestingly, were percent organic matter and C in microbial biomass, which were similar or somewhat higher compared to tilled beds with all residues incorporated, possibly due to tillage induced mineralisation rates being lower than mineralisation through burning. The apparent amelioration of Na levels for permanent beds with partial or full residue retention may have significant relevance for irrigated saline areas.

- Second, both full retention and partial retention of residues had similar yields, indicating that for irrigated systems with associated high residue yields, substantial amounts of residue can probably be removed for other economic uses without causing a yield decline. In addition, although the yields of properly managed permanent beds are not

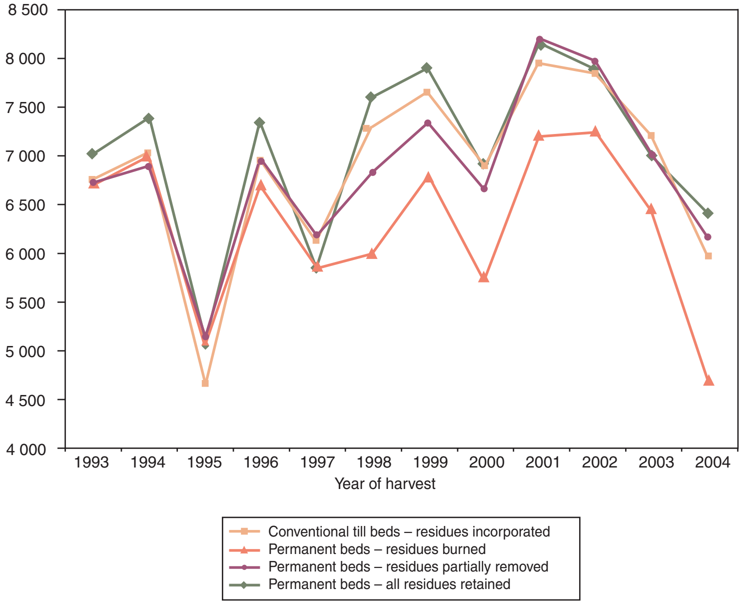


Figure 3. Effect of tillage and residue management over several yield (kg/ha at 12% H_2O) when 300 kg/ha N are applied at the 1st node stage at CIANO/Cd. Obregon {LSD (0.05) = 555 kg/ha}.

markedly higher than conventional till beds with residue incorporation, as will be seen, permanent bed production costs are markedly lower.

- Third, when N responses are considered (Figure 4), significant small tillage/residue by N rate interactions are observed, but permanent beds with full residue retention showed the highest yields over the full range of N rates.
- Fourth, it seems clear from Figure 3 that research to characterise tillage and residue management issues must include a time horizon of more than 5 years to ensure adequate time for potential differences between management practices to be expressed.

Another long-term trial was initiated with wheat planted during the winter cycle and maize during the summer under irrigated conditions at CIANO in the Yaqui Valley in 1994 to compare permanent beds with and without residue burning versus conventional tillage with and without burning. In 2001 the permanent bed treatments were split to compare results with and without the use of a small subsoil shank to break possible compaction in the bed without inverting and destroying the bed structure. Figure 5 presents the mean wheat yields for all these management practices from 2001 to 2004.

Permanent beds with retained residue again yielded markedly more than permanent beds with burned residues. Use of the subsoil shank slightly reduced yields for permanent beds where residue was retained but significantly increased yield where residues were burned. It appears that soil disturbance can overcome some of the adverse effects associated with zero tillage on top of the beds combined with residue burning. Conventional tilled beds, on the

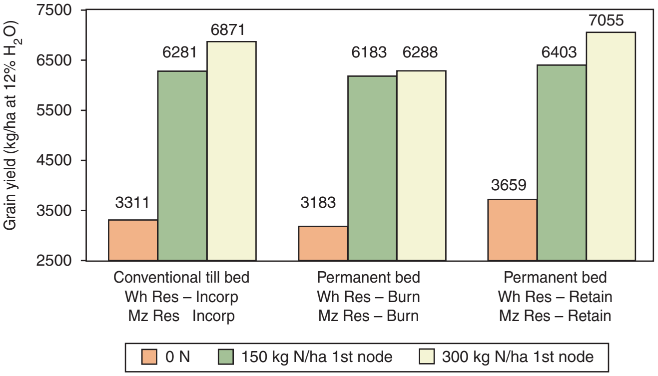
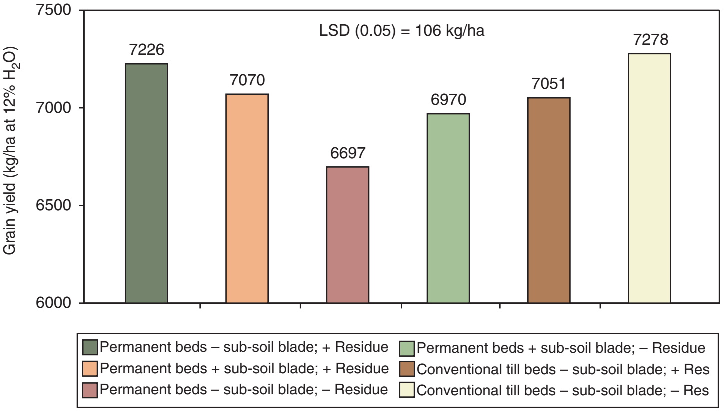


Figure 4. Effect of tillage/crop residue management and N rate of wheat grain yield averaged over 11 years (1993–2004) at CIANO, Cd. Obregon (LSD (0.05) till/res by N rate = 163 kg/ha).



Small-scale sub-soil with side wings, used to about a 15–20 cm depth in the centre of the bed to break possible compaction. Structure is maintained with no soil inversion.

Figure 5. Effect of tillage and crop residue management on average bread wheat grain yield from 2001 to 2004 at CIANO, Cd. Obregon.

other hand, yielded significantly higher with burned residues compared to incorporated residues. A strong interaction, therefore, was observed for tillage versus residue management.

Permanent beds with residue retention had similar yields to tilled beds with residues burned. The differential yield response to residue management is thought to be associated with soil N dynamics. Full incorporation of the high annual residue amounts (7–8 t/ha for wheat and 8–9 t/ha for maize) with tillage may lead to N tie-up, followed by N release out of phase with crop growth, thereby favoring N losses by leaching or volatilisation.

Weed and pathogen observations from long-term trials

Whenever possible, observations on weed and disease incidences have been made on the long-term permanent raised bed trials being conducted in northwestern Mexico. Figure 6 indicates that where residue is removed from permanent beds for fodder, the incidence of *Phalaris minor*, the most problematic grass weed, increased when compared to conventional tillage with residue incorporation. Residue burning with permanent beds dramatically reduces phalaris incidence but the level of incidence for permanent beds with full residue retention is similar. Our experience has shown that, with time, the incidence of most annual weeds markedly declines with permanent raised beds if an adequate level of crop residue mulch is retained on the soil surface.

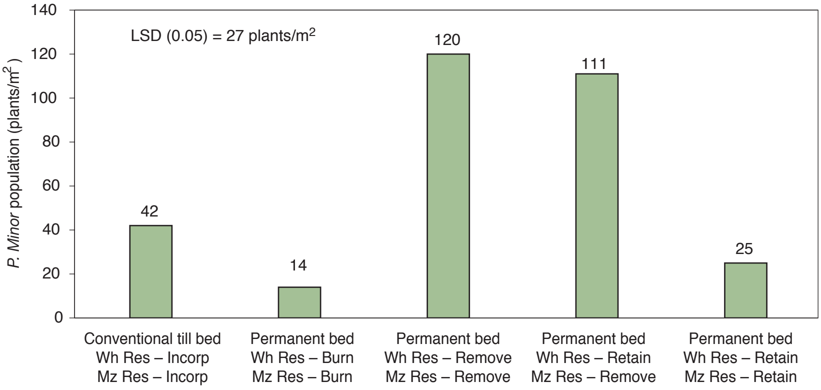
We have also monitored the incidence of *Pratylencus thornei* (root lesion nematode). As observed in Figure 7, the number of nematodes extracted from the soil is markedly less for permanent beds with full crop residue retention on the soil surface.

Similarly, evaluations of the levels of wheat root disease scores (Figure 8) show increased disease levels (causal pathogens not identified) in permanent beds with burned residues. When the markedly higher microbial biomass levels for permanent beds with residue retention are considered, it is suggested that the presence of the residue is enhancing the level of beneficial soil organisms acting as ‘predators’ on the nematode and/or root disease organisms.

Moderate rainfall location in central Mexico

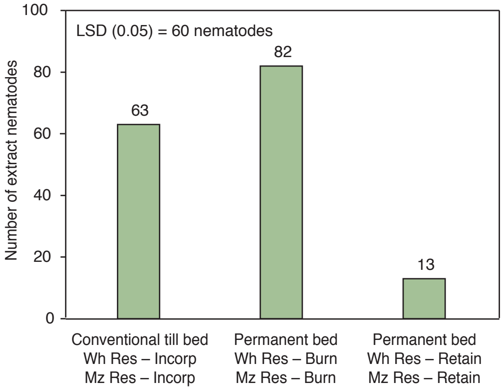
As mentioned above, we have also been investigating the potential for permanent beds under moderate rainfall, non-irrigated conditions at El Batan, located at 2200 masl in the central plateau of Mexico. Rainfall at this location occurs from April to November during the cropping season. Only one crop each year is produced due to the cold, dry winter period. The soil type at this site is a fine, mixed, thermic Cumulic Hapludall with a texture similar to the soil in the Yaqui Valley but, apparently due to differences in clay type, it does not have the extensive swelling and cracking Vertisol characteristic.

Maize is the most common crop in this area but wheat and barley are also produced. The trial follows a maize–wheat rotation, all bed planted. Management practices include some conventional tilled beds (ie new tilled beds each year); the remaining treatments are all permanent beds with full or partial residue retention or with full residue removal. Treatments with tied ridges are also used for both the partial residue retained and full residue removed



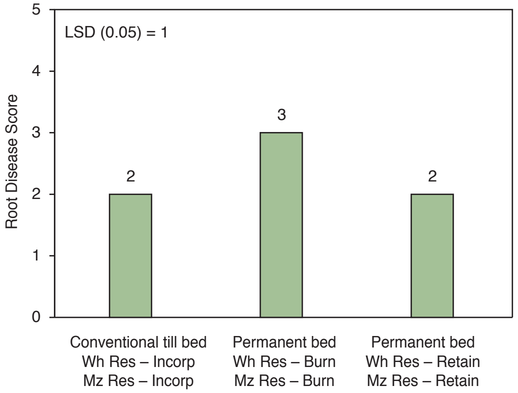
* Wh = wheat; Mz = maize; Res = Residue; Incorp = Incorporate; Retain = Residue chopped and left on soil surface; Remove = Residue removed for fodder (60–70%).

Figure 6. Effect of tillage/crop residue management on the population of *Phalaris minor* during the fifth wheat crop for a long-term trial initiated in 1993 at CIANO, Cd. Obregon, Sonora, Mexico.



* Wh = wheat; Mz = maize; Res = residue; Incorp = Incorporate;
Retain = Residue chopped and left on soil surface;
Remove = Residue removed for fodder (60–70%).

Figure 7. Effect of tillage/crop residue management on the population of *Pratylencus thornei* extracted from soil (0–20 cm) during the seventh wheat crop for a long-term trial initiated in 1993 at CIANO, Cd. Obregon, Sonora, Mexico.

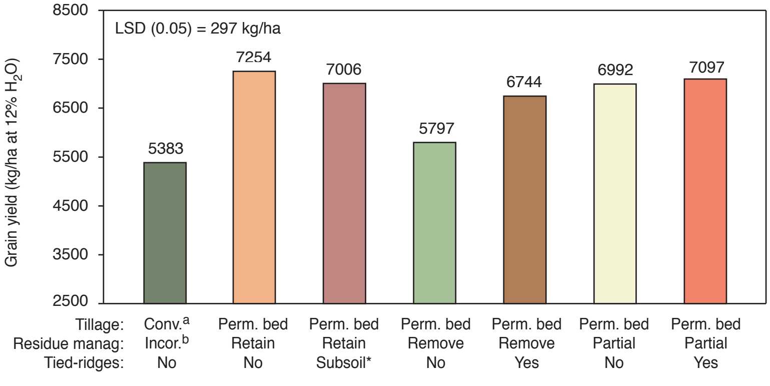


* Wh = wheat; Mz = maize; Res = residue; Incorp = Incorporate;
Retain = Residue chopped and left on soil surface;
Remove = Residue removed for fodder (60–70%).

Figure 8. Effect of tillage/crop residue management on the wheat root disease score during the seventh wheat crop for a long-tern trial initiated in 1993 at CIANO, Cd. Obregon, Sonora, Mexico (Root Disease Score 0 to 7).

treatments, and a treatment with full residue retention combined with the use of a small subsoil shank is also included.

Figures 9 and 10 present the average maize and wheat yields from 1999 to 2004, respectively. For both crops the highest yields occurred in permanent beds with full residue retention, without tied ridges and without use of the small subsoil shank; partial retention gave a slightly lower yield in each case. For maize the lowest yield occurred in conventional tilled beds with incorporation of residues, and for wheat it was in permanent beds with no residue retention and no tied ridges. For both maize and wheat, tied ridges provided a small yield advantage when compared with residues fully removed but there was not much benefit from tied ridges with partial residue retention. Similarly, there was no yield response by either crop to the use of the small subsoil shank.



[a] Conv: Conventional tillage, new beds made for each crop. Perm. bed: Permamanent beds, no tillage except to reshape as needed.
[b] Incor. = Incorporate; Retain: Chop and leave on surface; Remove: Remove for fodder;
Partial: Remove wheat straw cut by combine and remove maize stove to just below the ear.
* A small sub-soil knife was used in the centre of the bed to a depth of 15–20 cm instead of tied ridges.

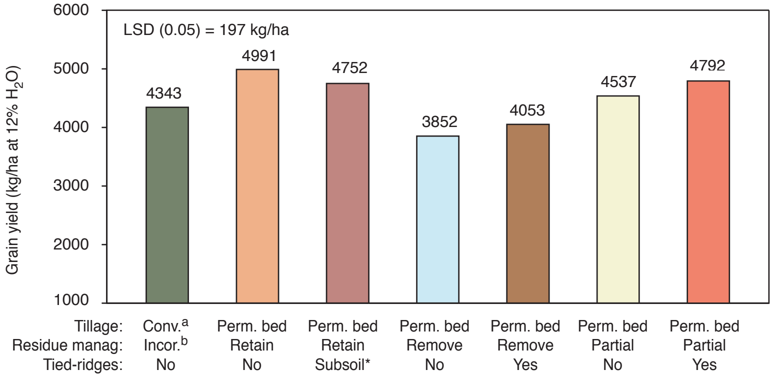
Figure 9. Effect of tillage, residue management and field ridges on average maize grain yields produced in a rainfed, annual maize–wheat rotation from 1999 to 2004 during the summer crop cycle at El Batan.

These results indicate the potential for permanent beds in rainfed conditions where moisture is limiting. Perhaps more importantly, it is of great interest that permanent beds with partial residue retention for both crops have provided similar yields to those with full retention. Since there is intense competition to use residue for fodder and other reasons in many rainfed areas, especially by small- and medium-scale farmers, it is encouraging that 50–70% of the residue can be removed, and retention of the remaining portion will provide adequate benefit to the soil.

High rainfall location in central Mexico

A similar trial to that at El Batan has been conducted at the high rainfall Toluca station. Bed planting in this location has been used mainly as a strategy to provide drainage of excess water from the field following heavy rain events. The soil type at this site has not been fully classified but its texture is a silty loam.

The trial has compared the use of normal narrow beds (76 cm furrow to furrow), where 2 rows of wheat or 1 row of maize is planted on each bed,



[a] Conv: Conventional tillage, new beds made for each crop. Perm. bed: Permamanent beds, no tillage except to reshape as needed.

[b] Incor. = Incorporate; Retain: Chop and leave on surface; Remove: Remove for fodder; Partial: Remove wheat straw cut by combine and remove maize stove to just below the ear.

* A small sub-soil knife was used in the centre of the bed to a depth of 15–20 cm instead of tied ridges.

Figure 10. Effect of tillage, residue management and field ridges on average wheat grain yields produced in a rainfed, annual maize–wheat rotation from 1999 to 2004 during the summer crop cycle at El Batan.

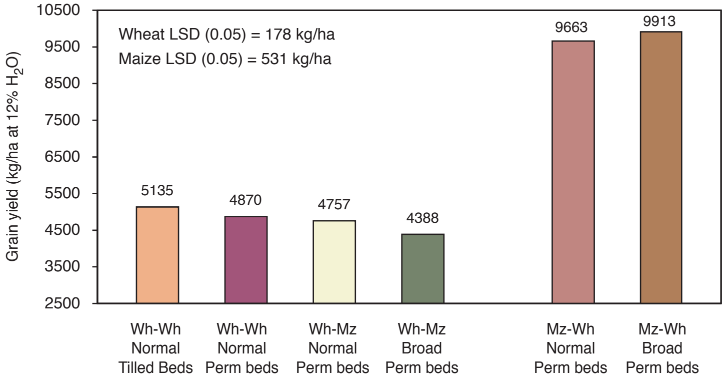


Figure 11. Comparison of average maize and wheat yields (2001–2004) when grown on normal beds (76 cm) versus broad beds (152 cm) with retention of wheat residue and removal of maize residues under rainfed conditions during the summer cycle at Toluca.

versus broad beds (152 cm furrow to furrow), where 6 rows of wheat and 2 rows of maize are planted on each bed. Figure 11 presents the average yields from 2001 to 2004 for several treatments for wheat (continuous wheat on tilled and permanent beds, and wheat in rotation with maize on permanent narrow beds and broad beds). Residue was retained in all treatments.

Wheat yield was higher for continuous wheat on beds with tillage than for continuous wheat on permanent beds. However, wheat planted on narrow permanent beds in rotation with maize yielded significantly more than that on broad beds. Maize in rotation with wheat yielded more on broad beds although the difference was not significant. These results show little advantage to broad versus narrow beds.

Based on the results of the performance of permanent bed planting systems in these three diverse conditions (surface irrigated, low rainfall rainfed and high rainfall rainfed), we feel very confident that there is a great potential value for farmers from both developing and developed countries in adopting this planting system.

Economic and environmental benefits

Limited economic analysis of permanent bed planting systems has been conducted, especially in farmer fields. We are, however, conducting a training/extension module in cooperation with the main farmer association in southern Sonora. It has about 5 ha planted with permanent beds alongside 5 ha planted with conventional tilled beds using a wheat–maize rotation. Table 3 presents a rough comparison of variable production costs for wheat from this module using 2001 winter crop cycle variable cost estimates. The estimate of variable production costs for permanent beds was 22% lower than for conventional tilled beds.

Figure 12 presents a comparison of wheat grain yield, variable costs and returns over variable costs between conventional tilled beds and permanent beds. Clearly, all are favorable towards permanent beds, with 62% greater net returns. The main reason that permanent bed yields are higher than tilled beds in this module is that, in the true field situation, it was possible to plant the permanent beds 10–15 days earlier than the tilled beds (by planting immediately after harvest). In all the experiments reported above, planting dates have been kept the same for all treatments, which has minimised the yield differences between permanent and tilled beds.

We can see many environmental benefits of the permanent raised bed system we are using. Straw burning can be eliminated and, as results from the long-time trials show, permanent beds combined with rational retention of adequate crop residues on the soil surface produce major improvements in most soil quality parameters, indicating a more sustainable production system. Considerable reductions in the use of fossil fuels by tillage operations also arise, reducing carbon dioxide emissions. Biodiversity of soil microflora and fauna are seen to change, with enhancement of the presence of beneficial organisms that are potential predators on pests. Marked gradual reductions are also being seen in many weed species, especially annual grasses and broadleaf weeds, reducing the need for selective herbicide applications.

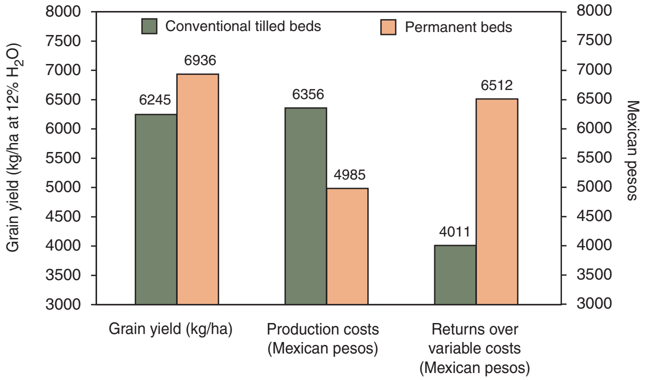


Figure 12. Comparison of average wheat grain yields, variable production costs and returns over variable costs for wheat produced on conventional tilled beds versus permanent beds an CIANO, Cd. Obregon for the 2003–04 crop cycle (11 pesos = 1 US$).

Table 3. Costs for growing wheat on tilled and permanent raised beds in 2001 in southern Sonora, Mexico.

Conventional tilled beds		**Permanent beds**	
variable costs (million pesos)/ha		variable costs (million pesos)/ha	
Chop straw	120	Chop straw	120
4-disc harrowing	1440	Reform beds	135
Apply basal fertiliser	90	Apply basal fertiliser	90
Field levelling	122		
Make beds (pre-irrigation)	122		
Remake bed (pre-planting)	122		
Planting	120	Planting	120
Apply brominal	200	Apply Round-Up	200
Apply 2nd N/cult.	80	Apply 2nd N	80
Apply insecticide	200	Apply insecticide	200
Harvest	450	Harvest	450
Seed cost	450	Seed cost	450
Fertiliser cost	1600	Fertiliser cost	1600
Irrigation cost	1000	Irrigation costs	1000
Brominal cost	150	Round-Up cost	450
Insecticide cost	90	Insecticide cost	90
TOTAL COSTS	**6356**		**4985**

Constraints to adoption

Without question, the lack of appropriate permanent bed seeders, especially for small grain crops, has been the main factor limiting adoption of permanent bed planting in Mexico and elsewhere. Many farmers plant winter crops such as wheat on tilled beds but then need to use these same beds (with or without residue retention) for planting summer crops like maize. For large seeded crops, row spacing is wider and more zero-till seeders are available, thereby leading to the 'hybrid tillage system'. This lack of appropriate seeders is also coupled with weak national research programs and ineffective mechanisms to introduce and extend this new technology to farmers individually or to farmer groups or associations.

Conclusions

Both farmers and researchers in Mexico are firmly convinced that raised bed planting technologies with furrow irrigation offer many better opportunities, especially compared to basin/flood irrigation. Bed planting does not usually result in immediate, large yield increases for irrigated production conditions but provides improved production/input use efficiencies and reduced production costs. However, as has been observed in the Yaqui Valley in northwestern Mexico, once farmers and researchers (especially wheat breeders) begin to develop appropriate varieties for bed planting, improved yields can occur. The latest economic survey (Aquino 1998) has indicated that the average bed-planted wheat yield is about 10% higher than for flood irrigation.

Farmers and researchers also agree that permanent raised bed planting with rational surface residue retention and furrow irrigation offers the next step in improved technology to allow further cost reductions; provide more advantageous crop turnaround times; and enhance soil biological, physical and chemical properties associated with long-term sustainable production opportunities. However, improved, appropriate and cost-effective implements must be developed before permanent raised beds will be widely adopted.

Finally, on an international scale, there has been a significant contribution as a result of the training in Mexico in the last 10 years of nearly 60 NARS scientists from nearly 20 developing countries. Most of these countries now have programs to test bed planting technologies and extend this knowledge to their farmers. This process usually begins by changing from flood irrigation on the flat with tillage to bed planting with tillage, followed later by development and extension of permanent bed technologies. However, in some instances, especially where there is a tradition of furrow irrigation, direct adoption of permanent beds is occurring.

Acknowledgments

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Performance of raised beds in rice–wheat systems of northwestern India

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Abstract

Rice–wheat (RW) is the dominant cropping system in northwestern (NW) India and a major contributor to national food production. However, the productivity and sustainability of RW systems are under threat. Current rates of groundwater extraction for RW systems in NW India are not sustainable and there is evidence of yield stagnation or decline, especially in rice. Using permanent raised beds has been proposed as a means to increase the productivity, profitability and sustainability of RW systems. The benefits of growing wheat on beds compared with conventional tillage include similar or higher yields and reduced irrigation applications. However, in the few reports to date on permanent raised bed RW systems, the performance of wheat on permanent beds has been variable, and usually inferior to fresh beds, possibly due to permanent beds becoming very hard and dense over time. Given the low organic matter status and hard setting nature of the soils of NW India, long-term evaluation of permanent bed RW systems, including organic matter and stubble management, is urgently needed.

The performance of rice on beds in NW India has been variable. Even with similar irrigation scheduling, yields on permanent beds are generally 20–40% lower than with puddled transplanted rice (PTR), with serious problems of iron deficiency, weeds, variable sowing depth and sometimes nematodes, particularly in direct-seeded rice on beds. Strategies for overcoming all these problems are urgently needed, including breeding and selection for rice grown in aerobic soil and for the wide row spacing between adjacent beds.

There are many reports of substantial irrigation water savings with rice on beds compared with flooded PTR. However, some studies suggest that where similar irrigation scheduling is used, irrigation water use of transplanted rice on beds and puddled flats is similar, or even higher on beds due to higher percolation rates in the non-puddled furrows and the longer duration of direct-seeded rice. Irrigation and soil management strategies are needed for rice on permanent beds to reduce potential bypass flow losses through macropores such as rat holes and cracks. Evaluation of the impact of soil and water management on components of the water balance in full-size farmer fields, over the entire rice–wheat–fallow cropping system, is needed to understand the potential true water savings of changing from conventional soil and water management to permanent beds.

While there has been much progress, many challenges remain in successfully developing profitable, productive permanent raised bed RW systems in NW India. The development and evaluation of strategies to overcome the problems is still in its infancy. Approaches to build up soil organic matter to help improve soil structure and fertility are needed, as is evaluation of the long-term performance of permanent bed RW cropping systems. The potential gains from being able to direct drill both crops, and the opportunity for flexibility and diversification in response to market opportunities, are worthy of serious pursuit.

Introduction

The rice–wheat (RW) rotation is one of the most important production systems in South Asia, occupying about 13 Mha, with about 10 Mha in India, 2 Mha in Pakistan and 0.5 Mha in each of Nepal and Bangladesh (Timsina & Connor 2001). RW systems in northwestern (NW) India are critical for food security; for example, the small states of Haryana and Punjab contribute 20% of the total national grain production, including 50% and 85% of the government procurements of rice and wheat, respectively (Singh 2000). RW systems in NW India mostly include indica rice grown during the monsoon season

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and spring wheat grown in winter, with insufficient time for a third crop. Traditional rice culture involves puddling to form soft, saturated soil for ease of transplanting and establishment of rice seedlings above a compacted subsoil layer that reduces percolation losses from the ponded fields. Because wheat cannot tolerate the anaerobic conditions in which rice is well established, the dominant feature of RW systems as they are currently practised is the biannual switching between aerobic and anaerobic soil conditions. These conversions have significant effects on the physical, chemical and biological status of the soil, which affects the fertility of both crops; and on the micro-environment, which affects the ecology of the total RW system.

Challenges for the sustainability of RW systems in NW India

The area and productivity of RW systems in NW India increased tremendously during the 1960s to 1990s as a result of the introduction of short-stature high-yielding rice and wheat varieties, increased use of fertilisers and biocides, and expansion of irrigation. The biggest change was the increase in the area of rice. For example, the rice area in Punjab increased from about 0.4 to 2.5 Mha. With current cultural practices, rice consumes very large amounts of irrigation water, typically 1,500 to 3,000 mm (Hira & Khera 2000; Sharma et al 2002; Singh et al 2002). The number of tube wells in NW India increased rapidly as the rice area expanded (eg a 6-fold increase in Punjab in just 20 years), resulting in a rapid decline in groundwater levels in many locations (Harrington et al 1993; Pingali & Shah 1999; Singh 2000; Sondhi et al 1994). In the central zone of Punjab, the area where the watertable was below 10 m increased from 3% in 1973 to 25% in 1990 and 53% in 2000 (Hira & Khera 2000). Thus, water is likely to become the major limiting factor for sustained production in the next decade in the Indo-Gangetic Plain (IGP). It is projected that the watertable in central Punjab will fall below 25 m in 50% of the area in 2013 and 66% of the area in 2023 compared with the current 3% (Hira 2005). Rapidly growing urban areas and industry will compete with agriculture for good quality water. To safeguard food security and preserve precious water resources, ways must be found to grow rice using substantially less water while maintaining high yields.

Yield stagnation, or possibly decline, is also a major issue for RW systems in NW India (Ladha et al 2003). In Punjab and Haryana, district yields have stagnated since 1990. Results of long-term experiments in these states with recommended rates of N, P and K show variable trends, with rice yields changing by -0.11 to $+0.16$ t ha^{-1} yr^{-1}, and with positive but small increases in wheat yields from 0.01 to 0.21 t ha^{-1} yr^{-1}. Furthermore, district yields of both rice and wheat are only about 60% of potential yields. The causes of the yield gap and yield stagnation or possible decline are not known. Ladha et al (2003) suggest that fertiliser recommendations for N and K, and N management, may need to be revised. Soil organic matter has declined to low values (typically 0.3–0.5% C), but whether this is contributing to the problems of yield stagnation and yield gaps is unproven. There is considerable opinion and some evidence that the effects of puddling for rice on soil structure are adversely affecting wheat production. Continuous ponding and high percolation rates for rice on the coarse-textured soils of NW India have led to the development of micronutrient deficiencies for rice (Fe) and wheat (Mn), as well as contamination of groundwater. Global dimming and climate change may also be contributing to the problems of yield stagnation or decline. Air pollution from straw burning, especially rice straw, is also a serious problem for human health in the NW IGP.

Clearly there are many serious challenges to the sustainability of RW systems in NW India. Connor et al (2003) hypothesised that permanent raised bed RW systems could help overcome current constraints on the productivity and sustainability of RW systems. However, they also recognised that successful implementation would require addressing a host of other production and environmental factors which would be affected by such a radical change. There are currently many workers across the IGP attempting to develop and evaluate permanent bed RW systems, many operating under the umbrella of the Rice-Wheat Consortium of the Indo-Gangetic Plains. This paper discusses the implications of changing from conventional tillage to permanent raised bed systems, and reviews the performance of rice and wheat on raised beds in NW India, including the few results available for permanent bed systems.

Implications of changing to raised beds

Switching to furrow irrigated permanent raised beds is a radical change for RW systems, involving cessation of puddling and continuous flooding for rice, and implementation of direct seeding and furrow irrigation on raised beds for both crops.

Avoidance of puddling

The impact of puddling (Figure 1) for rice on the performance of wheat after rice appears to be variable, depending on site history, soil type, degree of puddling and management of the wheat crop (Humphreys et al 2004). Aggarwal et al (1995) and Kukal and Aggarwal (2003a, b) showed that the effects of pud-

Figure 1. Puddling at Phillaur, Punjab, India, in June 2003 (E. Humphreys).

dling on soil physical properties increase with intensity, depth and history of puddling. It may take one to several years before this significantly affects the performance of wheat when starting with a soil with no puddling history or a compacted layer. Puddling for rice induces high bulk density, high soil strength and low permeability in subsurface layers (Aggarwal et al 1995; Kukal & Aggarwal 2003a; Sharma & DeDatta 1986), which can restrict root development and water and nutrient use from the soil profile for wheat after rice (Gajri et al 1992; Ishaq et al 2001; Sur et al 1981). The hardpan also leads to aeration stress in wheat at the time of the first irrigation after sowing, resulting in a yellowing of the leaves which is typical of N deficiency, despite the presence of adequate N in the soil. This problem is widespread in the region (Kukal et al 1995) and may be associated with subsurface compaction or heavy-textured soils. Kukal and Aggarwal (2003b) found that wheat grain yield decreased by 8% after the third year of puddled transplanted rice (PTR) due to the formation of a dense soil layer at 14–20 cm depth and restricted growth of roots in the lower layers. While avoidance of puddling may help improve soil structure and wheat yield, the implications for rice establishment and water use also need to be considered. However, it is well known that puddling *per se* is not a prerequisite for achieving high rice yields.

In changing from puddled flat fields to direct-drilled raised beds on soils with a long history of puddling (and therefore a well-developed hardpan), there is also the question of whether the hardpan should be broken by deep tillage prior to bed formation. There may be implications in doing this for water use and performance of both crops. Gajri et al (1992) showed that for a given wheat yield, higher inputs of water and N were required with zero-tilled wheat compared with conventional and deep (40 cm) tillage after puddled rice on a sandy loam. However, there were no differences in wheat yield, water and N use efficiency between conventional and deep tillage. Nor did McDonald et al (2005) find any effect of deep tillage prior to rice on the performance of wheat after rice on a silty loam with deficit irrigation. These findings are difficult to reconcile with other studies which show that wheat yields decline in the presence of a shallow hardpan, and which reinforce the need for further examination of the desirability of deep soil amelioration to remove the hardpan prior to construction of permanent raised beds.

Avoidance of continuous ponding for rice

Interest in the use of raised beds for RW systems was inspired by success with wheat on beds, where substantial irrigation water savings were achieved, and the prospect of even greater water savings with intermittently irrigated rice on beds. Growing rice on furrow irrigated beds requires the rice to be grown in aerobic or partially aerobic conditions. Therefore, the first prerequisite for rice on beds is its ability to yield well in the absence of continuous ponding.

Rice yields normally decrease as soil water content declines below saturation (Bouman & Tuong, 2001). However, many studies throughout India have shown that continuous ponding is not necessary to maintain rice yields at reasonable levels (Hira & Khera, 2000; Kukal et al 2005; Sandhu et al 1980; Sidhu et al 2004) (Figure 2). Studies from NW India consistently show substantial irrigation water savings (20–40%) with no or small yield loss of PTR when changing from continuous submergence to irrigating 1–3 days after the floodwater has disappeared (Chaudhary 1997; Sandhu et al 1980; Sharma 1999; Sidhu et al 2004). Rice can withstand soil water tensions up to 15–20 kPa (Kukal et al 2005; Sharma 1989), which can occur within 2–5 days after disappearance of ponded water, without a significant reduction in yield. However, all these investigations involved transplanting into puddled soil which was also flooded for the first 2–3 weeks after transplanting. Puddling and flooding help to rapidly create anaerobic conditions by reducing the percolation rate and transport of oxygen into the soil (Ponnamperuma 1972). Rice seedlings are grown in waterlogged nurseries where iron and phosphorus are readily available, and rice plants take up much of their requirement of these elements during this early stage (Shuman 1991). Puddling, transplanting and continuous flooding also offer major benefits for weed control.

Trials in farmers' fields in NW India and Punjab, Pakistan, suggest comparable yields of direct-seeded rice (DSR) on the flat compared with PTR (Gupta et al 2002). However, in replicated experiments on sandy loam and silty loam soils in NW India, iron and zinc

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Figure 2. Puddled transplanted rice (PTR) using continuous flooding (CF) or irrigation 2 days after ponding ceases (2d), transplanted rice on beds (TRB) and direct-seeded rice on beds (DSRB) at Ludhiana, Punjab, India, in September 2004 (E. Humphreys).

deficiency, nematodes and weed control were serious constraints to the productivity of non-puddled, intermittently irrigated DSR (Sharma et al 2002; Singh et al 2002).

Transplanting rice onto beds is a significant change because the top few centimetres of the beds are likely to be aerobic almost all of the time, compared with intermittently irrigated rice on the flat, where the whole area is regularly ponded. The bulk of the soil (10–12 cm) below the raised beds will also fluctuate between aerobic and anaerobic conditions, the degree depending on the frequency, depth and duration of furrow irrigations and rainfall. Direct seeding onto beds is an even bigger change from continuously flooded PTR as the plants must also establish in an aerobic environment.

There are numerous reports of large irrigation water savings when changing from continuously flooded rice to alternate wetting and drying on puddled soils, but whether these field level savings translate into real water savings or simply energy savings is unknown, and will depend on site-specific conditions (Humphreys et al 2004). Water use data from puddled rice in small plots should also be interpreted with great caution due to the possibility of very large edge effects, in particular seepage losses under bunds and the non-puddled ‘borrow’ area adjacent to the bunds (Tuong et al 1994, table 4). Most of the data on the effect of water management for rice on water use in NW India have probably come from small plots by either monitoring the decline in plot water depth or measuring applications onto the plots, although the method is commonly not reported nor compared with in-plot infiltration rate. There is an urgent need for evaluation of the effects of layout and water management on water use and other components of the water balance at the farmer field scale, where edge effects are realistic and quantified.

Performance of rice and wheat on raised beds

Successful production of rice and wheat on beds requires the use of varieties suited to the changed planting geometry (ie with the ability to develop leaf area rapidly to close the furrow gap). This has been demonstrated clearly in the case of wheat (Meisner et al 2005; Ram et al 2005). Meisner et al (2005) found that the highest yielding wheat varieties with conventional tillage also performed well on beds, and suggested that selection for high yield with conventional planting may already produce the desired attributes for beds. Successful production of rice on beds also requires rice varieties suited to aerobic conditions. Meisner et al (2005) emphasised that rice varieties are evaluated and selected under puddled, transplanted, anaerobic conditions, and that breeding and selection for aerobic conditions are urgently needed if permanent bed RW systems are to succeed. For conditions in the NW IGP, useful characteristics would include the ability to absorb iron and phosphorus under aerobic conditions, resistance to cereal cyst nematodes, and good early vigour to better compete with weeds.

Wheat

Many studies across the IGP have shown that wheat can be grown successfully on raised beds in a range of crop sequences and produce similar or higher yields compared with conventional tillage on the flat (Ram et al 2005). Growing wheat on beds has many advantages including reduced irrigation water use (by 30–50%), reduced seed rate (by 25–30%), reduced lodging, reduced waterlogging, reduced germination of *Phalaris minor,* the opportunity for mechanical weeding and fertiliser placement, and improved timeliness of operations due to better surface drainage. However, to date there has been little adoption of wheat on beds in RW systems because the beds have to be destroyed after wheat harvest so the soil can be puddled for rice, then reconstructed again after rice harvest. Adoption of wheat on beds in RW systems is likely to remain low until systems for successfully growing rice on beds are developed, allowing all the advantages of permanent bed RW systems to be realised.

These advantages include direct drilling of both crops, offering large cost savings (diesel, labour, and machinery wear and tear); quicker turnaround between crops (more timely sowing); reduced dependence on labour (labour shortage being a major constraint to establishing rice crops at the optimum time to increase water use efficiency while maintaining yield; Hira & Khera 2000); improved soil structure through controlled traffic and reduced tillage; and reduced greenhouse gas emissions from burning diesel. Importantly, permanent bed systems also offer cropping flexibility – the ability to readily diversify into a range of non-rice or wheat crops in response to market opportunities, in particular the ability to grow waterlogging sensitive crops during the monsoon season (Ram et al 2005).

While there are many advantages to growing wheat on beds, in saline–sodic situations the performance of wheat on beds can be inferior to conventional tillage on the flat (Sharma et al 2002; Yadav et al 2002). On coarse-textured soils, particular care needs to be taken to avoid water deficit stress during establishment, as the soil in the beds dries more rapidly than in flat layouts (Kaur 2003; Yadav et al 2002; Yadvinder-Singh et al 2005b). Finally, the limited available data show that the performance of wheat on permanent beds in RW systems of the NW IGP has generally been inferior to that on fresh beds (see below), although the majority of reports on wheat on beds to date have been for fresh beds.

Rice

There are many reports containing data on yields, irrigation water use and irrigation (or input = irrigation + rain) water productivity of rice on beds in RW systems across the Indo-Gangetic Plains (IGP). However, few of these reports are detailed scientific analyses. There is a lack of contextual information such as experimental design (eg small plots vs farmers' fields; fresh vs permanent beds), site and seasonal conditions, management (especially irrigation), and occurrence of biotic and abiotic stresses. Therefore, it is difficult to know exactly what is being compared, to be able to assess the rigour of the evaluations, interpret results or extrapolate the findings.

Early results of participatory farmer evaluations of rice on beds at Ghaziabad were extremely promising (Table 1) (Balasubramanian et al 2003; Gupta et al 2002) (Figures 3a, 3b). Mean yields of transplanted rice on beds (TRB) on 19 farmer fields were 6% higher than mean yields of puddled transplanted rice

Table 1. Performance of rice on beds in farmers' fields at Ghaziabad, Uttar Pradesh (adapted from Gupta et al 2002 and Balasubramanian et al 2003).

	No. of fields (total area, ha)		Grain yield (% of PTR)		Total irrigation time (% of PTR)
	2000	2001	2000	2001	2001
PTR[a]	8	35 (14)	100	100	100
TRB[b]	–	20 (12)	–	106	61
DSRB[c]	8	22 (14)	96	95	63

[a] PTR = puddled transplanted rice
[b] TRB = transplanted rice on beds
[c] DSRB = direct-seeded rice on beds

Figure 3a. Transplanting rice on beds in farmers' field at Phillaru, Punjab, India, in June 2004 (S.S. Kukal).

Figure 3b. Darryl Gibbs (Australia) admiring transplanted rice on beds in a farmer's field at Ghaziabad, Uttar Pradesh, India, in September 2004 (E. Humphreys).

(PTR), while mean yields of direct-seeded rice on beds (DSRB) in 22 farmer fields were only 5% lower than yields of PTR. Irrigation water pumping time was reduced by 37–40% on beds in comparison with PTR, indicating very large field irrigation water savings. Water management for PTR was not reported. Whether it was managed with continuous ponding or alternate wetting and drying is a very important consideration in assessing whether beds help to save irrigation water, or if the saving was simply a result of using intermittent irrigation which could also be achieved on puddled flat layouts.

As more results emerge, it appears that the performance of rice on beds in the IGP is variable relative to conventional PTR in terms of yield and irrigation or input water use and water productivity (Balasubramanian et al 2003; Gill & Rehman 2004; Gupta et al 2002; Hossain et al 2001; Jat & Sharma 2005; Jehangir et al 2002; OFWM 2002; Sharma et al 2002; Singh et al 2002; Talukder et al 2002). Many reports show similar yields with TRB and conventional PTR, while some find that TRB is inferior. Some reports show similar yields of DSRB and PTR, but most show small to large yield losses with DSRB. The reported causes of reduced rice yield on beds include increased weeds and nematodes, suboptimal sowing depth due to lack of precision, and micronutrient (iron, zinc) deficiencies. Clearly, there are many challenges to be overcome to be able to reliably produce rice on beds with comparable gross margins in NW India.

Many reports indicate irrigation water savings of 12–60% for rice on beds in comparison with PTR, and increased irrigation or input water productivity, especially for TRB. However, some studies in the NW IGP show little effect of rice on beds on input water productivity (typically around 0.30–0.35 g kg^{-1}) because the decline in water input was accompanied by a similar decline in yield (Jehangir et al 2002; OFWM 2002; Sharma et al 2002; Singh et al 2002). As mentioned above, such evaluations need to be done in farmer-size fields where edge effects are realistic.

Permanent bed RW systems

The few available reports of permanent bed RW systems indicate that crop performance on permanent beds can be inferior to both fresh beds and conventional practice, and in some instances yields have declined as the beds get older. However, the oldest beds for which results are currently available are still only 3–4 years old.

Rice

Singh et al (2005) found significantly lower rice grain yield on permanent beds compared with PTR in three consecutive rice seasons (Table 2; Figure 4(a–e)). Rice yield on the permanent beds decreased progressively over the years relative to PTR, from 87–92% of PTR in 2002 to 58–68% of PTR in the low rainfall year of 2004. They did not suggest reasons for the yield decline on permanent beds. In contrast, at four sites in Punjab, India, and Punjab, Pakistan, there were no consistent trends in rice yield on permanent beds over time. However, at the sites in India yields on the permanent beds of the first rice crop (2nd crop) were already significantly reduced compared with PTR due to higher damage from nematodes and/or iron deficiency

In all studies in Table 2, yield of rice on permanent beds was significantly lower than yield of PTR. Across all sites, yield of TRB was generally lower than PTR by 20–25%, while DSRB yield was generally lower by 30–40%. The main causes of lower yield of DSRB in Punjab, India, appeared to be

Table 2. Yields of rice and wheat in permanent bed RW experiments.

Rice t'ments	Wheat t'ments	Layout	Grain yield, t ha^{-1} 2002 Rice	2002–03 Wheat	2003 Rice	2003–04 Wheat	2004 Rice	2004–05 Wheat	Mean Rice	Mean Wheat
	Marginally sodic silty loam; 3 replicates, plots 15 m × 6.7 m; Modipuram, U.P., India (Singh et al 2005)									
PTR	CTW	Flat	7.27		7.20		8.80		7.76	
TRB	DDW	Perm. beds	6.71		6.30		6.00		6.34	
DSRB	DDW	Perm. beds	6.29		5.40		5.10		5.60	
LSD (0.05)			0.45		0.80		1.10			
	Sandy loam; 4 replicates, plots 12 m × 7 m; Ludhiana, Punjab, India (Yadvinder-Singh 2005)									
PTR	CTW	Flat		4.78	5.71	3.75	6.03	3.78	5.87	4.10
PTR-CF[a]	WB	Flat / fresh beds	4.26	6.12	4.11	5.61	3.10	5.87	3.82	
TRB	DDWB	Perm. beds		4.26b	4.63	4.01	4.16	3.02	4.40	3.52
DSRB	DDWB	Perm. beds		4.26b	3.79	3.13	4.10	2.89	3.95	3.01
LSD (0.05)				0.41	0.65	0.46	0.65	0.38		
	Loam; 4 replicates, plots 12 m × 1 m; Phillaur, Punjab, India (Yadvinder-Singh 2005)									
PTR	CTW	Flat		4.70	5.02	4.52	6.22	4.90	5.81	4.83
PTR-CF	WB	Flat / fresh beds	4.60	5.76	4.90	5.85	4.26	5.62	4.46	
TRB	DDWB	Perm. beds		4.60[b]	4.64	4.79	3.74	4.41	4.19	4.60
DSRB	DDWB	Perm. beds		4.60[b]	3.32	4.60	1.51	4.44	2.42	4.52
LSD (0.05)				n/s	0.37	0.43	0.57	0.25		
	Sandy loam; 4 replicates, plots 2.7 m × 12 m; Ludhiana, Punjab, India (Yadvinder-Singh 2003, 2004, 2005)									
PTR	CTW		7.57	4.46	6.63	4.96	7.05	4.11	7.08	4.51
TRB	DDWB	Perm. beds	5.70[b]	3.82	5.78	4.64	5.32	3.59	5.60	4.02
TRB	DDWB	Perm. beds + mulch	6.07[b]	4.06	5.86	4.76	5.53	3.84	5.82	4.22
DSRB	DDWB	Perm. beds	5.50[b]	3.78	4.06	4.67	4.06	3.52	4.54	3.99
DSRB	DDWB	Perm. beds + mulch	4.63[b]	3.94	2.65	4.78	4.17	3.59	3.82	4.10
LSD (0.05)			0.37	0.42	0.56	0.52	0.54	n/s		
	3 sites (replicates), 0.5 acre fields; Punjab, Pakistan (Gill & Rehman 2004)									
PTR	CTW	Flat	3.83	3.30	3.85	3.45	3.95	3.08	3.88	3.28
TRB	WB	Fresh beds	3.70	3.75	3.53	3.80	3.05	3.45	3.43	3.67
TRB	DDWB	Perm. beds	3.10	3.70	3.40	3.23	3.20	2.63	3.23	3.19

[a] CF = continuous flooding;

[b] fresh beds in first crop, permanent beds thereafter

iron deficiency and poor establishment (especially at Phillaur in 2004, probably due to sowing too deep) (Yadvinder-Singh et al unpublished). Cereal cyst nematodes were also a serious problem for TRB on the sandy loam in 2003; and weeds were a major problem for both TRB and DSRB, but DSRB required more hand weeding.

Soil tension in permanent beds on the sandy loam and loam soils in Punjab fluctuated closely around 10 kPa at 10 cm depth, similar to (or wetter than) the values in PTR with the same irrigation scheduling, suggesting that soil moisture status was adequate for the rice on beds (Yadvinder-Singh et al unpublished). Sharma et al (2002) also observed that rice grain yield was halved from 10.3 $t\ ha^{-1}$ in PTR with continuous flooding to 5.0 $t\ ha^{-1}$ on beds irrigated when soil tension at 15 cm depth increased to 10 kPa. Delaying irrigation until the tension increased to 20 kPa had little further effect on rice yield. It is notable that rice yields on the puddled flat layouts were so much higher than on the beds, despite similar irrigation management and matric potential at shallow depths in PTR and beds in both studies.

While there are many reports of significant water savings for rice on beds, this is not always the case. In a replicated small plot experiment on 3-year-old beds, Singh et al (2005) found much higher irrigation water use with DSRB (3,634 mm) than with PTR (2,390 mm), while irrigation water use with TRB (2,581 mm) was only 8% higher than with PTR (Table 3). Possible reasons include longer growth duration of the direct-seeded rice, and higher percolation losses from the unpuddled furrows and macropores which may develop in the permanent beds/furrows. On 1- and 2-year-old permanent beds, Kukal et al (unpubl) found similar irrigation water

Figures 4(a–e). Rice and wheat yields on fresh and permanent beds relative to puddled transplanted rice on the flat.

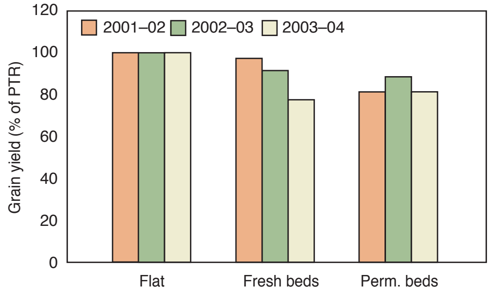

Figure 4a. Rice in Punjab, Pakistan (Gill & Rehman, 2004).

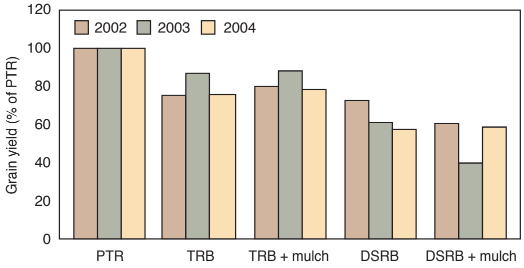

Figure 4b. Rice on sandy loam in Punjab, India (Yadvinder-Singh 2003, 2004, 2005) – starting with fresh beds in 2002.

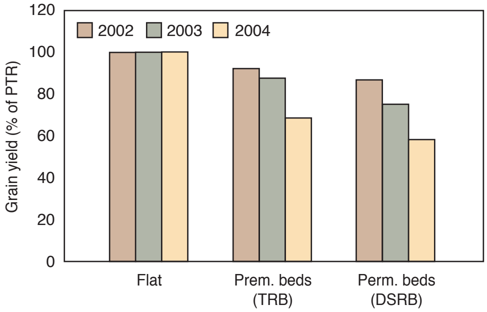

Figure 4c. Rice on silty loam in Uttar Pradesh, India (Singh et al 2005).

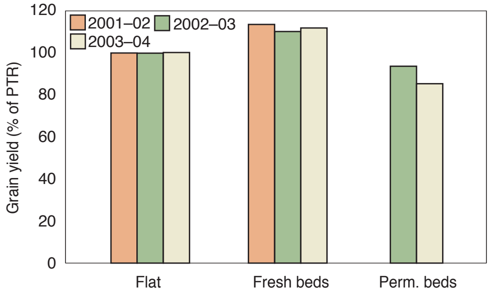

Figure 4d. Wheat in Punjab, Pakistan (Gill & Rehman 2004).

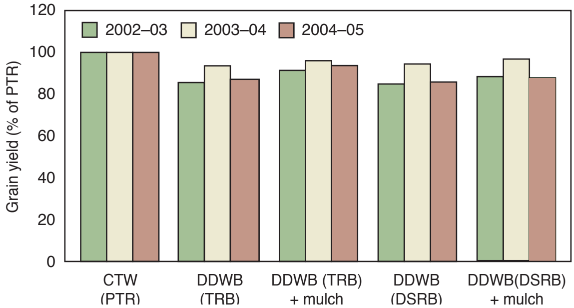

Figure 4e. Wheat on sandy loam in Punjab, India (Yadvinder-Singh 2003, 2004, 2005).

use for DSRB and TRB as for PTR with the same irrigation scheduling (ie irrigating 2 days after the free water has disappeared) on a sandy loam in both years, but about 20% higher irrigation water use on the permanent beds on the loam in both years (Table 3).

Irrigation water use in TRB on the loam was about 6% higher than in DSRB in both years, due to the delayed maturity and extended irrigation period of the DSRB by up to 3 weeks (Yadvinder-Singh et al unpublished). In the 1-year-old beds/furrows, the infiltration rate in continuously ponded furrows was

Table 3. Irrigation water use (mm) in rice on flats and beds in small plot replicated experiments in NW India.

	Sandy loam Ludhiana Punjab		Loam Phillaur Punjab		Silty loam Modipuram Uttar Pradesh	Silty loam New Delhi	Silty loam Modipuram
	2003	2004	2003	2004	2001	2001	2004
Rain–PTR	541	302	587	395	360	249	444
Rain–beds	541	312	587	452		361	466
PTR–CF[a]	4311	3256	3170	4353	3880	1360[e]	
PTR	2238[b]	2661[b]	1675[b]	2325[b]			2390[i]
TRB	2306[b]	2309[b]	2055[b]	2612[b]			3634[i]
DSRB	2339[b]	2532[b]	2176[b]	2778[b]	1990[c]	567[e,f]	2581[i]
DSRB					1710[d]	497[e,g]	
DSRB						419[e,h]	
DSRB–CF	4946	4420					
Source		Kukal et al (unpubl)			Sharma et al (2002)	Singh et al (2002)	Singh et al (2005)

[a] CF = continuous flooding
[b] irrigated 2 days after ponding ceased
[c] irrigated when soil tension at 15 cm mid-bed increased to 10 kPa
[d] irrigated when soil tension at 15 cm mid-bed increased to 20 kPa
[e] data do not include irrigation prior to cultivation, bed formation and puddling
[f] irrigated to keep soil tension in furrow between 0 and 10 kPa
[g] irrigated when soil tension at 20 cm mid-bed increased to 20 kPa
[h] irrigated when soil tension at 20 cm mid-bed increased to 40 kPa
[i] water management not known

almost triple that in continuously flooded PTR on the sandy loam (seasonal mean 4.3 vs. 12.7 mm d^{-1}) (Figure 5), despite the presence of a hardpan within the 15–30 cm layer as a result of a long history of puddled rice. In contrast, infiltration rates were similar in PTR and the furrows of the permanent beds on the loam (5.2 vs. 6.6 mm d^{-1}).

Sharma et al (2002) also found a higher seasonal mean percolation rate in 1-year-old TRB (20 mm d^{-1}) compared with PTR (12 mm d^{-1}). In the beds irrigated 2 days after the furrows had drained on the loam, there was significant cracking between irrigations, which may have increased bypass flow (Kukal et al unpubl data). They also observed increased numbers of old rat holes in direct-seeded permanent beds compared with puddled transplanted flats and transplanted beds. Soil and irrigation water management practices need to be developed for furrow irrigated permanent beds to minimise deep drainage losses from the intermittently irrigated furrows. Water depth and frequency of irrigation could be manipulated to minimise the hydraulic head and cracking. Some form of tillage and/or compaction of the furrows may be needed to close macropores (such as rat holes) and cracks that develop during the long hot dry period prior to rice establishment in cracking soils.

Only a few studies report infiltration rates as well as total irrigation applications (or water use based on decline in plot water depth) (Table 4). The few available data suggest that edge effects (seepage losses under and adjacent to bunds) in small plots can be huge, accounting for more than 50% of the total water balance. Edge effects in small plots, with typical perimeter:area ratios of 0.4, are unlikely to be representative of farmers' fields (typically 1 acre, with a perimeter:area ratio in a square 1-acre field of 0.06). Determination of components of the water

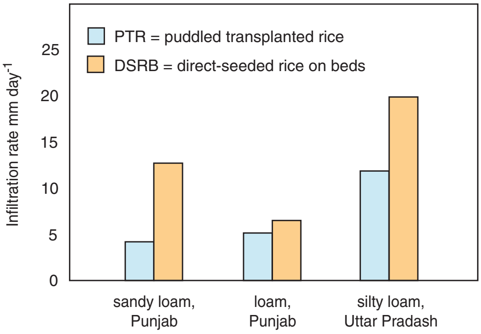

Figure 5. Infiltration rate in puddled transplanted rice compared with rice on permanent beds (measurements made in furrows in Punjab and in beds in Uttar Pradesh).

Table 4. Water balance components (mm) of continuously flooded, puddled transplanted rice in replicated small plot experiments.

Soil	Location	Irrig + rain	ET	Infiltration	Seepage^{c}	Source
Loam 2003	Phillaur, Punjab	3757	684^{b}	457	2616	Kukal et al (unpublished)
Sandy loam 2004	Ludhiana, Punjab	3558	482^{b}	523	2553	Kukal et al (unpublished)
Silty loam 2001	Modipuram, UP	4240	1020^{a}	996	2224	Sharma et al (2002)
Sandy loam 2003	Ludhiana, Punjab	4852	631^{b}	404	3817	Kukal et al (unpublished)
Loam 2003	Phillaur, Punjab	3757	684^{b}	457	2616	Kukal et al (unpublished)
Sandy loam 2004	Ludhiana, Punjab	3558	482^{b}	523	2553	Kukal et al (unpublished)
Loam 2004	Phillaur, Punjab	4748	520^{b}	515	3713	Kukal et al (unpublished)

^{a} estimated from meteorological data using modified Penman equation

^{b} estimated from meteorological data using CSM-CERES Rice

^{c} calculated: seepage = I + R – ET – Infiltration

balance in farmers' fields for different soil and water management is urgently needed.

Wheat

Results to date show a consistent trend for higher yields of wheat on fresh beds compared with permanent beds in RW systems (Table 2; Figures 4, 6(a–c)). Gill and Rehman (2004) found that wheat yield on permanent beds declined over time relative to conventional practice and fresh beds, and ascribed this to the permanent beds becoming hard and dense. However, there are few data to date to support this hypothesis. Yadvinder-Singh et al (unpublished) found higher unsaturated hydraulic conductivity and root length density (at 0–15 cm depth) in fresh beds compared with permanent beds on a sandy loam and, corresponding with this, significantly higher yields on the fresh beds. Conversely, on a loam soil there were no significant differences in conductivity or root length density between the fresh and permanent beds but, consistently, yields were also similar. There was no trend for wheat yield decline in permanent beds compared with that after PTR on a sandy loam at a site adjacent to the above sandy loam site (Yadvinder-Singh 2003, 2004, 2005). However, yield on the permanent beds was already significantly lower than with conventional tillage in the first wheat crop (2nd crop).

Figures 6(a–c). Wheat after rice at Ludhiana, Punjab, India, in February 2004 (E. Humphreys).

Figure 6a. Direct-seeded wheat on permanent beds after direct-seeded rice.

Figure 6b. Conventionally tilled wheat after puddled transplanted rice.

Figure 6c. Fresh beds after puddled transplanted rice.

Total system performance

The total productivity, resource use efficiency (especially water) and financial performance of permanent bed RW systems compared with conventional practice have received little attention to date. Yadvinder-Singh et al (2005) found average total annual system production of 9.5–10.5 t ha^{-1} for conventional RW systems on two soil types in Punjab. The introduction of permanent beds lowered total production to 8.6–9.2 t ha^{-1} where rice was transplanted onto the beds, and to 6.1–8.1 t ha^{-1} where the rice was direct seeded onto the beds. Components of the water balance need to be determined for the entire rice–wheat–fallow sequence for different soil and water management strategies in full-sized farmers' fields.

Straw management for permanent bed RW systems

Stubble management may be an important factor in improving soil physical, chemical and biological properties and maintaining yields in permanent bed systems. In a maize–wheat system in Mexico, Sayre et al (2005) found that after the first 5 years, wheat yields on permanent beds declined with residue burning compared to residue retention. The yield advantage appeared to be associated with gradual improvements in a range of soil properties where tillage was reduced and crop residues retained (Limon-Ortega et al 2000). In most of the RW studies in Table 2 the residues were manually removed. However, studies by Yadvinder-Singh (2003, 2004, 2005) included treatments with residue retention, in which 6 t ha^{-1} of rice and wheat straw were mulched immediately after sowing wheat and rice, respectively. There were no differences between the mulched and non-mulched treatments during crops 2 to 6, and no interaction between N application rate and stubble management on yield during the first six crops. Clearly, long-term studies on residue retention for permanent bed systems are required.

With widespread mechanisation and the use of combine harvesters in NW India, the majority of rice residues and significant amounts of wheat straw are burnt in the field, creating serious air pollution in addition to the loss of nutrients and soil organic matter (Gajri et al 2004; Yadvinder-Singh et al 2005). Adoption of stubble retention requires the development of machinery with the capability of sowing into rice residues. Even then, farmers are unlikely to retain stubbles unless significant advantages can be demonstrated (eg yield increase, reduced fertiliser requirement) or unless they are forced by implementation of government policy. Government policy to ban stubble burning was introduced in Punjab in 2003 but it has not been strictly implemented to date.

Direct drilling into rice stubble is a particular problem because of the tough nature of rice straw, which leads to clogging of machinery with loose straw and 'hair-pinning' (failure to cut the straw, resulting in the seed remaining on or near the surface). There has been considerable progress in the development of technology for direct drilling into stubbles on the flat, including double- and triple-disc assemblies, the star wheel punch planter (RWC 2002) and the 'Happy Seeder' (Sidhu et al 2005). The Happy Seeder combines the stubble mulching and seed drilling functions into the one machine, and is further described by Ram et al (2005). Versions are available which can be used in flat or bed layouts by simply changing the seed drill behind the mulcher (Figures 7a–c). The impact of mulching on components of the water balance for RW systems needs to be evaluated.

Figure 7a. Sowing wheat into rice stubble on beds with first prototype of the Happy Seeder at Ludhiana, October 2002 (John Blackwell).

Conclusions

The RW systems of NW India are critical to the country's food security. However, yield stagnation or decline since the 1990s, and the large gap between potential and farmer yields, are major concerns given the need to increase production to match population growth. Declining soil organic matter and soil structure as a result of puddling are likely contributors to the inability to raise yields. Furthermore, current rates of extraction of groundwater for RW systems are not sustainable, causing rapid watertable decline.

Use of permanent raised beds has been proposed as a means to increase the productivity, profitability and sustainability of RW systems, principally through improving soil structure and drainage for wheat, direct drilling of both crops, and reducing irrigation requirements for both crops through furrow irrigation. The benefits of growing wheat on beds

Figure 7b. L to R Wheat establishment through 4, 8 and 0 t ha^{-1} of rice mulch (sown by Happy Seeder, then mulch removed and redistributed to create three rates) (E. Humphreys).

Figure 7c. Direct-drilled wheat on permanent beds with four N rates (foreground L to R 0, 120, 80, 160 kg ha^{-1} N) at Ludhiana, Punjab, India, in February 2004. Plots in the foreground were all mulched with 6 t ha^{-1} rice stubble after sowing (all rice stubble removed prior to sowing) (E. Humphreys).

compared with conventional tillage include similar or higher yields and reduced irrigation applications. However, in the few reports to date on permanent raised bed RW systems, the performance of wheat on permanent beds has been variable, and usually inferior to fresh beds, possibly due to permanent beds becoming very hard and dense over time. In most of these studies the straw was probably removed. Given the low organic matter status and coarse texture of the soils of NW India, long-term evaluation of permanent bed RW systems, including organic matter and stubble management, is urgently needed.

The performance of rice on beds in NW India has been variable, but generally disappointing to date. Even with similar irrigation scheduling, yields of TRB on permanent beds are generally 20–25% lower than PTR despite similar soil water tensions at 10–15 cm depth. Yield loss with DSRB is even higher (30–40%), with serious problems of iron deficiency, weeds, variable sowing depth and sometimes nematodes. Strategies for overcoming all these problems are urgently needed, as is breeding and selection for rice grown in aerobic soil and for wide row spacings between beds.

There are many reports of substantial irrigation water savings with rice on beds compared with PTR; however, almost none describe the water management used in the comparisons. Some studies suggest that where similar irrigation scheduling is used (eg irrigating 2 days after the floodwater has disappeared), irrigation water use of transplanted rice on beds and puddled flats is similar, or even higher on beds due to higher percolation rates in the non-puddled furrows and longer duration of direct-seeded rice. Irrigation and soil management strategies to reduce potential bypass flow losses through macropores such as rat

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holes and cracks may need to be included in designs for rice on permanent beds.

Many of the studies on the impacts of water management on irrigation water use in PTR in NW India have been done in small plots, where edge effects (seepage losses under and adjacent to the bunds) can dominate the water balance. There is an urgent need to evaluate the impact of water management and bed systems in full-size farmer fields, where edge effects are much smaller and irrigation times (and opportunity for deep drainage losses) are realistic. An important part of this evaluation is the quantification of components of the water balance. This is needed to assess the potential for real water savings (reduced unrecoverable losses) as opposed to simple energy savings due to reduced deep drainage losses to the groundwater, from where the water can be recovered by pumping.

There are many challenges to be overcome to develop profitable, productive permanent raised bed RW systems in NW India. The development and evaluation of strategies to overcome the problems is still in its infancy. Approaches to build up soil organic matter to help improve soil structure and fertility are needed, as is long-term evaluation. The potential gains from being able to direct drill both crops, and the opportunity for flexibility and diversification in response to market opportunities, are worthy of serious pursuit.

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Performance of upland crops on raised beds in northwestern India

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Abstract

Over the past decade there has been increasing interest in the development, evaluation and adoption of raised bed planting technology for a wide range of crops in northwestern (NW) India. This interest has arisen from initial success with planting wheat on raised beds, from associated opportunities for intercropping and crop diversification (including financial benefit for farmers), and from the large irrigation water savings being achieved on beds. Serious concern about the sustainability and productivity of the dominant rice–wheat cropping system is also driving the search for crops with a lower water use requirement than rice. Raised beds offer possibilities of diversifying to waterlogging sensitive crops such as soybean and maize during the monsoon season, and of increasing yields by irrigation of winter crops sensitive to waterlogging, such as chickpea.

Many studies report similar or higher yields for crops on beds compared with flats; and large reductions (by 30–50%) in irrigation used for wheat on beds, with smaller reductions for summer crops on beds. Permanent raised beds offer the additional possibility of direct drilling, and of reducing tillage costs and associated greenhouse gas emissions. However, there have been very few studies to date of permanent beds, or direct drilling of crops on permanent beds, in NW India. There are no long-term studies to evaluate crop performance; effects on soil physical and chemical properties; components of the water balance; or effects of weeds, diseases and pests. There are also few reports to date on residue and soil management for crops on permanent beds, and optimum bed geometry for different soil types. Varietal evaluation and selection and breeding for beds are also needed for the range of crops that could potentially be grown on beds in NW India, as is fine tuning of the agronomy including sowing geometry and rate, and irrigation and nitrogen management. Concurrently, changes in crop price support and input subsidy policies of the Government of India and State Governments, as well as marketing reforms, are needed to enable diversification from traditional rice–wheat systems.

Introduction

Challenges for cropping systems in NW India

Northwestern (NW) India is the home of the 'green revolution'. Between the 1960s and 1990s there were rapid increases in the yields and areas under cultivation of rice and wheat, and of rice–wheat (RW) cropping systems, due to adoption of improved rice and wheat varieties, increased use of chemical fertilisers and pesticides, and expansion of irrigation (Ladha et al 2000; Woodhead et al 1994; Yadav et al 1998). The Government of India rice and wheat price support system and subsidies on fertilisers, together with State Government subsides for irrigation water and power, made RW systems the most profitable use of land. Rice replaced traditional crops of maize, sorghum, pearl millet, cotton, groundnut and pulses, while wheat replaced barley, pulses and mustard. Between 1970–71 and 2001–02, the area of rice in Punjab increased from 0.39 to 2.49 Mha while the wheat area increased from 2.30 to 3.42 Mha. The small states of Punjab and Haryana now contribute about 54% and 84% of the total Indian Government

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rice and wheat procurements, respectively. As the area of rice increased in Punjab, the area of maize decreased from 0.56 Mha in 1970–71 to 0.17 Mha in 2001–02 (www.punjabgov.net). Over a slightly longer period (1960–61 to 2001–02) the area of pulses in Punjab decreased from 0.90 to 0.05 Mha and the area of oilseeds from 0.19 to 0.08 Mha.

Over the past decade rice and wheat yield growth rates have declined or stagnated (World Bank 2003), coinciding with a decline in soil organic matter levels, development of micronutrient deficiencies, formation of a hardpan at 15–20 cm depth, and build-up of weed, pathogen and pest populations. Furthermore, the environmental sustainability of RW cropping systems in NW India is threatened by unsustainable rates of groundwater extraction, groundwater pollution and atmospheric pollution (particulates, greenhouse gases). Ponded rice is a profligate user of water because of the very high evaporative demand during summer (especially prior to the onset of the monsoon), the permeable nature of the soils in NW India, and the fact that rice yield declines as the soil dries below saturation (Bouman & Tuong 2001; Hira & Khera 2000). The adoption of a heavily irrigated rice culture on non-ideal soils (eg highly permeable sandy loams) in NW India led to micronutrient deficiencies, including Fe deficiency in rice due to insufficient reduction and solubilisation of Fe, and Mn deficiency in wheat (Nayyar et al 2001). The shift from upland crops such as maize to rice also led to deterioration in soil physical conditions and reduced wheat yields (Meelu et al 1979; Sur et al 1981). The urgent challenge facing NW India is therefore the development of alternatives to RW cropping systems in their current form. Such systems must be profitable for farmers and environmentally sustainable. Achieving this will require changes in government support, price and subsidy policies, and reform of the marketing system (World Bank 2003).

A range of 'resource conserving technologies' (RCTs) is under development for RW and alternative systems, and much of this work is being done under the umbrella of the Rice Wheat Consortium for the Indo-Gangetic Plains (IGP) (Gupta et al 2002; Hobbs & Gupta 2003). The goals of these technologies include increasing profitability for farmers, increasing food production and its nutritional value to match population growth, and environmental sustainability. Achieving these goals will require increasing both the productivity and the water and nutrient use efficiency of cropping systems, reducing water use, reducing atmospheric and groundwater pollution, and reversing the decline in soil organic matter content. RCTs at various stages of investigation, development and adoption include direct drilling, retention of stubbles, raised beds, laser levelling, and use of leaf colour charts for guiding N application.

The development and rapid adoption of direct drilling of wheat into rice stubble has been a major advance in reducing production costs, increasing yields and reducing greenhouse gas emissions (no burning of diesel for tillage) (Hobbs & Gupta 2003; Malik et al 2004). Zero tillage, especially with retention of residues, has the potential to reverse the decline in soil organic matter and improve soil nutrient supply and structure (Rasmussen & Collins 1991). Bed planting, another promising RCT, was introduced for wheat in the mid 1990s and produced similar or higher yields compared with conventional tillage and sowing on the flat. Furthermore, bed planting offers many other benefits, including the opportunity for mechanical weed control as well as reductions in lodging, sowing rate and waterlogging. Irrigation water use is also greatly reduced (by 30–50%) on beds in NW India, but whether this is a total water saving is uncertain (Humphreys et al in press).

In addition to the need for improved cultural practices, the need to diversify away from RW systems is now recognised, and in particular to diversify away from rice because of its high water use requirement. It has been suggested that reducing the area of rice in Punjab by 1 Mha would solve the problem of unsustainable extraction of groundwater, and this is the goal that the state has set for itself (World Bank 2003). While many other crops are currently grown in rotation with rice and wheat in NW India, their total production is very small. These crops include maize, chickpea, lentil, oilseed rape, mustard, fodder crops and vegetables in winter (November–May); and maize, soybean, green gram, pigeon pea, sorghum fodder, sugarcane and vegetables in summer (June–October) (Timsina & Connor 2001). Crop diversification should also reduce problems of diseases, pest damage and weeds, and improve nutrient use efficiency. However, many of these alternative summer and winter crops are sensitive to waterlogging (eg maize, soybeans, cotton, chickpea) (Bishnoi & Krishnamoorthy 1991; Chandrakar et al 1991; Dhillon et al 1998a; Grieve et al 1986; Patel et al 1987; Singh & Ghildyal 1980; Thongbai et al 2001; Wein et al 1979).

Raised beds offer the potential to reduce waterlogging stress through improved surface drainage, and the opportunity to diversify into waterlogging sensitive crops. Permanent raised beds add the opportunity for direct drilling of all crops in the system, with associated benefits including rapid turnaround between crops and reduced tillage costs and greenhouse gas emissions. Improved soil structure and nutrient status result from a reduction in oxidation of soil organic matter and disruption of biopores during tillage. Permanent beds also enable crop flexibility, rapid response to market opportunities and intercropping. At present the main application of permanent beds in NW India is intercropping of sugar cane with other crops, predominantly mustard and wheat, with approximately 24,000 ha in 2004–05 (R. Gupta, pers comm). Permanent beds with stubble retention have the potential to further improve soil organic matter status, reduce soil evaporation and reduce atmospheric pollution from stubble burning.

Research on raised beds in NW India began in earnest with wheat in the mid 1990s, followed soon after by other crops, and was inspired by the achievements in wheat–maize systems in Mexico (Meisner et al 1992). Most reports in the literature on beds in NW India relate to fresh beds and individual crops, with few reports on permanent raised beds and cropping systems. This paper reviews the performance of non-rice crops on both fresh and permanent beds in NW India, and in particular in the state of Punjab.

The climate and soils of NW India

The climate of NW India is characterised by hot, wet summers and cold, dry winters. Annual rainfall ranges from 400 to 800 mm, increasing from west to east, and is equivalent to around 40% of pan evaporation. About 80% of the rain falls during the monsoon season. The soils of the region are predominantly coarse-textured sands, loamy sands, sandy loams and loams with smaller areas of clay loams, silty clays and clays. Traditional rice soils have loam to clay loam texture, but the non-traditional rice soils, which came under cultivation to rice from the mid 1970s, are coarser textured and more permeable sands, loamy sands and sandy loams. Currently, about 60% of the rice soils of Punjab are non-traditional rice soils. Soil organic carbon (0–15 cm) has decreased from 0.5% in the 1960s to 0.2% in the late 1990s (Sinha et al 1998). The lack of recycling of organic matter is considered to be the principal cause of this decline.

Bed planting

Raised beds are formed by moving soil from the furrows to the area of the bed, thus raising its surface level. The furrows serve as irrigation channels, drains and traffic lanes. Changing from flat to bed layouts alters the hydrology of the system and allows greater control of irrigation, better surface drainage and possibly better capture and use of rainfall. The irrigation water moves laterally from the furrow into the bed, and is driven upwards towards the bed surface by evaporation and capillarity, and downwards largely by gravity. The altered hydrology affects nutrient transformations and transport compared with irrigation on the flat. For example, transport of solutes towards the surface of the beds can create problems such as salinisation of the seed zone and reduced availability of nutrients to the crop. Normally only the top of the bed is planted, in defined rows, but in some situations the furrows or sides of the beds may also be planted.

Ridges are similar to raised beds, and there are several reports on the performance of crops grown on ridges in India going back to the 1970s, well before the introduction of bed planting in the mid 1990s. Ridges are similar to narrow beds, and are either constructed manually or by using a potato ridger for experimental purposes, then sown manually. Typically, they are about 25–30 cm high with about 50–70 cm between furrows. For many years farmers have also created ridges using a pair of discs, into which they manually plant potatoes.

The first bed planter in NW India was developed in 1995 by Dr S.S. Dhillon of Punjab Agricultural University and M/s A.S.S. Foundry and Agricultural Works, Jandiala, Amritsar. It was a major breakthrough in the introduction of bed planting to the region, providing the capability of simultaneously forming and planting the beds (Figure 1), and later doing inter-row cultivation by removing the bed shapers and attaching inter-row weeding tines (Dhillon et al 1998b).

Performance of non-rice crops on beds in NW India

Field experiments evaluating raised beds for non-rice crops have been conducted at a range of locations in NW India (in Delhi, Haryana, Punjab and Uttaranchal states). Most of these studies involved the use

Figure 1. Bed formation/sowing with bed planter (J. Timsina).

of fresh beds, where cultivation of a flat field was followed by bed formation and then destruction of the beds prior to tillage and establishment of the next crop. There are very few reports for crops and crop sequences on permanent beds. In permanent bed cropping systems, the beds are commonly reshaped using the bed planter. This usually involves cleaning out the furrows and returning the soil to the beds, then reshaping in a single pass at the same time as sowing, with minimal disturbance of the soil in the bed. Occasionally, renovation is carried out, which involves additional disturbance of the soil in the beds with tines. Unless specified otherwise, the studies in NW India used a bed spacing of 67.5 cm mid-furrow to mid-furrow, a furrow depth of 15 cm and a width at the top of the bed of 37.5 cm. Features of typical bed planters are described in Yadav et al (2002a).

Winter crops

Wheat

The performance and management of wheat on beds has been studied far more comprehensively than for any other crops in NW India, in both replicated experiments and farmers' fields. The majority of this work has been for wheat on beds grown in rotation with puddled transplanted rice. After rice harvest the stubble is burnt, the soil cultivated and the wheat normally planted simultaneously with bed formation. Unfortunately, reports on the performance of wheat on beds generally do not indicate whether the wheat was grown in rotation with rice or with other crops. This may be an important consideration as fields with a history of puddled flooded rice are likely to have altered chemical and physical properties, such as reduced availability of micronutrients and a hardpan at 15–20 cm. Research on bed planting of wheat in NW India commenced at Punjab Agricultural University (PAU) in 1994. The new technology of growing wheat on raised beds became a recommended package of practices to the farmers of Punjab in 2002 (PAU 2002–03). While the technology has many advantages, adoption has been relatively slow, with an estimated 4000 ha of wheat on beds in Punjab in 2004–05 as a sole crop (eg Figure 2) or intercropped with sugarcane or mentha.

Experience over the past 10 years has shown that wheat can be grown successfully on beds in NW India, with similar or higher yields and lower irrigation water use than for conventional sowing (Aggarwal & Goswami 2003; Dhillon et al 2000; Hobbs 2001; Hobbs & Gupta 2003; Kaur 2000; Kaur, C. 2003; Kumar 2002; RWC 2004, 2005; Shivakumar & Mishra 2001; Singh 1995; Singh et al 2002; Yadav et al 2002b; Yadvinder-Singh et al unpublished data) (Tables 1–2). While tiller and spike density are generally lower on beds, this is compensated for by more grains per spike and higher grain weight. Beds also confer additional advantages including reduced seed rate requirement (by 25–30% – Dhillon et al 2004), reduced germination of *Phalaris minor*, reduced irrigation water requirement (by 30–50%), reduced waterlogging (especially in soils with low permeability – Gill et al 1993; Sharma & Swarup 1988), opportunity for mechanical weed control and fertiliser placement, reduced lodging and opportunity for intercropping. With conventional flat layouts many farmers in Punjab do not irrigate after heading to minimise the risk of lodging and associ-

Figure 2. Dr Tony Fischer and Dr S.S. Dhillon inspect wheat growing on beds in Punjab, NW India (E. Humphreys).

Table 1. Yields of wheat on flats and raised beds in replicated experiments at locations across northwestern India.

Location	Grain yield (t ha^{-1})		Reference
	Flat	Raised bed	
Delhi	4.93	4.99	Shivakumar & Mishra (2001)
Haryana	5.67	5.50	Singh (1995)
Haryana			Yadav et al (2002)
non-saline soil	4.83	5.07	
saline soil	4.00	2.33	
Punjab	5.45	5.67	Kaur (2000)
Punjab	3.48	3.68	Kumar (2002)
Punjab	4.62	4.29 (2 rows × 70 cm bed)	Dhillon et al (2000)
	4.62	4.38 (3 rows × 70 cm bed)	
	4.22	4.37 (2 rows × 65 cm bed)	
Uttaranchal	5.00	5.19	Hobbs (2001)

Table 2. Performance of wheat on beds in farmers' fields at Karnal, Haryana, and various locations in Punjab.

Year	No. of locations	Total area (ha)	Time required for irrigating one ha (hours)		Grain yield (t ha^{-1})	
			Bed	Flat	Bed	Flat
			Haryana			
1997–98	3	1.2	7	14	4.46	4.11
1998–99	8	6.0	5	9	5.20	5.00
1999–00	16	14.0	6	11	5.66	5.43
2000–01	9	20.0	6	12	5.82	5.51
Mean (total)	(36)	(41.2)	6	11.2	5.29	5.01
			Punjab			
3 years	8	–	–	–	5.74	5.46

Source: Singh et al (2002) for Haryana; Dhillon et al (2002) for Punjab

ated yield loss. As a result water can become limiting during grain filling, suppressing yield (Hobbs 2001). Beds offer the opportunity for higher yields by increasing irrigation and N application with reduced risk of lodging.

However, there are some situations where the performance of wheat on beds has been inferior to that on flats using varieties suited to beds (Sharma et al 2002; Yadav et al 2002b; Yadvinder-Singh et al unpublished data). It is important to understand the causes of lower yield to help identify the best management to increase yields on beds, and situations where beds are less suited than conventional layouts. Sharma et al (2002) reported significantly lower (by 16–18%) wheat yield on beds compared with flats sown on a marginally sodic silt loam. This may have been due to accumulation of salts on the beds, as evidenced by higher pH in the top 10 cm at flowering. On a salt-affected soil (pH 9.0, EC 0.80 dS m^{-1}) with saline irrigation water (EC 7.5 dS m^{-1}) grain yield of wheat was markedly reduced on beds (2.33 t ha^{-1}) compared to flats (4.00 t ha^{-1}) due to accumulation of salts on the surface of the beds (Table 1; Yadav et al 2002). Yadvinder-Singh et al (unpublished data) found significantly lower yields (by 11%) of wheat on fresh beds on a sandy loam, which appeared to be due to water deficit stress and lack of tillering during the vegetative stage. The results highlighted the need for earlier irrigation after sowing on beds because of the more rapid drying of the soil on the beds. On the same soil a year later, yields of wheat on permanent beds (3rd crop) after direct seeded rice were inferior to yields on fresh beds with both conventional tillage and zero tillage. However, yields of wheat on permanent beds after transplanted rice were similar to yields on fresh beds. The reasons for these differences, which are associated with methods of rice establishment, are not currently understood, because similar differences did not occur on a loam soil with the same management.

Table 3. Effect of planting method on soil properties, grain yield, water use and water use efficiency (WUE) of wheat on a sandy loam at Delhi.

Planting method	Bulk density (0–10 cm) (mg m^{-3})	Infiltration rate (cm h^{-1})	Weed density at 90 DAS (no. m^{-2})	Grain yield (t ha^{-1})	Water applied (cm)	WUE (kg grain ha^{-1} cm^{-1})
Raised bed – 3 rows/bed	1.35	0.83	65	5.31	21.4	186
Conventional sowing	1.42	0.62	793	5.09	24.9	157
LSD (0.05)	0.05	NS	270	0.37	–	27

Source: Aggarwal & Goswami (2003)

Bed configuration and sowing management

There are few reports on optimum bed width in relation to soil type and other factors. For major soil types (sandy loam to loam) and crops grown in the IGP, a ridge–furrow system of 67 cm width (width of top of bed 37 cm; furrow width 30 cm) is often considered optimum. For varieties suited to beds, Dhillon et al (2000) reported similar yields with 2 rows on beds with 75 cm spacing (mid-furrow to mid-furrow) and 3 rows on beds with 90 cm spacing. Dhillon et al (2000) found differences in the performance of different varieties on beds; those with a more spreading canopy that can quickly close the furrow gap were more suited to beds. Two rows per bed (70 cm) yielded as well as 3 rows per bed for varieties better suited to beds, but with the added advantage of mechanical cultivation with 2 rows per bed. Other studies also found similar yields for 2 and 3 rows per bed (Brar 2003; Singh 1995, 1998). For varieties less suited to beds (a more upright structure such as HD 2329), 3 rows per bed (or 2 on the bed and 1 in the furrow) are required to achieve yields similar to or higher than on flats (Aggarwal & Goswami 2003; Dhillon et al 2000). For late sown wheat 3 rows per bed also result in higher yields than 2 rows per bed (Deol 2001; Singh et al 2002). Singh (1995) reported that a seed rate of 66.7 kg ha^{-1} is optimum for wheat sown on raised beds, compared to 100 kg ha^{-1} for flat-sown wheat. Singh et al (2002) conducted 36 evaluations in farmers' fields over four seasons from 1997 to 2001 in Karnal district. Mean yields on beds each year were slightly higher than with conventional tillage (Table 2), with mean sowing rates of 94 and 115 kg ha^{-1}, respectively.

Effect of beds on weed populations

Establishment of *Phalaris minor* in wheat is generally much lower on the surfaces of beds compared with conventional flat layouts, probably due to the drier soil surface of the beds. Much larger *P. minor* populations are observed in the furrows, but in the furrows they can readily be controlled by cultivation. Aggarwal and Goswami (2003) reported a 10-fold reduction in weed density on beds (Table 3). Yadav et al (2002b) also reported that the number of broadleaf weeds on raised beds (80 m^{-2}) was less than half the number with flat sowing (190 m^{-2}). Dhillon et al (in press) observed 47% and 84% higher weed (*Phalaris minor*) biomass on conventional flats than on beds during 2000–01 and 2001–02, respectively. Weed control was best using Clodinafop and Sulfosulfuron (mean weed biomass 14% of that in unweeded control) compared with one or two hoeings (mean 53%) or Isoproturon (mean 30%).

Effect of beds on soil physical properties

The results of several studies suggest that soil physical properties in the topsoil of beds in NW India are similar to or better than those with conventional tillage. Aggarwal and Goswami (2003) found lower bulk density (0–10 cm depth) at sowing, but no significant difference in infiltration rate measured at harvest on beds compared with flats on a sandy loam at Delhi (Table 3). Sharma et al (2002) found higher air-filled porosity at 0–7.5 cm and 7.5–15 cm on permanent beds (2nd crop, wheat after rice) around 50 days after sowing on a marginally sodic silty loam. On a sandy loam at Ludhiana at the booting stage of wheat, unsaturated hydraulic conductivity (at 7 kPa tension using a disc permeameter) on fresh beds (147 mm h^{-1}) was approximately double that in permanent beds (2nd wheat crop in a RW rotation) and triple that with conventional tillage or direct drilling on the flat. On a loam at the same stage, unsaturated hydraulic conductivity on fresh and permanent beds was similar (~12 mm h^{-1}) and significantly higher than with conventional cultivation (7.5 mm h^{-1}). However, there were no significant differences in bulk density at 0–5 cm on either soil, in contrast to the above findings. Nor were there differences in saturated hydraulic conductivity (which was highly variable) at 15 and 25 cm depths, but this is not surprising given that these measurements were made below both the cultivation depth and the beds and into the pre-existing plough pan formed as a result of many years of puddled rice. The question of whether beds should simply be imposed on top of existing fields regardless of management history and resultant soil physical and chemical properties, or whether there should be some amelioration prior to establishment of permanent bed systems, has received little attention to date.

Nitrogen management for wheat on beds

Singh (1998) reported a significant response of wheat sown on raised beds to an increase in N rate up to 120 kg ha^{-1}, increasing the grain yield by 172% over control. Yadvinder-Singh (unpublished data) found no response to increased N rate above 120 kg ha^{-1} in the first wheat crop after rice in a permanent bed RW rotation on a sandy loam soil. However, in the second wheat crop there was a significant increase in yield when N rate was increased from 120 to 160 kg ha^{-1} (Table 4). This effect was observed on beds both with and without retention of stubble as a mulch (6 t/ha mulch on the beds after establishment of each wheat and rice crop). There was no interaction between mulching and N rate on yield on beds (or flats) in the first two wheat crops. The N was applied in two equal splits, half broadcast prior to bed reshaping and half banded at about 5 cm depth between the rows on the beds before the first irrigation.

Results to date suggest that a 50:50 split application on beds is better than a single application at sowing, as for conventional wheat cultivation on the flat. Kumar (2002) found that tiller density, grain yield and N use efficiency of wheat were significantly reduced when all the fertiliser N was broadcast at sowing compared with application in two equal splits (at sowing and with first irrigation after sowing) on a sandy loam at Ludhiana. Brar (2003) reported that grain yield of durum wheat sown on beds was similar for two or three split applications of fertiliser N.

Mechanised bed planting offers the possibility of banding topdressed fertiliser below the soil surface, with the potential to reduce N losses and increase N use efficiency. However, Kumar (2002) found that grain yield and N use efficiency were similar for broadcast and drilled topdressing just prior to irrigation 21 days after sowing. In a 2-year field experiment at two locations on clay loam soils in Haryana, Singh et al (2002) achieved a yield of 5.91 t ha^{-1} by topdressing 98 kg ha^{-1} N on top of the beds, compared with 5.53 t ha^{-1} from a uniform broadcast application of the same amount, but whether the yields were statistically different was not reported. Increasing the topdressing rate to 128 kg ha^{-1} N produced similar yields (~6.00 t ha^{-1}) with both methods of application. Jakhar et al (2005) reported that wheat yield on beds with 125 kg ha^{-1} N was similar to the yield on flats with 150 kg ha^{-1} N on a clay loam soil at Karnal, Haryana, suggesting a possible fertiliser saving of 25 kg ha^{-1} N. Further evaluation of the method of N topdressing is needed for a range of soils and seasonal conditions. Ammonia volatilisation losses are likely from broadcast urea onto a wet soil surface with a high pH. The transport and transformations of urea broadcast onto the top of the beds prior to the first irrigation need to be investigated in comparison with banding below the bed surface and broadcasting in the furrows

Table 4. Effect of N rate and mulching on yield of wheat on permanent beds on a sandy loam at Ludhiana (5th crop in the sequence – 2nd wheat crop).

Treatment[a]	Nitrogen rate (kg ha^{-1})				Mean
	N0	N80	N120	N160	
PTR/CTW	2.14	3.65	4.16	4.96	3.73
TRB/DDWB	2.06	3.53	4.05	4.64	3.57
DSRB/DDWB	2.51	3.46	3.97	4.67	3.65
TRB/DDWB + straw mulch[b]	1.55	3.26	3.79	4.76	3.34
DSRB/DDWB + straw mulch	1.63	3.43	4.04	4.78	3.47
Mean	2.02	3.51	4.05	4.79	–
LSD (0.05):	Main x sub: 0.52				

[a] PTR = puddled transplanted rice on the flat; CTW = conventionally tilled wheat on the flat; TRB = transplanted rice on permanent beds; DDWB = direct drilled wheat on permanent beds; DSRB = direct seeded rice on permanent beds

[b] 6 t ha^{-1} rice straw applied after wheat sowing, 6 t ha^{-1} wheat straw applied after rice sowing

Source: Yadvinder-Singh (unpublished data) immediately prior to irrigation and fertigation (dissolving the urea in the irrigation water near the point of entry into the field).

Irrigation management for wheat on beds

Yadav et al (2002b) reported potential problems with germination of wheat on beds due to rapid drying of the soil surface in coarse-textured soils. C. Kaur (2003) compared the effect of pre- and post-bed formation/sowing irrigation on a loamy sand at Ludhiana. She found higher establishment and grain yield when irrigation was applied after bed formation (Table 5). There was a consistent trend for better crop performance with irrigation immediately after sowing into dry beds compared with sowing after irrigation of the beds, with significant ($P < 0.05$) differences in tiller density and almost significant differences in yield.

Many studies across NW India have shown that the optimum irrigation management of wheat with conventional tillage on the flat involves one irrigation prior to cultivation and one at the crown root initiation stage (3–4 weeks after sowing into moist soil), followed by irrigation scheduled on the basis of cumulative pan evaporation (CPE) adjusted for rainfall (CPE-rain, in mm). Irrigation is scheduled when CPE-rain since the last irrigation reaches 6,070 mm, with an irrigation application depth (I, in mm) to CPE-rain ratio = 0.9–1.0 (Prihar et al 1974, 1976, 1978a,b). Consistent with this, on beds on a loamy sand, C. Kaur (2003) found that irrigation scheduling based on I/CPE-rain = 1.0 was more effective in increasing yield and water use efficiency of wheat than irrigation at fixed growth stages, which does not take into account the amount and incidence of rainfall during the cropping season. Kaur et al (2003) reported that irrigation of beds (at an irrigation depth of 50 mm) when CPE-rain reached 50 mm significantly increased leaf area index, grains/spike, seed weight and grain yield compared with irrigation at CPE-rain of 60 or 80 mm for late sown wheat. However, irrigation water productivity during the relatively wet season of 1999–2000 was highest with irrigation application based on CPE-rain of 60 mm. Singh (2001) reported that irrigation scheduling based on I/CPE-rain = 0.95 was optimum for obtaining maximum grain yield on a loamy sand in comparison with ratios ranging from 0.65 to 1.10 and with an irrigation application rate of 50 mm. Thus, optimum irrigation scheduling for wheat on beds appears to be similar to that for flats, with the exception that the first irrigation after sowing may need to be sooner on beds than on flat layouts, especially on coarse-textured soils, as the topsoil in beds dries more rapidly than on flats.

Issues for wheat on beds

Yadav et al (2002b) identified a range of potential problems for beds using current bed planting technology in NW India. These included the presence of crop residues, which are problematic during bed formation (or renovation), and potential problems with termites on the dry bed tops. They also found that in a saline sodic situation, beds were inferior to flats (42% yield reduction from 4.0 to 2.3 t ha^{-1}), and attributed this to accumulation of salts on the bed surface. They highlighted the need for further research to evaluate wheat varieties and fertiliser N management for beds. These issues are likely to be relevant to all crops grown on beds, not just wheat.

Chickpea

With the advent of high-yielding and disease resistant varieties suitable for irrigation, farmers are now beginning to grow more chickpea in rotation with a range of upland crops and rice. However, when grown after rice on conventional flat layouts, yellowing and plant death are common after irrigation. This is due to waterlogging because of poor drainage through the hardpan caused by puddling for rice (Sekhon et al 2004).

Results of replicated experiments in different parts of Punjab show a consistent trend for similar

Table 5. Effect of method of crop establishment and scheduling of first irrigation on establishment, tiller density, grain yield and water use efficiency of wheat at Ludhiana.

Treatment	Emergence (no. m^{-2})	Tiller density (no. m^{-2})	Grain yield (t ha^{-1})	WUE (kg grain ha^{-1} cm^{-1})
Flat sowing (pre-sowing irrigation)	173	425	4.20	99
Bed sowing (pre-sowing irrigation)	156	393	3.99	97
Bed sowing (dry sown) followed by irrigation	176	474	4.52	110
Bed sowing (sown after applying irrigation to dry beds)	167	427	4.21	103
LSD (0.05)	13.3	44.1	0.32	–

Source: Kaur, C. (2003)

yields of chickpea on beds (Figure 3) and flats in the absence of irrigation, increased yield on beds but reduced yield on flats with one irrigation, and generally no further increase in yield on beds with two irrigations (Anon. 2002; Sekhon et al 2004; Singh 2002). For chickpea grown in rotation with rice, the reduction in yield with one irrigation on the flat is very large (38% and 52% reduction in replicated experiments in two different years, and 75% average reduction in three farmers' fields over two seasons), while yields on beds with one irrigation increased by 8–18% in replicated experiments (Table 6) and 23% in three single replicated on-farm trials. However, for chickpea grown after maize (with no rice for the previous 10 years), there were no significant effects due to layout (beds with 2 or 3 rows per bed, or flats) or number or irrigations (0, 1 or 2). In farmers' fields, yields on beds were consistently lower than on flats (by an average of 13%) in the absence of irrigation, whereas they were similar in replicated experiments. However, with irrigation of chickpea on beds in farmers' fields, yields were consistently higher than with non-irrigated chickpea on the flat (by an average of 8%; Sekhon et al 2004).


Figure 3. Chickpea on beds (E. Humphreys).

Singh (2002) found significantly higher yields with 2 rows per bed than 1 row per bed (2.11 vs. 1.96 t ha^{-1}), while Sekhon et al (2004) found no differences for 2 and 3 rows per bed at two locations in Punjab in two different years, suggesting that 2 rows per bed is optimum, as for wheat (for varieties adapted to beds and sown on time).

Winter maize

Randhawa (2004) found significantly higher mean winter maize yield (6.03 t ha^{-1}) on beds compared with conventional flat sowing (5.73 t ha^{-1}) on a loamy sand at Ludhiana. The higher yield of maize on beds was mainly due to more grains/cob.

Oilseed rape

Erratic and inadequate water supply limits wheat yields in southwestern Punjab. Therefore, diversification to lower water use winter crops would help to match demand with the limited water supplies. In this regard, rapeseed and mustard offer good promise because they require less irrigation water than wheat.

Table 6. Effect of planting method and number of irrigations on grain yield (t ha-1) of chickpea sown after maize and rice at three sites in Punjab, India.

Planting method	Non-irrigated	One irrigation	Two irrigations
		Site I. Gurdaspur (1998–99) – after maize	
Flat	1.41	1.35	1.32
Raised beds – 2 rows/bed	1.20	1.48	1.36
Raised beds – 3 rows/bed	1.30	1.40	1.51
LSD (0.05)	planting method: NS; irrigation number: NS; interaction: NS		
		Site II. Rauni (1999–2000) – after rice	
Flat	1.30	0.62	0.44
Raised beds – 2 rows/bed	1.18	1.41	1.50
Raised beds – 3 rows/bed	1.25	1.46	1.54
LSD (0.05)	planting method × irrigation: 0.16		
		Site III. Langroya (2001–02) – after rice	
Flat	2.26	1.40	–
Raised beds – 2 rows/bed	2.15	2.47	–
Raised beds – 3 rows/bed	2.32	2.48	–
LSD (0.05)	planting method: 0.14; irrigation number: 0.11; interaction: NS		

NS, not significant

Source: Sekhon et al (2004)

In a 3-year study on a sandy loam in southwestern Punjab, Aujla et al (1992) observed that with Indian rape (*Brassica napus*), irrigating each furrow (45 cm wide) required 18% less irrigation water, and each alternate furrow 41% less irrigation water, compared with flood irrigation of the flat layout, with no effect on grain yield.

On a sandy loam at Ludhiana, bed planting of rape (1 row/bed) yielded 1.66 t ha^{-1} compared with 1.42 t ha^{-1} using conventional tillage on the flat (Yadvinder-Singh et al, unpublished data).

Summer crops

Soybean

Ridge sowing of soybean has been reported to increase seed yield and profits compared with flat sowing on clay loam and heavy clay soils in other parts of India (Jain & Dubey 1998; Jayapaul et al 1995; Raut et al 2000; Srivastava & Pahalwan 1972). However, there are also experiments showing no yield advantage of bed planting of soybean over flat planting when there was no limitation of water availability (Bharambe et al 1999; Kaur, M. 2003; Nandurkar et al 2000; Ram, unpublished data; Singh et al 2004).

On coarse-textured soils in NW India, soybean yield on beds is consistently similar to or higher than yields on conventional flat layouts. Randhawa (2004) reported significantly higher seed yield on fresh beds than with conventional tillage (by about 0.1 t ha^{-1} or 5%) over three seasons from 2001 to 2003 on a sandy loam in a winter maize–soybean rotation at Ludhiana. The higher yields on beds were associated with more pods/plant (58–68 vs. 52–63), and better root development and nodulation. On a similar soil at Ludhiana during the same period, Dhillon (unpublished data) found significantly higher seed yield of soybean on both permanent and fresh beds compared with conventionally tilled flats in the first year, but similar yields in the second year, in a wheat–soybean rotation. Similarly, on a loamy sand at Ludhiana, M. Kaur (2003) found higher yields on beds than on flats in 2001, but no difference in 2002. Ram (unpublished data) found no significant differences in growth or yield of soybeans on permanent beds, fresh beds and flats with conventional or zero tillage in 2003 and 2004 at Ludhiana (Table 7). The soybeans were grown in rotation with wheat on a loamy sand. The crops received only one irrigation of 75 mm (on flats) and 50 mm (on beds) in 2003 due to well distributed summer rains, but five or six irrigations on flats and beds in the unusually dry summer of 2004. Maximum soil temperature (at 0–5 cm) between sowing and emergence was higher on the beds (34.1°C) than on the flats (33.0°C), probably due to exposure of more surface area to the incident solar radiation than under the flat layout.

Raut et al (2000) found significantly higher seed yield with 2 rows per bed compared with 1 row per bed, although there were more pods per plant with 1 row per bed. In contrast, on a loamy sand at Ludhiana, M. Kaur (2003) found similar yields with 1 and 2 rows per bed over 2 years (Table 8). M. Kaur (2003) reported that bed planted soybean with 1 or 2 rows/bed, and paired rows on the flat on a loamy sand, produced significantly more pods per plant and grain yield than conventional (45 cm row spacing) flat sowing in 2001, but there were no significant differences between the layouts in 2002 (Table 8).

M. Kaur (2003) also observed that during the unusually dry summer of 2002, irrigation at CPE-rain of 50 mm produced significantly higher seed yield (1.25 t ha^{-1}) than irrigation at CPE-rain of 75 or 100 mm (0.74–0.80 t ha^{-1}). In 2001 there was no significant effect of the irrigation schedule on soybean yield (Table 9). Total water productivity was much higher in 2001 (mean 31.5 kg ha^{-1} cm^{-1}) than in 2002 (mean 17.4 kg ha^{-1} cm^{-1}), largely due

Table 7. Yield, water use and water productivity in soybean as affected by tillage, layout and mulching in a soybean–wheat rotation on a loamy sand at Ludhiana.

Treatment (soybean–wheat)	Grain yield (t ha^{-1})		Irrigation (mm)		Soil profile water depletion (mm)		Total water use (irrig+rain+SW		Total water productivity (kg ha^{-1} cm^{-1})	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
CT/CT	1.48	1.69	75	375	119	75	764	759	19.4	22.3
FB/CT	1.41	1.68	50	300	130	49	750	658	18.8	25.5
PB/PB	1.34	1.80	50	300	121	47	741	656	18.1	27.5
PB+S/PB	1.36	1.85	50	300	104	30	724	639	18.8	29.0
LSD (0.05)	NS	NS	–	–	–	–	–	–	–	–

CT = conventional tillage (flat); FB = fresh beds; PB = permanent beds; S = wheat straw mulch

Source: Ram (unpublished data)

Table 8. Effect of planting method on photosynthetic active radiation interception (PARI) at 90 DAS, pods/plant and seed yield of soybean at Ludhiana.

Planting method	PARI(%)		Pods/plant		Seed yield (t ha^{-1})	
	2001	2002	2001	2002	2001	2002
Beds (1 row/bed)	77.5	83.7	88.0	81.9	1.15	1.03
Beds (2 rows/bed)	83.2	90.9	82.6	79.8	1.12	1.05
Flat	66.2	79.4	70.9	74.8	0.85	0.91
Paired rows on flat	73.6	81.3	76.8	81.4	1.00	1.07
LSD (0.05)	4.5	4.1	5.0	NS	0.16	NS

NS, not significant

Source: Kaur, M. (2003)

to lower irrigation amounts in 2001 and lower yields in treatments with longer irrigation intervals in 2002. Irrigation water productivity was higher in 2002, with irrigation at CPE-rain of 50 mm, than with less frequent irrigation.

Summer maize

Ridge planting of maize has out-yielded conventional flat sowing in many studies conducted in different parts of India (Bhagwandin & Bhatia 1990; Debebe 1999; Joshi & Dastane 1966; Sharma 1991). Lal et al (1988) reported that grain yield of maize was about 27% higher on ridges or raised beds (Figure 4) compared with flat sowing.

As for soybeans on coarse-textured soils, in NW India, the performance of summer maize on beds in comparison with ridges, flats and trenches has been variable, with similar or higher yields on beds compared with conventionally tilled flats. The cause of variable performance is likely to be variable seasonal conditions (incidence and amount of rain).

Aggarwal et al (2000) and Kaur (2002) reported significantly higher yields (by 27 and 34%) and total water productivity of maize on beds than on flats on sandy loam and loamy sand soils, respectively. Kaur (2002) also found that ridge planting significantly increased yield compared with flat planting, with similar yields on beds (one row per bed) and ridges (Table 10). The higher yield from bed planting was due to more cobs/plant and grains/cob than on the flats. Yield with 2 rows per bed was significantly lower than with 1 row per bed, with fewer cobs/plant and grains/cob, presumably due to competition for light. The rainfall during the cropping season was more (847 mm) than average and was well distributed, and only one irrigation was applied. This resulted in a small difference in consumptive water use among different treatments, but raised beds with 1 row per bed had much higher water productivity due to higher yield.

In contrast with the results of Aggarwal et al (2000) and Kaur (2002), Ram (unpublished data) found no significant differences in growth, yield or yield components of maize on permanent beds, fresh beds and conventionally tilled flats in a maize–wheat rotation on a loamy sand at Ludhiana (Table 11). These findings were consistent over two seasons, the first (2003) with well-distributed monsoon rains so that no irrigation was required, the second an unusually dry season with late rains and total irrigation of 250–300 mm over four to five irrigations. For soybeans with the same treatments (see Table 7), maximum soil temperature (at 0–5 cm) between sowing and emergence was higher on the beds than the flats. There was a consistent trend for higher soil profile (at 0–180 cm) water depletion on beds than on the flat (by 34 mm in the dry summer of 2004). Total water use and water productivity were similar for beds and flats in both years. Similarly, in a 2-year

Table 9. Effect of irrigation scheduling on yield and water use efficiency of soybean on raised beds.

Irrigation schedule (CPE)	Seed yield (t ha^{-1})		Water use (cm) (irrig+rain+SW)		WUE (kg ha^{-1} cm^{-1})	
	2001	2002	2001	2002	2001	2002
50 mm	1.28	1.25	40.5	57.5	31.7	21.7
75 mm	1.26	0.84	40.2	52.3	31.3	16.0
100 mm	1.35	0.70	40.4	47.8	33.4	14.6
LSD (0.05)	NS	0.12	–	–	–	–

Source: Kaur, M. (2003); CPE = cumulative pan evaporation

Figure 4. Darryl Gibbs inspects a maize crop showing higher yield on beds compared with flat sowing (E. Humphreys).

study on a sandy loam at Ludhiana, Dhillon (unpublished data) observed no significant differences in maize yield between permanent beds, fresh beds and conventionally tilled flats in a maize–wheat rotation.

Kaur (2002) also observed no significant yield differences between irrigation schedules based on CPE-rain in maize on a loamy sand soil at Ludhiana (data not shown). Being a wet year, the maize received only one irrigation during its growth cycle. The study, however, indicated that during a relatively dry season, irrigation based on CPE of 50 mm may be needed for higher yield and higher water use efficiency of maize planted on beds.

Ram et al (2004) reported that early sown (20 May and 10 June) maize planted in trenches out-yielded all other methods of planting, but for late sowing (1 July) planting on raised beds or ridges gave significantly higher yield than flat or trench sowing (Table 12). With early sowing, trench planting helped reduce water deficit stress during crop establishment, but with late sowing the crop in the trenches experienced waterlogging during establishment, which coincided with the onset of the monsoon rains.

Cotton

Cotton is an important crop grown in the south-western region of Punjab. Most of the underground waters in this zone have high residual sodium carbonate and/or high electrical conductivity and can only be used with caution. Aujla et al (1991) compared different methods of irrigation on yield and water use efficiency of cotton on a sandy loam in southwestern Punjab. Because of the unavailability of a mechanical ridge planter, the ridges were

Table 10. Effect of planting method on growth, yield and water use efficiency of maize on a loamy sand at Ludhiana.

Planting method	LAI at 60 DAS	No. of cobs/ plant	No. of grains/ cob (t ha^{-1})	Grain yield	*Consumptive water use (cm)	WUE (kg ha^{-1} cm^{-1})
Flat	3.60	0.9	226	3.27	43.6	75.0
Ridge	4.21	1.2	345	3.89	41.3	94.1
Raised bed – 1 row	4.49	1.3	373	4.35	40.1	108.4
Raised bed – 2 rows	7.13	0.9	269	3.58	41.4	86.6
LSD (0.05)	0.87	0.2	28.1	0.58	–	–

* Consumptive water use was calculated as the sum of effective rainfall + irrigation + soil water depletion

Source: Kaur (2002)

Table 11. Grain yield, water use and water productivity of maize in a maize–wheat rotation on a loamy sand at Ludhiana.

Treatments (maize–wheat)	Seed yield (t ha^{-1})		Irrigation (mm)		Soil profile water depletion (mm)		Total water use (irrig+rain+SW) (mm)		Total water productivity (kg ha^{-1} cm^{-1})	
	2003	2004	2003	2004	2003	2003	2004	2003	2004	2003
CT/CT	5.51	5.45	0	300	93	63	644	639	85.6	85.2
FB/CT	5.52	5.44	0	250	111	96	662	622	83.4	90.5
PB/PB	5.41	5.61	0	250	102	98	653	624	82.5	89.8
PB+S/PB	5.50	5.85	0	250	104	67	655	593	84.0	98.7
LSD (0.05)	NS	NS	–	–	–	–	–	–	–	–

CT = conventional tillage (flat); FB = fresh beds; PB = permanent beds; S = wheat straw mulch

Source: Ram (unpublished data)

prepared manually after planting in 75-cm-wide rows and before applying the first irrigation. They found that in comparison with flood irrigation, irrigating each furrow required about 26% less water, and each alternate furrow 43% less water, compared with conventional tillage on the flat, and with little or no yield loss.

Spring groundnut

In the pre-‘green revolution’ era groundnut was an important oilseed crop in Punjab, grown on well-drained coarse-textured soils. With recent increasing emphasis on crop diversification, cultivation of groundnut is again gaining popularity among farmers. Dhillon (unpublished data) found significantly higher yield of groundnut on beds than on flats in 2002–03 (3.1 vs. 2.8 t ha^{-1}) on a sandy loam, and similar yields (3.5 t ha^{-1}) in the second year. Use of polythene mulch significantly increased yield on the beds by 0.2 t ha^{-1} in the first year, but not in the second year.

Evaluation of cropping systems with raised beds

Tripathi et al (2004) evaluated the financial performance of eight cropping systems based on results of a replicated experiment over 3 years (six crops) at Karnal, Haryana, during 2001–03. The cropping systems ranged from conventional RW through conventional rice in rotation with wheat on beds (with or without the inclusion of a 3rd or 4th crop — pigeon pea and/or green gram on beds) to conventional rice in rotation with a range of other crops such as vegetables, green gram and maize. Intensification by growing vegetable pea in between rice and wheat, and green gram after wheat, with all non-rice crops on beds gave higher net returns and sustainable value index (a measure of yield and price stability) compared with the conventional RW system. Weed biomass was greatest in conventional RW or RW with the first rice crop replaced by sorghum. Diversification and intensification reduced total weed biomass by as much as 70% in the rice–vegetable-pea–wheat–green-gram rotation, with all crops other than rice on beds.

Residue management for permanent beds

There are few reports on residue management for permanent bed cropping systems. Techniques that allow direct drilling into retained residues are needed to reverse the decline in soil organic matter levels and reduce atmospheric pollution from residue burning (80% of rice stubbles and about one-third

Table 12. Grain yield of maize as affected by planting method and sowing dates at Nawanshahar, Punjab.

Planting method	Sowing date		
	20 May	10 June	1 July
Raised bed	5.37	5.58	5.09
Ridge	5.60	5.80	5.01
Flat	5.01	5.13	4.11
Trench	6.60	6.61	3.83
LSD (0.05)	Planting method × sowing date: 0.43		

Source: Ram et al (2004)

of wheat stubbles in NW India are burnt). Hari Ram (unpublished data) found similar crop performance for maize and soybeans on permanent beds with and without 6 t ha^{-1} of wheat straw mulch over two seasons. There was also a fairly consistent trend of small reductions in total crop water use (as calculated from irrigation + rain + soil water depletion) and increased total water productivity with mulching (Tables 9 and 11). There are several reports of irrigation water savings (or increased yields where water is limited) with mulching in conventional cropping systems on the flat (Humphreys et al 2004). The potential for mulching to save water in summer and winter crops requires further investigation, as do the long-term impacts on soil physical properties and nutrient cycling, and their consequences for management, resource use efficiency and yield.

Direct drilling into stubble can cause problems in mechanised culture due to clogging of the machinery with the loose straw and hair-pinning. There has been considerable progress in the development of technology for direct drilling into stubbles on the flat, including double- and triple-disc assemblies and the star wheel punch planter (RWC 2002). However, loose residues are a major problem with currently used versions of the bed planter in NW India. A novel recent approach with much promise is the Happy Seeder, which combines the stubble mulching and seed drilling functions into one machine (Sidhu et al 2005). The stubble is cut and picked up in front of the sowing tines, which therefore engage bare soil, and deposited behind the seed drill as a mulch. The original Happy Seeder simply involved coupling a forage harvester and a seed drill, and enlarging the chute on the forage harvester to deposit the stubble behind the seed drill (Figure 5a). The concept can be applied to both flat and bed layouts by coupling the desired planter with the forage harvester. One of the first tests of the Happy Seeder was in establishing wheat into standing rice stubble on permanent beds (as a 2nd crop) (Blackwell et al 2004). There was no difference in wheat crop performance with 0, 4 or 8 t ha^{-1} of rice stubble mulch). Since this early work there have been many improvements to the Happy Seeder, including the development of the compact Combo Happy Seeder, weighing 540 kg and with hydraulics built on the machine, enabling it to be used with any tractor (Figure 5b).

General discussion

Results to date suggest that raised beds have the potential to enable diversification and increase the productivity of cropping systems in NW India through growing a much wider range of crops in the monsoon season and increasing yields of waterlogging sensitive crops by irrigation. These results also suggest significantly reduced irrigation water requirements for crops on beds, saving costs and energy, although whether this is a real water saving is yet to be determined. Permanent beds offer the additional possibility of direct drilling, with advantages of rapid turnaround between crops, reduced tillage and energy costs, reduced greenhouse gas pollution from burning diesel, and improved soil structure due to controlled traffic and reduced disruption of biopores and oxidation of soil organic matter.

Much useful information on how to get the best performance from beds has already been produced, especially for wheat. Research suggests using varieties suited to beds, choosing optimum row spacing,


Figure 5a and 5b. The Happy Seeder combines stubble mulching and seed drilling functions into one machine (J. Blackwell and H.S. Sidhu).

varying the sowing rate, and optimising irrigation scheduling and N management. However, this type of information is less available for other crops. Furthermore, most evaluations for crops on beds in NW India have been done on fresh beds on coarse-textured soils with deep watertables. Future investigations need to be extended to fine-textured soils and include situations with shallow watertables.

There are very few reports to date on direct drilling of crops on permanent beds, and no long-term studies to evaluate crop performance and effects on soil physical and chemical properties; components of the water balance; and weeds, diseases and pests such as insects, nematodes and rodents. There are also very few studies on residue management for crops on permanent beds. The Happy Seeder offers the potential for simultaneously cutting and picking up crop residues, direct drilling into bare soil, and mulching of the sown area. The impact of mulching on reducing non-beneficial evaporative losses needs to be investigated, together with its impact on nutrient cycling and soil physical properties.

There have been few investigations of soil management for permanent bed systems, including questions such as the need for bed renovation (disturbance), and whether the hardpan in rice fields should be destroyed before introducing permanent bed systems, as well as the impact of this on crop performance, irrigation water use and deep drainage losses. Zero tilled permanent raised beds may develop greater permeability (continuous pores to the surface through old root channels and other biopores, including those created by termites and rodents), increasing percolation rates, deep drainage and leaching losses. Alternatively, compaction of furrows on coarse-textured soils may be useful for reducing deep drainage and leaching losses. Investigations of optimum bed width across soil types have also been very limited to date.

Varietal evaluation and selection and breeding for beds are needed for the range of crops that could potentially be grown on beds, as is fine-tuning of the agronomy, including sowing geometry and rate, and irrigation and N management.

Perhaps most important of all, changes in crop price support and input subsidy policies of the Government of India and State Governments, and marketing reforms, are needed to make diversification from traditional RW systems affordable to farmers.

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Effect of permanent raised beds on water productivity for irrigated maize–wheat cropping system

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Abstract

Agricultural production in Pakistan is constrained by scarce water availability, land degradation, soil salinity/sodicity and waterlogging problems. In addition, irrigation application losses in the field are around 25–40%. Farmers mostly follow traditional farming systems, with lack of financial resources, small land holdings and lack of awareness being the main hurdles to adopting modern technology. A study was conducted for 4 consecutive years (2000–04) in farmers' fields near Mardan to compare soil and water productivity in permanent raised beds versus the traditional basin system under maize–wheat double cropping. The results indicated that for the maize crop there were increases of 30%, 32% and 65% in grain yield, water saving and water productivity, respectively, under permanent raised beds compared to basins. Similarly, permanent raised beds demonstrated 13%, 36% and 50% higher grain yield, water saving and water productivity, respectively, for the wheat crop. Weed infestation was also 24% and 31% lower for maize and wheat crops, respectively, under permanent raised beds, which maintained lower soil bulk density and high infiltration rates. Partial budgeting showed that raised beds generated 54% and 35% increased net benefit for maize and wheat, respectively. District farmers' experience with raised beds demonstrated similar results, with 34% water saving, and 32% and 19% higher yields for maize and wheat, respectively.

Introduction

Pakistan is an agricultural country with the world's largest contiguous irrigation system, the Indus Basin Irrigation System (IBIS). Agriculture is the mainstay of the economy, employing 60% of the labour force and accounting for 26% of GDP. Of the total cultivated area of the country, 82% is irrigated. However, the total availability of water at farm gate is only 102 billion cubic metres to irrigate a canal command area of 14.64 million ha (Anon. 2002). The low cropping intensity and low crop productivity are mainly the result of the shortage of canal water and secondary salinisation. To supplement the canal supplies more than 53,000 tube wells are pumping about 62 billion cubic metres of groundwater annually, up to 70–80% of which is hazardous (marginal to brackish; Ahmad 1993).

Waterlogging and salinity are worsening the land degradation problems. Heavy monsoon rains cause temporary waterlogging, especially on sodic soils with low permeability, and about 35% of the Indus basin is affected by either waterlogging or salinity or both (Anon. 1997b). Basin-wide estimates indicate that a 25% loss of productivity in the IBIS is due to waterlogging and salinity (World Bank 1997). With around 68% of the country's population living in rural areas, it is estimated that almost 16 million people are currently adversely affected by waterlogging and saline and/or sodic soils, and this number is predicted to double by the year 2020 (Qureshi & Lennard 1998).

Most of the crops grown in the IBIS are sown on the flat in basins using the flood irrigation method. With application losses of around 25–40% (World Bank 1997), the irrigation efficiencies are quite low. Causes of low application efficiencies include over-irrigation, improper irrigation methods and timing, non-specific irrigation scheduling and non-levelled fields (Gill 1994). Improved irrigation and soil management practices, along with appropriate cropping systems, are urgently required. Some early work in Pakistan on non-permanent beds and furrow irrigation produced yield increases of 20% for

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wheat (Hameed & Solangi 1993) and 48% for cotton (Berkhout et al 1997). Realising the problem, and the productive potential of the irrigated area, a study of permanent raised beds was conducted to improve productivity of water use for an irrigated maize–wheat cropping system.

Methods

Characteristics of study area

The study area is located at Mardan in North West Frontier Province of Pakistan (34°12´E, 73°03´N). It falls in the semi-arid zone for both summer and winter seasons, with mean seasonal rainfall of 250 mm in summer (May–September) and 300 mm during winter (October–April). The soil belongs to the Mardan soil series, and is classified as fine Ustertic Camborthid, developed in filled basins and river beds, grayish brown, a non- to slightly calcareous material of Holocene age. The soil texture class is sandy clay loam with AB-DTPA-extractable P and K of 2.56 and 72 mg/kg, respectively, and 0.52% organic matter.

Study layout and sowing

The study was laid out using a completely randomised block design, with two treatments (basin and permanent raised beds) and three replicates in an approximately level field. Irrigations were measured using broad-crested weir-type flumes. Maize and wheat were both sown for 4 consecutive years in their respective seasons (May 2000–April 2004). Fertiliser was applied to each crop at 90 kg/ha N and 60 kg/ha P_2O_5, with half of the N and the full dose of P_2O_5 being applied at sowing and the remaining N as a topdressing with the first/second irrigation. Urea and diammonium phosphate (DAP) were used as sources of nutrients. Under the basin system, sowing was done using a local drill (20 cm row spacing for wheat and 75 cm for maize), while in raised beds a bed-shaper-cum-drill from Australia was used. The beds were 180 cm centre-to-centre (125 cm at the top of the beds) wide and 20 cm high. Each raised bed carried 7 wheat rows (20 cm apart) or 2 maize rows (100 cm apart across the furrow and 80 cm on the bed top). The raised beds developed for the first crop (maize) in 2000 were kept as permanent beds for subsequent crops, with some renovation (mostly in the furrows) being done before the sowing of each crop. Basin plots, however, were traditionally prepared using cultivators and rotavators before sowing each crop.

Data collection and analysis

Irrigation was scheduled based on soil moisture content, as determined by drying to constant weight at a temperature range of 100–110°C. The criterion for time of irrigation was 75% depletion of the available water in the top 30 cm depth, and the soil moisture depletion trend was used to predict the date of next irrigation. Two to three days before the predicted date of irrigation, soil samples from 0–15, 15–30, 30–60 and 60–90 cm depths were collected to determine the exact soil moisture deficit. This deficit amount was then applied through the flume. The basins and raised beds were managed separately with respect to irrigation timing and amount, depending on the soil moisture depletion in each treatment.

A non-recording rain gauge was installed at the experimental site to measure rainfall depths. Dry straw and grain yield data were also recorded for both crops and all seasons. Weed infestation was determined through measurement of weed dry biomass. Water productivity was calculated for all crop seasons, using the amount of irrigation water applied to each treatment and the respective grain yields.

In addition to irrigation and yield data, some soil parameters were also studied. Bulk density samples were collected after sowing of the first crop and then at harvest of each successive crop for 0–15 and 15–30 cm soil depths from both raised beds and basins. Infiltration characteristics were also studied using a double ring infiltrometer. Data were recorded in the basin, in the furrow bottom and at the top of the bed at the time of harvest of each crop. These soil parameters were used to monitor structural changes.

Results

Seasonal rainfall

During summer maize seasons the rainfall was in the range of +9% to +122% of the average rainfall of 250 mm (Figure 1). During high rainfall periods

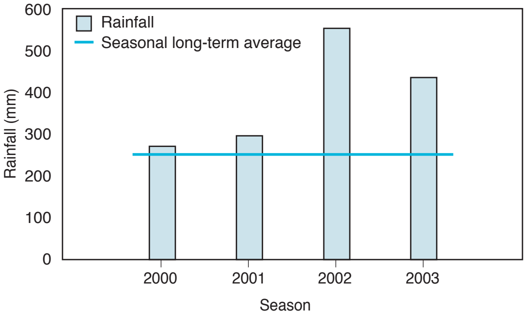

Figure 1. Seasonal rainfall during summer maize crop.

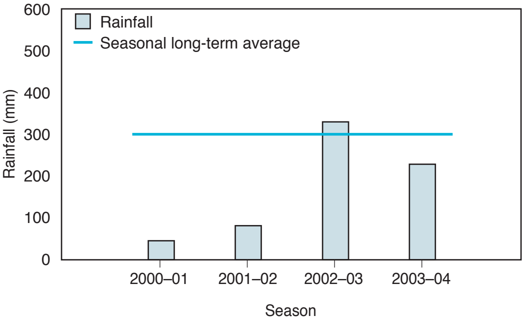

Figure 2. Wheat crop seasonal rainfall.

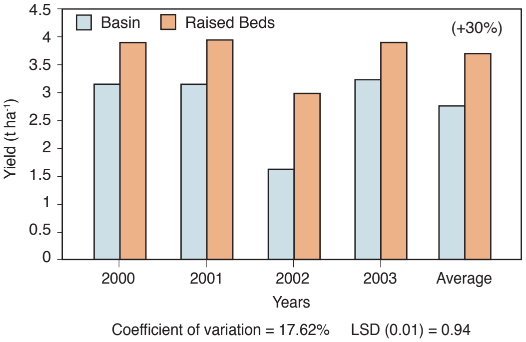

Figure 3. Yield of maize.

water ponded in the basins and drained into the furrows between the raised beds. The summer season is one of comparatively high rainfall so this temporary ponding is common.

Wheat crop seasonal rainfall was mostly below the mean (300 mm) and ranged from –85% to +10% of the average (Figure 2). Germination of the centre rows on the raised beds under irrigation alone was poor, particularly whenever there was no rain early in the wheat season.

Maize yield

Using yield as the criterion of performance, maize on the raised beds out-yielded the basins in all years. The increase in grain yield was more than 20% for each of the 4 years, with an average value of 30% (Figure 3). In most of these seasons good rainfall occurred (Figure 1). Maize yield was lowest (1.65 t/ha in basins versus 3.03 t/ha in beds) during 2002 because the high rainfall (555 mm) in that season caused temporary ponding and waterlogging. Maize is a water-sensitive crop, and maize yields in the basins in the area were declining day by day because of temporary ponding and logging during rain periods. In raised beds excess rainwater flowed into the furrows and drained away, and the crop did not come into direct contact with water, whereas it was not possible to drain all water from the basins. This resulted in increased yield under permanent raised beds compared to basins. Furthermore, the permanent raised bed soil, being loose, had a better environment for aeration, water movement and root development.

Wheat yield

Wheat grain yield was on average 13% higher in the raised beds compared to the basins (Figure 4). Yield increases with beds were 8.5%, 19%, –4% and 29% compared to basins across the 4 years, respectively. In one season out of four, the basin crop produced a similar grain yield, but for the other 3 years raised beds showed increased yield. Most of these wheat seasons were dry with less than average rainfall, which affected the raised beds of wheat, especially in the centre rows. Unlike maize, which is sown close to the shoulders of the bed, wheat is sown evenly across the full width of the bed. The size of the bed top (125 cm) was too wide for this type of soil, and the two centre rows could not get sufficient water by lateral movement from the furrows. In 2002–03 the beds did not perform as well as in other years because in that season the first rainfall only occurred 40 days after sowing, and the centre row germination was accordingly delayed. The maximum yield increase under raised beds in any one season was 29% in 2003–04 when the first rainfall was received 6 days after sowing. In general, in spite of the weak performance of the centre rows, the extraordinary compensation of the edge rows in the raised beds resulted in better overall yield compared to basins. Maximum wheat productivity will presumably only result when all rows across a bed have easy and reliable access to irrigation water throughout the crop

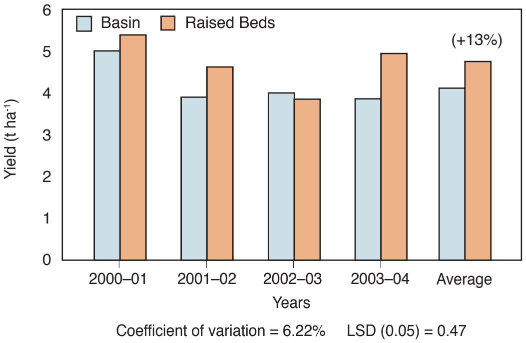

Figure 4. Yield of wheat.

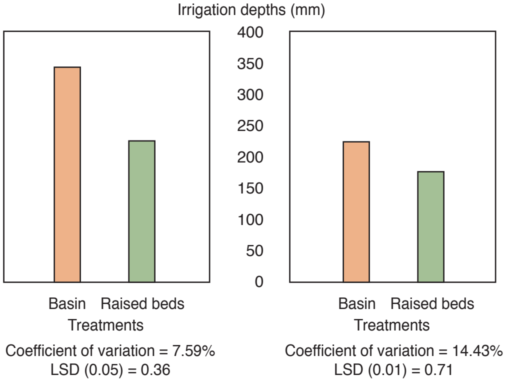

Figure 5 (L). Mean irrigation depths for maize (2000–03).
Figure 6 (R). Mean irrigation depths for wheat (2000–01 to 2003–04).

season. Thus, raised beds have more potential to produce even better yields with appropriate bed size.

Irrigation water use

For each season maize on raised beds consumed less irrigation water compared to basins. The water savings of raised beds over basins ranged from 16% to 83%, with an average value of 32% (Figure 5). There were seasonal variations in irrigation depths because of different rainfall amounts and distributions in each season. The least irrigation water applied was in 2002 when 555 mm rainfall was received. The number of irrigations applied was sometimes higher in raised beds but the amount of water applied in each irrigation was always less than for basins. The average amount of water per irrigation was 45 mm for beds and 70 mm for basins.

During all four wheat seasons, raised beds saved irrigation water in a range of 16% to 50%, with an average value of 36%, compared to basins (Figure 6). The seasonal differences in total irrigation amount varied because of the rainfall received and its distribution over each period. Lower overall irrigation water applied to raised beds is probably the result of reduced evaporation, less area wetted and soil configuration in the raised beds, and over-irrigation in the basins. The average amounts of water per irrigation for this crop were 46 mm for raised beds and 78 mm for basins.

Water productivity

Water productivity (WP), calculated by dividing the grain yield of each crop by the total amount of water applied to that crop, was determined for all maize crops under basin and permanent raised bed treatments. The increase in WP of raised beds over basins

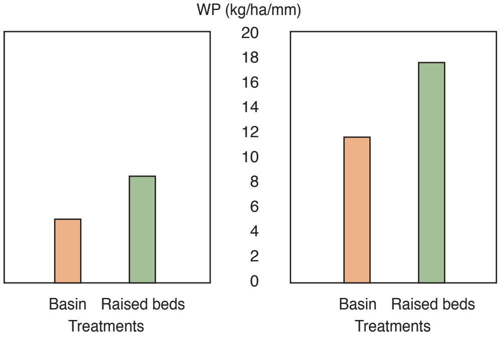

Figure 7 (L). Mean water productivity for maize (2000–03).
Figure 8 (R). Mean water productivity for wheat (2000–01 to 2003–04).

ranged from 27% to 94%, with an average value of 65% (Figure 7).

With wheat the raised beds followed the same increasing WP trend as that of maize. The increases in WP of permanent raised beds over basins ranged from 21% to 130%, with an average value of 50% (Figure 8). Irrigation water savings largely explained the higher WP in the case of wheat.

Dry weeds biomass

Permanent beds experienced less weed infestation than the basin irrigation system. Under raised beds weeds were mainly concentrated in furrows because of the lack of crop cover there and the higher moisture content. On a cumulative basis weed dry biomass under permanent beds was 24% and 31% lower than in basins for maize and wheat crops, respectively (Figures 9, 10). However, there

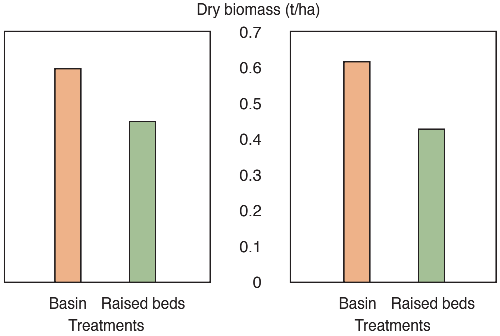

Figure 9 (L). Mean dry weeds biomass for maize (2000–03).
Figure 10 (R). Mean dry weeds biomass for wheat (2000–01 to 2003–04).

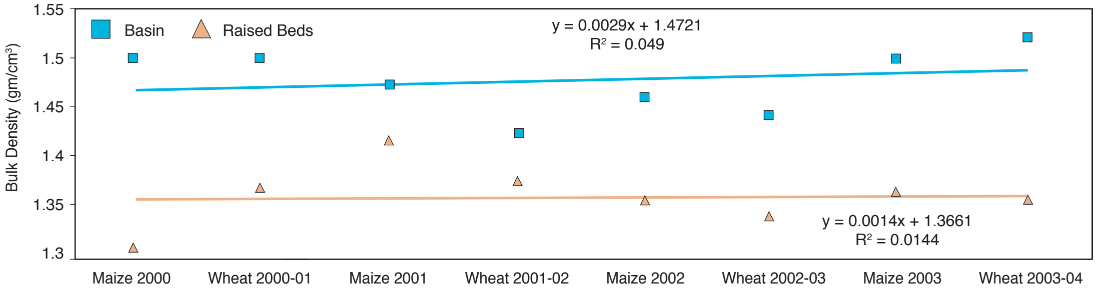

Figure 11. Bulk density in the upper layer (0-15 cm).

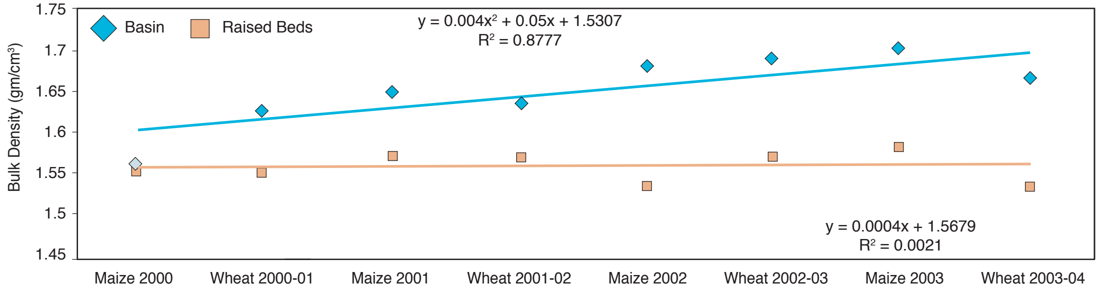

Figure 12. Bulk density in the lower layer (15–30 cm).

was seasonal variation, which may be attributed to the total amount of rainfall and its distribution. The drier soil surface condition of the centre of the raised beds, especially in dry years, appears to be the main cause of this phenomenon. Because of the concentration of weeds in furrows their control was easy and economical in raised beds.

Soil characteristics

Figures 11 and 12 show that the soil on the top of permanent raised beds retained structural stability and lower bulk density than that in basins for both soil depths. During the 4-year period bulk density increased by 2% in the upper soil layer and compaction increased by 6% in the lower layer in basins compared to raised beds. The differences arose presumably because there was less structural disruption of aggregates and settlement in the unsaturated condition of the raised beds compared to the saturated condition of the basins. Furthermore, the movement of tractors and other machinery in the basins and furrow bottoms might have compacted the soil, while the bed tops remained untrafficked and loose.

Infiltration measures the ease of water movement into the soil. Data on infiltration rates was recorded for bed tops, bed furrows and basins for all crop seasons. The results show that the sorptivity, conductivity and cumulative intakes were higher on the top of raised beds compared to basins; and higher in basins than in the furrows between the beds (Figures 13, 14). After 20 minutes of reading, the sorptivity in raised beds was 3 times higher than in basins and 10 times higher than in furrows under wheat during 2003–04. The cumulative infiltration at the same time in raised beds was 2.8 times higher than in basins and 10 times higher than in furrows. Similarly, after 3 hours of reading, the conductivity was 4.3 times higher in raised beds than in basins and 8.7 times higher than in furrows; and the cumulative infiltration in raised beds was 3.6 times higher than in basins and 9 times higher than in furrows (Figures 13, 14). These results may be attributed firstly to the soil being in loose form in beds with more pore space available for water movement, whereas in basins the soil had a higher bulk density with less pore space available for water movement. The second reason might be that in basins and furrows movement of tractors and other machinery had caused a hardpan to form below the topsoil, which had further impeded water movement. With increasing compaction at the bottom of the furrows over time, ponding in the furrows will increase and lateral movement of water into the beds may improve.

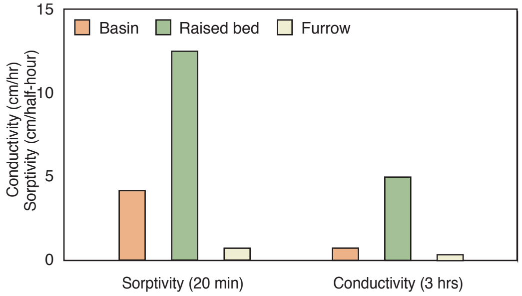

Figure 13. Sorptivity and conductivity at wheat harvest (2004).

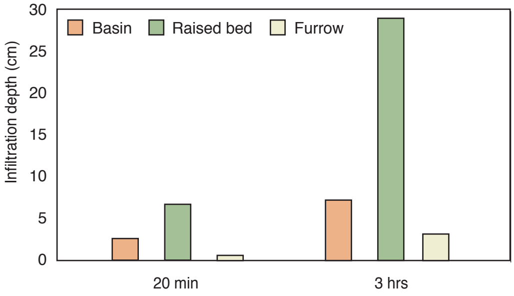

Figure 14. Cumulative infiltration at wheat harvest (2004).

Gross margin analysis

Economic analysis was carried out using actual expenditures for activities/input and prevailing prices for maize and wheat. On average, permanent raised beds under maize gave 54% greater net benefit compared to basins (Figure 15). The benefit:cost ratio in raised beds was 2.43 compared to 1.88 in basins. Similarly, on average, raised beds under wheat generated 35% higher net profit and 23% greater benefit:cost ratio compared to basins (Figure 16). Raised beds showed these economic benefits because they produced higher yields with less expenditure, and the additional cost used in tillage operations before sowing of each crop increased basin expenses. The cost of water saved is not included in these calculations because the canal water charges in the IBIS are based on crop type and area rather than on the actual amount used by each crop.

Demonstration trials

Demonstrations were conducted in the nearby district on 14 farms for 2000–01 maize crops and on 12 farms for 2000–01 wheat crops. The bed-former-cum-drill was used to make and seed 180 cm beds in farmers' fields, after which the farmers managed the crops. The raised beds on average saved 34% irrigation application time over the basins for both maize and wheat crops (Figure 17). At the same time maize and wheat grain yield increased 32% and 19%, respectively, under raised beds compared to basins (Figure 18). The farmers were generally satisfied with the performances on raised beds. They greatly appreciated the results of maize on raised beds because maize was becoming unprofitable due to ponding and waterlogging in basins in high rainfall years. They had little concern over the size of beds for wheat crops. In general, they were interested in raised beds because of less weeds, easy irrigation and water savings, less labour cost and high yields.

Discussion

It can be concluded that the data presented from the research clearly indicates the usefulness of permanent raised bed technology in terms of higher yields, irrigation water savings, increased water productivity and higher profitability. Improvement in soil struc-

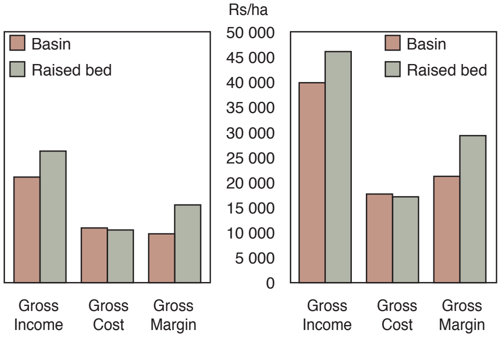

Figure 15 (L). Gross margin analysis for maize.
Figure 16 (R). Gross margin analysis for wheat.

Figure 17. Irrigation time of farmer demonstration trials.

Figure 18. Yield of farmers demonstration trials for wheat (2000–01) and maize (2000 and 2001).

ture was indicated by lower bulk density and higher infiltration rates.

All these improvements were achieved with less than adequate machinery, in terms of both size and design. Also, the size of bed (180 cm) formed was too large for this type of soil, and the machine used was too large for the size of available tractors and for the small fields. Therefore, the benefits are likely to be even greater once new Australian designed machinery and smaller bed widths are employed.

Farmer participation in the demonstration trials on maize and wheat has shown that raised beds also work managed by farmers. The trials have aroused farmer interest in raised bed cropping. They were enthusiastic to adopt the technology but its adoption depends on relatively high capital costs for machinery, which most farmers are unable to meet. The local manufacture of raised bed machines will help in reducing the costs.

Future plan

The second phase of the project has started, with the aim of achieving an optimum level of soil and water management practices for permanent raised beds to maximise productivity and minimise groundwater accessions, and also to facilitate the speedy adoption of the technology by farmers. A new set of bed forming and sowing machines have been provided: they are smaller, appropriate for available tractors and capable of forming one 130 cm bed or two 65 cm beds. With this improved machinery it should be possible to practise genuine no-till farming with good retention of root matter in order to build soil organic matter, retain loose soil conditions and further improve irrigation efficiencies and productivity. These smaller wide and narrow beds will be tested for maize, wheat, sugar beet, strawberry, vegetables and many other crops, to better understand the rate of soil improvement and the benefits of using either or both sizes of bed. It will be necessary for farmers to use herbicides in this mechanised no-till farming system, and to learn precise levelling techniques. The real benefit of permanent raised beds should be most evident in precisely levelled and reasonably sized fields.

Two farmer cluster groups have been organised, each with 20 members. These self-help groups were provided with two separate sets of machinery for forming and sowing permanent raised beds. The machines will be shared by group members, who will generate capital to repay the cost in easy instalments. These repayments will then be used to seed-fund and establish other farmer groups. Local industry will be involved to manufacture the Australian designed machine under agreement with the Australian manufacturer, so that it will be cheaper and more easily available to the farmers.

Acknowledgment

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Evaluation and performance of growing crops on permanent raised beds in Pakistan's Punjab

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Abstract

Pakistan's economy is mainly based on agriculture, which contributes 26% of the gross domestic product, provides 80% of total national exports, and employs 54% of the labour force. Availability of land and water resources, especially for agricultural purposes, is becoming scarcer in Pakistan. Over 90% of the agricultural production comes from irrigated areas, and nearly 50% of available irrigation water is lost in transit during application to the fields. This water deficiency scenario is posing a serious threat to food security for the future. Wheat is the main staple food crop of Pakistan, grown on about 8 million hectares every year. As a *Rabi* (winter) crop, wheat follows cotton and rice in cotton–wheat and rice–wheat cropping systems. In most years, Pakistan has to import wheat from international markets, at great expense, to fulfill its domestic requirement. Therefore, enhancement of crop productivity is imperative through encouraging the predominantly poor farmers to grow more crops with efficient use of land and water resources. A shift in crop production techniques using less flooded irrigation methods and more efficient water use, as has been actively adopted in many countries of South Asia, is being recommended. These resource conservation technologies mainly include bed planting of wheat and cotton, sowing of wheat using zero-tillage technology, and laser land levelling of fields. A study over a period of 4 years was conducted on farmers' fields to compare yields, water application requirements and net income for cotton sown on flats versus beds in Pakistan's Punjab.

Introduction

Cotton and rice are important crops in Pakistan after the main staple food crop, wheat, and play an integral role in the economy of the country. Almost half of Pakistan's foreign exchange is earned through export of rice, cotton or cotton textiles. It has been estimated that over 90% of the agricultural production comes from irrigated areas (Mohtadullah 1997), with about one-half of the irrigated area being sown under cotton (3 million ha) and rice (2.5 million ha) during Kharif (summer) season every year (Anon. 2003). Cotton and rice crops are very sensitive to water. As both excessive and restricted supplies of water to these crops are equally harmful, the adoption of effective irrigation application methods for crop production is required. Nearly 50% of available irrigation water is lost in transit during application to the fields (Gill 1994). On-Farm Water Management (OFWM), which has been working for the last two decades, has demonstrated efficient irrigation methods through better water application and conveyance techniques and watercourse improvement. The bed and furrow sowing technique is an important improvement in the application efficiencies of using irrigation water (Kahlown et al 2002).

In the Punjab province of Pakistan, cotton is grown in the south, where the groundwater is brackish. Although cotton is a salt-resistant crop, it requires fairly good quality water during germination for optimum crop production. Because good quality canal water is only available in very limited quantities, conjunctive use of canal and tubewell water is practised to irrigate the fields, which may increase soil sodicity. Punjab is also characterised by unexpected rainfall, which sometimes means that fields require immediate drainage of water, especially in cotton crops. All these constraints call for proper management of available water.

Surface irrigation is an ancient and widely used technique for irrigation in the Indo-Gangetic Plains of South Asia. Surface irrigation contributes to low application efficiency, which depends upon many factors, including infiltration soil characteristics, field

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undulation, intake discharge and run-off. Development of suitable crop-specific layouts can improve the application efficiency of available irrigation water resources. Different techniques have been developed for efficient utilisation of irrigation water and for reducing water loss in the field. The bed and furrow irrigation method is one of the most efficient surface water application methods (Kahlown et al 1998). The practice of bed planting of wheat followed by cotton, introduced in Pakistan's Punjab by OFWM, has been adopted by a considerable number of farmers, with over 40% of the area under cotton now grown on raised beds every year. Though widely used, there are growing concerns about the cost of production (Alberts & Kalwij 1999), higher weed populations and the compaction of soil/beds, which all require further monitoring while carrying out bed irrigation techniques. This paper presents a review of the on-farm experiments and observations from bed-sown cotton–wheat rotation techniques currently practised in the Punjab of Pakistan. OFWM has conducted a field study over 4 years with the objective of evaluating the impact of weed populations and compaction of beds on yields in cotton–wheat systems in the Punjab.

Irrigation scheduling for basin irrigation systems

Irrigation scheduling differs with the method of irrigation. There are generally two methods for irrigation of crops, namely basin irrigation and furrow irrigation. A third method, bed and furrow irrigation, is, however, being used on more than 40% of the area under cotton in the Punjab by progressive farmers. Cotton root development starts very rapidly and penetrates deep into the soil. Therefore, early cotton root development, being extensive, requires the soil to be wet to a depth of several feet prior to planting, and pre-planting irrigation is very important. Cotton yields can be correlated with the wetted depth of soil at sowing, and better yields are obtained if the first irrigation is applied once a plant has been fully established, thus avoiding the risks of over-irrigation.

Raising crops on beds, however, minimises the chance of such damage to cotton plants. Although wheat and rice are not as sensitive to over-irrigation as cotton, growing these crops on beds may save nearly half the irrigation water, which can then be used for other crops. There is a possibility that beds may need more frequent irrigation because of exposure of the increased surface area to the atmosphere, which increases evaporation from beds compared with flat soils. If beds are fresh, bed tillage may reduce the water-holding capacity of the soils, and irrigation scheduling should be designed carefully. All these factors depend upon soil conditions, crop variety, climatic factors, layout of fields and irrigation techniques.

Bed planting of crops for efficient irrigation

A bed and furrow irrigation system consists of alternate furrows and flat beds in ridges (Figure 1). This irrigation system has been introduced in Pakistan very recently. Better irrigation efficiency can be achieved by adopting the bed and furrow irrigation technique for growing of cotton and other row crops, with many benefits over conventional basin irrigation methods. Early rains can be very damaging for cotton crops because crusts created on newly sown cotton in flat fields can hinder germination of the seed. During the early crop stages, cotton often needs to be replanted if it rains heavily after the seed is sown or drilled in basin irrigation systems. Such rains literally crippled farmers during the spring of 1997 in Pakistan, when

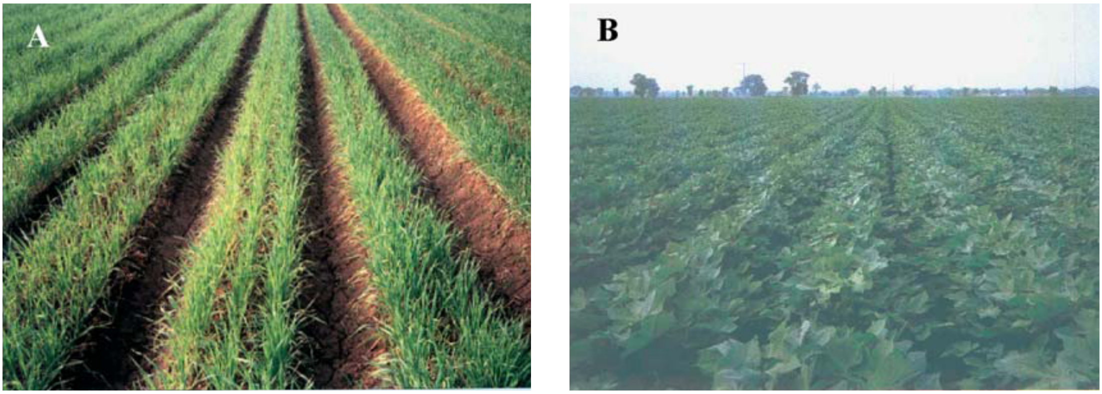

Figure 1. Bed planting of wheat (A) and cotton (B) in Punjab, Pakistan.

those farmers who had not shifted to this technology had to broadcast or drill the seed up to three or four times in one season.

Dissemination and monitoring of bed and furrow systems/technology for cotton in the southern Punjab

To improve irrigation efficiencies, trials of cotton on beds were conducted during Kharif in 1997, 1998, 1999 and 2000 at selected farms in the southern Punjab. The objective of this exercise was to enhance agricultural production by adopting this improved irrigation application method on beds. The OFWM staff provided training classes to motivate farmers to switch over to the bed and furrow irrigation system. The farmers were also given training about the use and benefits of the bed and furrow irrigation system and its effect on irrigation efficiencies and ultimately on yield.

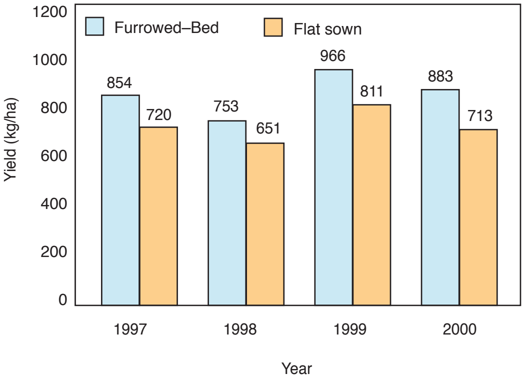

Figure 2. Cotton yield sown on bed and furrow plots compared with flat-sown (control) plots.

The Water Management staff established 88 demonstration plots covering an area of about 460 hectares during 4 years of experimentation, adopting bed and furrow irrigation systems where flat/basin irrigation systems had been used previously. Less use of water and better crop production were clearly demonstrated. Data analysis indicates that adoption of bed and furrow irrigation systems had a positive impact on cotton yields (Figure 2), and used less irrigation water (Figure 3), compared to conventional basin irrigation during the experimentation period. Growing wheat on beds increased the net farm income as well (Figure 4). Despite the fact that expenditure incurred on bed and furrow irrigation systems is marginally higher, there is an increasing trend towards adoption of this technology by farmers.

Observations from these trials are noted below:

1. Little damage occurs to cotton grown on beds in the case of heavy rainfall as the seed can still germinate because of drainage of water off the beds.
2. Water is accumulated in the furrows and does not harm the plants grown on the ridges.
3. In the rainy season, when conducting operations such as spraying (which is largely done by hand in Punjab), it is not easy to walk through a crop grown on flat fields but one can easily walk along the furrows in a bed system.
4. As seed is sown in soft disturbed soil on the ridges of beds, plant growth is better compared than that in flat-sown fields.
5. In beds, seeds can be easily replanted by hand in gaps left by plants that do not emerge.
6. Little training is needed for adoption of the bed and furrow technique compared to other high efficiency irrigation techniques such as drip/sprinkler irrigation.
7. Crops can also be grown successfully in salt-affected soils if a bed and furrow irrigation system is adopted.

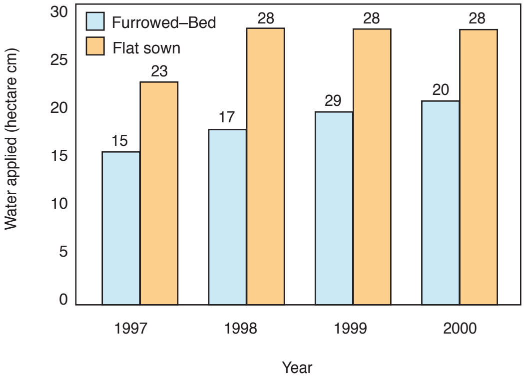

Figure 3. Amount of water applied on bed and furrow plots compared with flat-sown plots.

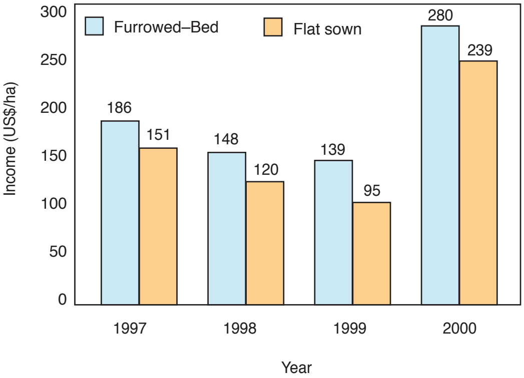

Figure 4. Income per hectare from cotton grown on bed and furrow plots compared with flat-sown plots.

8. Initially plant roots penetrate rapidly in the mounded soil of beds. The depth of this mounded soil can be up to 30 cm, compared with a depth of a few centimetres in ploughed soil in flat-sown crops.
9. Pre-planting irrigation is not required for crops grown on beds, and about half of the water required to irrigate flat fields is sufficient for fields in bed and furrow irrigation systems.
10. Although the irrigation interval for crops grown in beds is less than that for flat-sown crops, the overall amount of water used for raising crops on beds is 60% of the water used in flat-sown fields.
11. Since relatively less water is used, it is likely that nitrogen fertiliser is not leached, probably resulting in less water pollution caused by nitrification.
12. The timely availability of irrigation water is often a constraint to cotton production in Pakistan. Sometimes farmers are forced to sow cotton earlier than required due to irrigation rotation and availability, leading to a longer maturation time and more spraying required to protect the crop. Comparatively less yield is obtained from the early-grown cotton.
13. Crop operations are quicker in bed and furrow irrigation systems. About twice the area can be planted in a given time compared with a crop sown on flat fields, and early planting is therefore not required.
14. It was observed that cotton plants on beds are healthier than those planted on flat fields, resulting in better yields (Figure 2) and income (Figure 4). Because healthy plants are less affected by virus attack, they survive to a greater extent on beds than on flat fields (data not shown).
15. The crop is ready for picking 2 weeks earlier if grown on beds.
16. Management activities such as application of fertiliser or removal of weeds are easier on beds.
17. Beds do not need to be re-ploughed for planting other crops, such as wheat, after cotton. Thus beds can be used for many years with minor dressings in loamy and clay loam soils. Wheat after cotton has been grown on beds successfully, though this was on fresh beds.
18. Machines are easily available for planting cotton on beds but no such facility is available for planting cotton seed on narrow ridges.
19. One machine (furrow–bed-shaper) can plant seed cotton on 4–5 hectares in a day compared to 2–3 hectares on the flat.
20. When raising crops on beds, the first irrigation can be followed by a second irrigation within 5–7 days, depending on the climatic conditions. After the second irrigation, seed can be sown in the gaps where plants have not germinated. In order to keep the plant population optimal, excess plants can be removed within 25 days after the second irrigation.

Land preparation for bed and furrow systems

When preparing the land for sowing cotton in a bed system, some observations from the on-farm trials are relevant:

1. Weeds present in the fields must be removed prior to making beds for sowing cotton.
2. The land must be precisely levelled where a bed and furrow irrigation system is to be adopted. This allows uniform water application to ensure that the beds will remain dry. If the fields are not level, water application efficiency will be reduced and irrigation water will flow over the beds, resulting in excessive vegetative growth and ultimately reducing the number of cotton bolls produced.
3. Soil moisture should be low enough to enable the beds and furrows to be made to uniform depth.
4. Well-pulverised soil is needed to an equal depth throughout the field to ensure that beds and furrows maintain the same dimensions.

Method for making beds and furrows

A furrow–bed-shaper is commonly used for making the beds and furrows but a ridger can also be used. An average bed-shaper makes two furrows and one bed at a time, and in one day beds and furrows can easily be made over an area of 4–5 hectares. A shaper can make parallel beds with a width of 60–70 cm and furrows of similar height, and the use of a string can be very helpful to keep the furrows straight. The tractor has to be driven very slowly while making the beds, and the shaper needs to be lifted at the end of the field while turning around. The rear wheel of the tractor on its way back is tracked in the previously made furrow. The link between the tractor and the shaper/ridger can be adjusted to make furrows at a desired depth, eg 30 cm for sowing cotton. When irrigating a field with beds and furrows, the irrigation stream should be adjusted so that it does not erode the soil.

Weed control

Cotton fields must be free from weeds for at least the first 40–50 days as this is a very critical period in plant growth. Manual or mechanical removal of weeds from bed fields is normally a difficult job both before irrigation because of the hardness of the soil, and immediately after irrigation because the soil in the beds and furrows is soaked and softer. The weeds can be controlled by either applying herbicides or using intercultural cultivation with attachments on the bed-shaper equipment in moist conditions.

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Herbicides can be used in two ways. If spraying has to be done by hand, pre-emergence herbicides should be sprayed on dry beds and the field irrigated immediately after sowing. Alternatively, sowing on beds can be followed by irrigation, with herbicides sprayed after the irrigation water has been fully absorbed by the soil. Absorption of irrigation water may take 24–35 hours, depending on the soil type and width and height of the beds. The herbicides can be applied in such a way that half a band is sprayed above the line in which the seed is grown and half below the furrow slope using mechanical sprayers. Sowing and spraying can also be done simultaneously. A 'row comb' can used to remove weeds mechanically if the soil is not too moist.

Fertiliser application

Equal quantities of phosphorus and nitrogen fertilisers are required for better crop production before the crop is planted. Urea at the rate of 50 kg/ha and triple superphosphate or single superphosphate at the rate of 50 kg/ha will meet the crop requirements. In the case of compound fertilisers, NPK should be applied at the rate of 50:75:50 kg/ha or nitrophosphate at the rate of 50:75 kg/ha. The required fertilisers should be applied to dry soil before making the beds and furrows, and mixed with the soil using a cultivator or plough soon after application.

If nitrogen fertiliser is not applied at the time of cultivation, it can be applied after the first irrigation, but the weeds must be removed before application. If applied before cultivation, it can be reapplied after 40–45 days of emergence. A third application of nitrogen fertiliser must be made by mid-August, to save the crop from insects such as American pupa and white fly and to make the crop resistant to virus attack. Nitrogen fertiliser should not be used at a rate of more than 50 kg/ha.

Foliar nitrogen fertiliser needs to be sprayed if rains occur at the time of boll formation. In this case 8–12 kg each of urea and ammonium sulfate fertiliser can be mixed in 250–300 litres of water and applied on each hectare of cotton fields. The mixture should preferably be sprayed during evening hours. Such sprays are enough to meet the nitrogen demand of the plant for a period of 1 week only. Such spraying is needed again in the case of continuous rains but should not be used more than three times.

Issues concerned with adoption of permanent raised beds

The following issues associated with growing crops on permanent raised beds (PRBs) need to be considered:

1. Development of a multipurpose bed-planter is imperative to enhance adoption of growing crops on PRBs. The differences in plant size of wheat and cotton make it difficult to grow both crops on PRBs and therefore require resizing of beds between crops. The row spacing is 15–30 cm for wheat and 75–90 cm for cotton. A multipurpose bed-planter is yet to be developed for modification of bed width for a sequential cropping pattern, eg cotton and wheat. Besides width, technology and equipment are also required to adjust the height of beds according to the crop sown. Cotton is normally sown on higher beds but this height may not suit wheat or other crops which replace cotton in a rotation system.
2. The tractors owned by most farmers are of medium size (up to 65 hp), but the available bed-shapers are heavier or larger and cannot be easily operated with small to medium sized tractors. Thus, modification of the bed-shaper is needed for easy use. OFWM has developed a prototype bed-shaper suited to the local conditions in Pakistan based on one obtained from the Punjab Agriculture University in Ludhiana, India. Recently, the University of Agriculture, Faisalabad, developed a bed-planter to establish beds of suitable height and width for growing wheat in four rows as well as cotton. It is expected that a more precise bed-planter/shaper will be available in the near future.
3. Removal of carryover cotton sticks from the beds is another issue with PRBs. The presence of sticks in the next wheat crop may provide shelter to insect pests, and sprouting of the cotton sticks may cause shading problems for the wheat crop, as well as hindering spraying and harvesting operations and impairing productivity. There is a need to develop/fabricate equipment to overcome such hurdles.
4. Permanent beds may increase the infestation of weeds. Although it is easy to cultivate the weeds manually in the workable space between beds, manual operations are time consuming and labour intensive. Equipment is not available for cultivation of weeds mechanically and there is no better chemical method for control of weeds in crops sown on beds.

Further research and studies are, therefore, required to establish techniques for growing crops on permanent raised beds.

Rooting characteristics of crops grown on raised beds

Wheat and rice have shallow root systems. The soft soils of fresh beds not only help in the germination of seed but also encourage the growth of roots and consequently improve the vegetative growth of the crops (Sayre & Hobbs 2004). The response of these crops sown on PRBs has not been fully studied. OFWM has taken the initiative and begun a program with PRB field studies conducted on farmers' fields. Similarly, the feasibility of growing cotton on PRB needs further study. Apart from rooting characteristics, plant growth characteristics should be studied before disseminating the technology of raising crops on permanent raised beds in Pakistan.

Conclusions

It has been observed that crops can successfully be grown on raised beds only if requisite equipment and technologies are available for modification and re-shaping of beds and sowing of crops on beds. Selection of crop varieties suitable for sowing on beds is very important on the basis of root system, growth pattern and required intercultural operations. It has been observed that planting of wheat, cotton and other crops on beds may save up to 50–60% of irrigation water (Figure 3). Growing crops on beds also saves other resources such as labour and energy to a considerable extent.

The occurrence of weeds may increase if crops are gown on permanent raised beds. Although weeds can be cultivated manually with ease, optimum mechanical and chemical control on raised beds demands further research. Retention of residues from the previous cotton crop may cause difficulties in spaying operations, provide shelter to insects/pests and obstruct other intercultural operations. Removal or incorporation of carryover stubbles may solve the problem, and it is imperative to evolve techniques/technologies to handle/remove stubbles (eg cotton stalks) before sowing a successive crop. Retention of residues can increase soil fertility but their timely incorporation is very important. Farmers have shown great interest in the adoption of bed planting technology for raising crops, and committed resources will enable this technology to be successfully disseminated among farming communities.

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Permanent bed systems in the rice–wheat cropping pattern in Bangladesh and Pakistan

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Abstract

With the growing use of bed-sown wheat in the Indo-Gangetic Plains of South Asia, the use of permanent raised beds (PRB) within the rice–wheat system has become a researchable question for growers and scientists alike. Permanent bed use in the rice–wheat system in Bangladesh and Pakistan is limited to a few hectares for demonstration and on-station or on-farm research. However, initial findings indicate potentially sustainable increases in both productivity and profitability when the use of residue mulching on permanent beds is included. There are still major hurdles to overcome before the practice can become widespread, including:

- selection of rice germplasm that performs well under aerobic conditions such as PRB
- perfection of machinery design and manufacture that can deliver seed and fertiliser precisely, reliably and affordably using the 2-wheel tractors plentiful in Bangladesh or 4-wheel tractors in Pakistan
- involvement of all stakeholders, ie growers, agronomists, machinery manufacturers, agricultural engineers and equipment operators, to further extend and expand the use of PRB in Bangladesh while continuing to monitor and collect data on how its use can be maintained within the Bangladesh and Pakistan contexts.

When some of these major constraints can be overcome through participatory research with growers, agriculture manufacturers, scientists and machinery operators/service providers, the potential of this system in productivity, sustainability and profitability can continue to be developed.

Introduction

Grown within one calendar year, the rice–wheat cropping system represents the major food delivery practice for the Indo-Gangetic Plains (IGP) in South Asia, representing over 12 million hectares. Research on conservation tillage/agriculture in the rice–wheat system of South Asia was initiated by National Agriculture Research System (NARS) scientists, Consultative Group of International Agricultural Research (CGIAR) Centers and other advanced institutes. It began very successfully with zero tillage two decades ago, resulting in close to 2 million hectares of zero-tilled wheat followed by puddled rice during the past few years. Substantial savings in time, water and money were the major benefits, which are well documented in the literature (Abrol et al 1997; Hobbs et al 1997; Ladha et al 2003; Narang et al 2001; Pingali 1999; Timsina & Connor 2001).

However, because the potential for declines in productivity of crops still existed, the concept of systems using permanent beds with rice–wheat

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cropping evolved from three major institutes — the International Maize and Wheat Improvement Center in Mexico, Cornell University and the Australian Centre for International Agricultural Research (ACIAR). In Bangladesh and Pakistan work first began on wheat sown on beds followed by puddled rice, and this is now successfully done on thousands of hectares in growers' fields in both Pakistan and India. Access to tractors (4-wheeled in northwestern IGP) and competitive, motivated agriculture machinery manufacturers have made conservation tillage successful in India and Pakistan. In contrast, in Bangladesh conservation tillage work has been hampered by the lack of proper machinery, implements and accessories for the common 2-wheel tractors (estimated to number 200,000) and by less motivated machinery manufacturers.

This paper will illustrate the trials and errors made in the research and implementation of permanent raised beds in Bangladesh and, briefly, in Pakistan in the hope that it might assist others to continue the work in South Asia and elsewhere in the future.

Permanent raised bed systems in Bangladesh

Current status of mechanisation in Bangladesh

The introduction of 2-wheel tractors in Bangladesh was a critical prerequisite for the development of PRB systems (Figure 1). These tractors number over 200,000 and are well distributed over the country (Figure 2). In China, from where 2-wheel Dongfang or Saifang tractors are imported to Bangladesh, growers use accessories in a rice–wheat system that involves minimum tillage with a one-pass, power operated tiller/seeder (POTS) attached to the 2-wheel tractor after removing the 18-tine tiller (Figure 3).

CIMMYT, with multiple donors' assistance, tried to import as well as locally manufacture these accessories but had little success in expansion or purchase of these implements from 1996 until 2003. Participatory approaches involved biannual meetings of agricultural engineers, agricultural machinery manufacturers, agronomists, growers and 2-wheel tractor operators. Such approaches were used for more than 8 years in Bangladesh, starting in 1996, by CIMMYT Bangladesh to empower production of these accessories locally. Despite CIMMYT's best efforts, very few manufacturers were able to produce the accessories. However, during the last 2 years, over 40 imported POTS from China have been sold through an intensive participatory program that involves training operators (using materials including videos, booklets etc developed in Bangla) and loaning implements to growers and service providers at a slightly subsidised introductory price.

The main features of the permanent bed system

Concurrent with the work on the POTS, the idea of bed-sown wheat emerged, with a prototype bed planter being developed in CIMMYT Mexico using a toolbar approach attached to the 2-wheel tractor. After 3 years of intensive and participatory research and development similar to the method used with the POTS, a bed-sowing machine that can be attached to the 2-wheel tractor and can deliver seed and fertiliser reliably in a permanent or even non-permanent bed has not yet been perfected.

Currently, beds can be formed and reshaped with no problem. The bed size is usually 60–70 cm from furrow to furrow, with two or three rows on top of the bed for wheat and two rows for transplanted or direct seeded rice (Figure 4). Interestingly, many growers in South Asia prefer to transplant on top of

Figure 1. Chinese hand tractor with 18-tine tiller attached (C. Meisner).

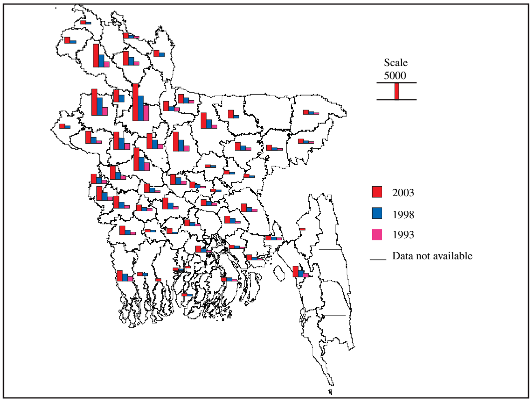

Figure 2. Numbers of 2-wheel Chinese hand tractors in Bangladesh over one decade (unpublished survey data).

Figure 3. Chinese hand tractor with power operated tiller/seeder (POTS) and 48-tine tiller, seeder and compacter attached (C.A. Meisner).

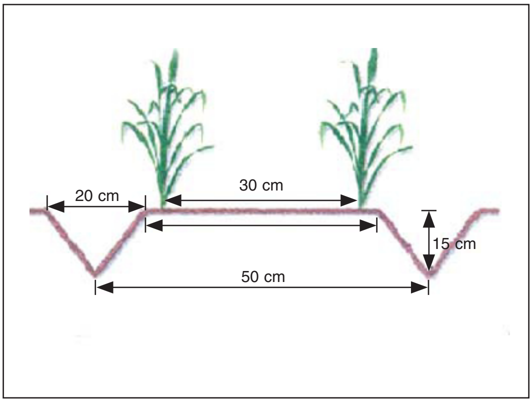

Figure 4. Usual bed size developed by bed formers in Bangladesh.

the beds to allow for early ground cover to compete with weeds. Direct seeding of rice requires greater management for weed control in some situations. Machinery to sow on top of permanent beds has only just emerged in the region for both 4-wheel and 2-wheel tractors.

In Bangladesh beds can currently be formed using two basic accessories attached to the Chinese hand tractor: either a toolbar accessory with shovels and shaper in pre-tilled soil (Figure 5), or the POTS coupled with a square or roller/cone shaper. A planter/fertiliser hopper can be used as well (Figure 6). Demonstrations in growers' fields with both these accessories showed variable machinery operation, requiring a depth control device/wheel to ensure proper seed depth placement. Also, the machinery is new, and operator training and experience should increase success over time. For permanent beds only the toolbar bed-former can be effectively used since the POTS bed-former makes two beds at a time, forcing the hand tractor wheels to travel on a pre-existing bed during a second crop season.

Experimental results on agronomic and economic performance of PRB in Bangladesh

In general, wheat sown on beds saves 30% irrigation water and increases nutrient-use efficiency (probably nitrogen), consistently increasing yields 10–18% over conventional tilled wheat on the flat (Hossain et al 2004; Talukder et al 2002; Talukder et al 2004). Evidence for increases in wheat yields under permanent beds includes greater biomass, longer spikes, greater number of grains per spike and plumper grains (Table 1), although numbers of plants or spikes per square metre is not increased

Figure 5. Bed planter based on toolbar concept (C.A. Meisner).

Figure 6. Bed former based on POTS with the Chinese hand tractor with square and cone shapers (C.A. Meisner).

Table 1. Effect of bed and conventional planting on wheat yield characteristics in Rajshahi sandy loam soil (average over 2 years). (Hossain et al 2004).

Tillage options	Initial plant population (plants/m^2)	Spikes/m^2	Spike length (cm)	Grains/ spike	1000 grain wt (g)	Grain yield (t/ha)	Biomass (t/ha)	HI (%)
Bed planting	207	283	9.8	45.7	45.9	3.77	9.38	38.6
Conventional	228	305	8.8	40.3	42.7	3.20	9.05	32.9
CV (%)	2.54	4.07	3.21	3.99	2.28	3.94	3.37	4.71

over conventional tillage. Rice sown on beds generally yielded up to a 25% increase over conventional puddled tillage on the flat, but the results were not consistent over years or locations, as was the case with wheat and varied crops (data not shown). Many experiments conducted in South Asia have indicated that when rice and wheat are grown on permanent raised beds, wheat yields generally always increase but rice yields decline. In Bangladesh this trend has not been observed. Part of the reason may be that the experimental design in Bangladesh is always a split plot where there is a continuous bed and furrow. Secondly, the rice is grown aerobically as most of the experiments are conducted by wheat scientists. Thus, the fields are irrigated in the same way as with wheat, providing adequate moisture but never flooded unless by monsoon rains which naturally flood the fields.

Data on a long-term trial of permanent beds with a soybean–wheat cropping system in Mexico show that after 10 years, PRB systems that don't retain some surface residue as mulch exhibit a declining productivity (Limon-Ortega et al 2000). Retaining the residue mulch affects soil moisture retention, nutrient-use efficiency and soil health/biota, and improves soil physical properties and hydraulic conductivity over time. Even if 25–50% of the residue is retained, it is generally sufficient to contribute to the effects described above. In South Asia crop residues are valuable commodities that serve as cattle fodder or fuel. Thus, they cannot always be retained without a cost.

System yields of rice and wheat on permanent beds in Bangladesh are also affected by whether straw is retained or removed. In Bangladesh most straw is completely removed by the growers at harvest or by community members as gleanings before the next crop because of its high value and use as a cattle feed and fuel. However, if shown to be economically feasible, growers do use straw mulch for other higher value vegetable crops. Straw retention has an additional advantage over no straw retained in that soil biota is increased (Limon-Ortega et al 2000). There is increased nodulation on mungbean when straw is retained (Talukder et al 2004).

A long-term experiment on a wheat–mungbean + maize–rice cropping system on permanent beds versus conventional flat has been conducted since

Table 2. Grain yields of various crops (2 years pooled) as influenced by straw management and N levels in a rice–wheat–maize+mungbean cropping system on permanent beds in Dinajpur sandy loam soil (Talukder et al 2004).

N Levels (% of recom.)	Grain yields (t ha^{-1})								
	Maize			Rice			Wheat		
	Straw removed	50% straw retention	100% straw retention	Straw removed	50% straw retention	100% straw retention	Straw removed	50% straw retention	100% straw retention
0	5.14 f[a]	6.15 ef [b](+20)	6.62 ef [c](+8)	2.32 d	2.97 cd (+28)	3.16 cd (+6)	2.07 g	2.39 fg (+15)	2.59 efg (+8)
50	7.27 de	8.53 cd (+17)	9.41 bc (+10)	3.64 bc	4.26 ab (+17)	4.79 a (+12)	3.04 def	3.20 de (+5)	3.74 cd (+17)
100	8.36 bc	11.00 ab (+32)	11.28 ab (+3)	3.79 bc	5.03 a (+33)	4.55 ab (–10)	3.75 cd	4.04 bc (+8)	4.23 bc (+5)
150	9.78 bc	11.03 ab (+13)	11.78 a (+7)	4.19 ab	5.12 a (+22)	4.53 ab (–12)	4.00 bc	5.03 a (+26)	4.63 ab (–8)
CV (%)	6.85			9.53			6.78		

[a] Within the treatment interactions the figures having the same letters are not significantly different at 5% level by DMRT.

[b] Numbers in parentheses represent percentage increase over straw removal.

[c] Numbers in parentheses represent percentage increase or decrease in grain yield over 50% straw retention.

2003 in Dinajpur, Bangladesh. The experiment used four nitrogen rates (0, 50, 100, 150% of the recommended 100 kg/ha N) and three straw retentions (removed, 50% retained, 100% retained as mulch). Results show that 50% straw retention plus 100% N treatment resulted in a 32% increase in maize grain yield over straw removal at the same N rate (Table 2). Maize yields from 50% and 100% straw retention at both 100% and 150% N rates were higher than the other N and straw treatments but not statistically different from each other. Subsequent rice yield with 50% straw retention plus 100% N rates also increased significantly by 33% over straw removal. There were no significant differences between 50% and 100% straw retention with 50% or 150% recommended N rates. The maximum grain yield of wheat (5.03 t/ha) was obtained from 50% straw retention plus 150% N rates, and was 26% higher compared to plots with straw removed. These yield increases with straw retention are probably due to the effects of mulches on conservation of soil moisture, less weed growth, and more efficient use of fertilisers. Often, however, when residue is retained and nitrogen rates are above the recommended, lodging occurs, reducing the yields.

Marginal analysis, under partial budgeting systems, was performed to find out the most economically profitable treatment of the above experiment on rice–wheat systems with and without straw retention. Variable cost factors that differ from treatment to treatment included quantity of straw, nitrogen level and labour for applying fertiliser, straw mulching and weeding. Other costs such as fertiliser, seeds and seeding, and irrigation were assumed to remain the same, and the existing market price was used in the analysis. The marginal analysis of non-dominated cost treatments showed that the marginal rate of return on investment was highest (1,945%) for 50% straw retention plus 50% recommended N treatment, followed by 50% retention plus 100% N (1,236%) (Table 3). The use of 50% or 100% recommended N with 50% straw retention optimised the yield and maximised the profit. Table 4 indicates that based on one crop only, in this case wheat, the economic benefit is less than with other tillage systems. The advantage in bed sowing is to have the beds remain ‘permanent’ and thus zero-tilled for future crops.

Researchers have been able to demonstrate about 5 ha of bed-sown wheat on growers’ fields in Bangladesh. Members of a young growers’ group have expanded permanent beds for a wheat–mungbean–rice cropping system in the Rajshahi region on 2 ha. They were able to show that for wheat and rice, yields were 50% and 35% higher respectively than those conventionally sown. They felt that water usage was 25–30% less for both crops using permanent beds and there was noticeably less rat damage compared to conventional methods. The group is in its second year of using permanent beds but feels that the wheat yields are declining compared to the fresh beds. Root penetration and depth were noticeably different between the two systems. The growers’ permanent beds lack any use of cereal residue as either mulch or incorporated into the furrows. The exception is mungbean where, after harvest, the remaining biomass is cut and spread on top of the beds and then covered with loose soil from the furrows. This system certainly can explain the increase in the subsequent rice yields but is hardly the recommended mulch needed for a permanent bed system’s sustainability.

Constraints on using PRB in Bangladesh

Machinery to strip till and seed on permanent beds is being devised which will ensure even seed depth on the beds. However, affordable, precision multi-crop seed delivery is the major constraint on using permanent raised beds in Bangladesh. Lack of machinery remains a limitation to the expansion of permanent beds using 2-wheel tractor bed-formers. Once this constraint is addressed, growers can further test permanent beds for their crops using appropriate machinery.

Table 3. Economic analysis of various treatments on wheat on permanent beds (from experiment conducted in Dinajpur over 2 years, data described in Table 2) (Baksh 2004).

Treatment	Variable costs (US\$ ha^{-1})	Gross margin (^{a}US\$ ha^{-1})	Marginal gross margin (US\$ ha^{-1})	Marginal variable cost (US\$ ha^{-1})	Marginal rate of return (%)
50% SR + 150% N	216	2089	96	45	213
50% SR + 100% N	171	1993	248	20	1236
100% SR + 50% N	151	1744	140	25	560
50% SR+ 50% N	126	1604	394	20	1945
100% SR + 0% N	106	1210	24	25	96
50% SR + 0% N	80	1186			–

^{a} 1 US\$ = 60 Taka; SR = Straw retention; N, % of recommended 100 kg ha^{-1}

Table 4. Economic analysis of various tillage systems with wheat (costs/benefits in US$ ha−1; based on data from experiment conducted in Dinajpur over 2 years, data described in Table 2) (Baksh 2004).

Cost / Return	POTS	Strip till	Zero till	Bed-sown	Conventional
Land preparation and bed-making cost	—	—	—	61	36
Seed cost	23	23	23	23	36
Seeding cost	24	12	12	8	1
Fertiliser cost	70	70	70	70	46
Irrigation cost	11	11	8	7	8
Labour cost	89	92	98	86	92
Total variable costs	217	208	211	255	219
Yield (t ha^{-1})	4.00	3.60	3.50	4.10	3.19
Gross return	754	679	660	773	601
Gross margin	537	471	449	518	382
Benefit–cost ratio	3.48	3.27	3.13	3.03	2.74

Though not quantified, the authors believe that the rice genotypes used are not selected under aerobic conditions and thus are not as responsive to an aerobic bed system as per their potential. Selection of rice varieties should be made under aerobic conditions and permanent beds. Under conditions of flooding, water pH measures around 7, making phosphorus (P) more readily available in either an alkaline or acidic soil when aerobic. However, aerobic rice needs to be selected under aerobic conditions where its P uptake efficiency must be higher than when selected under flooding conditions. This is due to the fixation of P under aerobic conditions compared to its increased availability under flooding. Data show that wheat varieties (while expressing some interaction with tillage) that are consistently higher yielding under conventional tillage are also responsive to permanent beds (Figure 7) (Hossain et al 2004; Talukder et al 2004).

High wheat groundcover scores (Figure 8) explain why there is less interaction with tillage — the data indicate that those three lines/varieties having the highest yields in Figure 8 also had the ability to fill the gap with foliage, a trait that is necessary for wheat varieties regardless of the sowing method. This trait is also appreciated by growers as it reduces weed growth in the furrow.

Permanent raised beds in Pakistan

Pakistan has a significant area under rice and wheat cropping systems where rice yields have been declining over the years. In order to test permanent raised beds with and without straw retention under their conditions, a permanent bed demonstration of 0.2 ha was placed on three farms in Sheikupara (State of Punjab, Pakistan) by the On-Farm Water Management team in 2002. The bed size was 65 cm and made with a bed planter manufactured in Pakistan. Data collected at each of these three sites from five samples of each crop on rice–wheat systems over 3 years, as well as observations made by the researchers and growers are reported below.

With rice, the plant population, panicle numbers per square metre, panicle length and plant height did not differ significantly between conventional and PRB (data not shown). However, there were fewer weeds with the PRB. Even so, paddy (basmati rice) yields were clearly greatest using conventional tillage and generally lowest in the permanent beds (Table 5). It should be noted that the basmati rice varieties were only selected under ideal flooded and puddle conditions. The authors suspect that if a rice variety were used that was selected under aerobic conditions, the yields might be different. The soils in the region are generally silty loam.

The wheat response to PRB was quite different (Table 6). The plant population and spike numbers per square metre were higher in PRB compared to

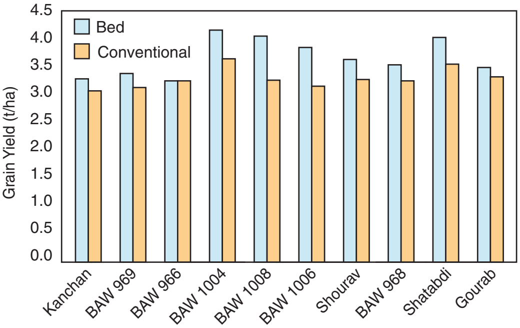

Figure 7. Wheat yields using bed sowing vs. conventionally sowing with high-yielding varieties and advanced lines (Hossain et al 2004).

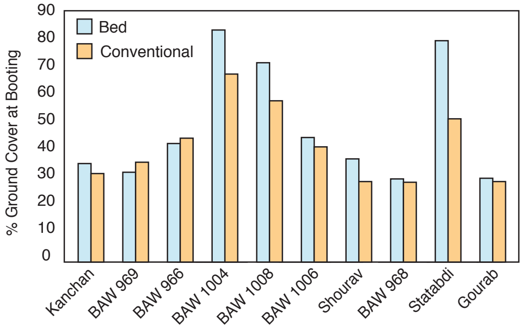

Figure 8. Ground cover scores at booting for bed sown vs. conventionally sown wheat with high-yielding varieties and advanced lines (Hossain et al 2004).

Figure 9. Permanent beds in Pakistan.

conventional tillage, but height did not differ significantly between conventional and PRB (data not shown). There were also savings of 40–50% of irrigation water and, again, less weed infestation with the PRB. Fresh beds always yielded higher than conventional, but wheat yields with permanent beds declined over the years. The major reason for the yield decline was lack of proper machinery that could seed wheat into high rice straw residue, which increased in amount each year. Thus, proper machinery that can sow wheat into growing amounts of rice stubble seems to be the major limitation. Observations by the researchers indicated that another reason for yield decline was hardness of the beds, resulting in smaller root systems (data not shown). Other yield constraints on permanent beds included more rodent attack, difficulty in transplanting rice on hard beds, crop lodging and poor crop stand due to imperfect machinery for permanent bed systems. Therefore, the adoption of permanent beds in the rice–wheat system needs further research, refinement, and availability of appropriate/quality equipment capable of reshaping beds in hard ground for both rice and wheat under high residues from previous crops.

Conclusions

The challenges of doing research and implementing permanent bed systems in Bangladesh, and to some extent in Pakistan, involve:

- perfecting machinery design and manufacture that can deliver seed and fertiliser precisely, reliably and affordably using the 2-wheel tractors plentiful in Bangladesh

Table 5. Rice paddy yield in t ha^{-1} over various methods of tillage/seeding on non-replicated on-farm trial in Punjab, Pakistan (Rehman et al 2004).

Method	2002	2003	2004	Mean
Fresh beds	3.70	3.52	3.05	3.42
Permanent beds	3.10	3.40	3.20	3.23
Conventional	3.82	3.85	3.95	3.79

Table 6. Wheat yield in t ha^{-1} over various methods of tillage/seeding on non-replicated on-farm trials in Punjab, Pakistan (Rehman et al 2004).

Method	2002	2003	2004	Mean
Fresh beds	3.75	3.80	3.45	3.66
Permanent beds	3.70	3.22	2.62	3.18
Conventional	3.30	3.45	3.07	3.27

- involving all stakeholders, ie growers, agronomists, agricultural manufacturers, agricultural engineers and equipment operators, to further extend and expand the use of PRB in Bangladesh while continuing to monitor and collect data on how its use can be maintained within the Bangladesh and Pakistan contexts
- selecting rice germplasm under aerobic PRB that performs well
- upscaling the concept to growers where permanent raised beds fit their soil and cropping systems and offer advantages in productivity as well as economic benefits.

The authors believe that continuing the emphasis in Bangladesh on upscaling of the POTS (for minimum tillage), emphasising mechanisation including bed-forming/seeding equipment, empowering growers to work with this new machinery, and demonstrating PRB with the newly designed equipment is important. The future success of PRB can only be assured if the growers find it suitable, and its economic performance and sustainability adequate, for a rice–wheat cropping system. For Pakistan, equipment needs to be designed, manufactured and sold for sowing wheat on beds in heavy straw residue. The potential for rice–wheat system yields is greater in Pakistan compared to Bangladesh because residue mulching is possible due to the lack of any economic benefit for the rice residue (most of it is currently burned).

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Permanent raised beds used for farming in the semi-arid tropics of southern Lombok, Indonesia: performance and adoption

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Abstract

In southern Lombok a short and uncertain rainfall season and poorly structured Vertisol soils limit production of the rainfed staple crops of rice (*Oryza sativa* L.) in the short wet season and soybean (*Glycine max*) in the dry season. The overall aim of our project is to increase farmers' incomes and nourishment through better management of water, soil and a diversity of crops. In field experiments at two sites in the wet and dry seasons, we compared various crops grown on permanent raised beds (PRB) with those on flat land, each with and without tillage. Rice did not grow well on PRB (1.2 m wide) with yields up to 5.5 t/ha, compared with rice on flat land with yields up to 6.2 t/ha. A complementary experiment suggested that narrower PRB (0.6 m or 0.9 m wide) may produce better yields of rice than those on PRB 1.2 m wide. The most profitable option (with least labour) for rice–soybean was flat land with no tillage. In the wet season onion (*Allium cepa*) on PRB without tillage was unreliable, but in the dry season chilli (*Piper nigrum*) on PRB without tillage was the most profitable of all crops and systems. One main advantage of PRB was that more water was harvested in the wet season, and stored and re-used in the dry season, compared with that on flat land. Based on the conclusions from the experimental sites, we encouraged farmers to grow successful crops of rice–soybean on flat land with no tillage on two-thirds of each farm, and vegetables (apart from onion) on PRB with no tillage on one-third of each farm in the wet and dry seasons. Support from the local government and a contract with a private seed company were essential to speed up adoption by farmers.

Introduction

Location

Subsistence farmers in southern Lombok, West Nusa Tenggara, Indonesia (Figure 1), are poor, poorly nourished, hardworking people producing crops with inconsistent yields. Crops are rainfed, mainly rice (*Oryza sativa* L.) in the wet season and soybean (*Glycine max*) in the dry season. The wet season is from November/December to March/April, and the dry season is from April/May to October/November. The average rainfall varies across the region (Figures 2, 3), with about 80% falling between September and February. April to August is extremely dry, recording only about 10% of the annual rainfall (Abawi et al 2002). The soils are Vertisols, with 50% clay dominated by montmorillonite. During the wet season the soil swells, with little deep drainage. During the dry season cracks 15–45 cm deep and 2–15 cm wide develop in the soil. The short and uncertain rainfall season and the poorly structured Vertisols limit crop production in southern Lombok (Mahrup et al 2005).

The overall aim of our project is to increase farmers' incomes and nourishment through better systems of management, including easier work, better use of the limited water available, better yields of crops, and better security through production of diverse high-value crops.

Socioeconomic indicators

Traditionally, the staple crops are grown on flat land, are risky and do not bring good returns. The flat land cannot be well drained in the wet season, preventing vegetables from being grown; however, vegetables are sometimes grown in the dry season. Socioeconomic constraints such as small farms and poor and poorly educated people, along with poor management, also contribute to low crop production and low incomes for

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Figure 1. Map of Indonesia and location of field experiments with PRB.

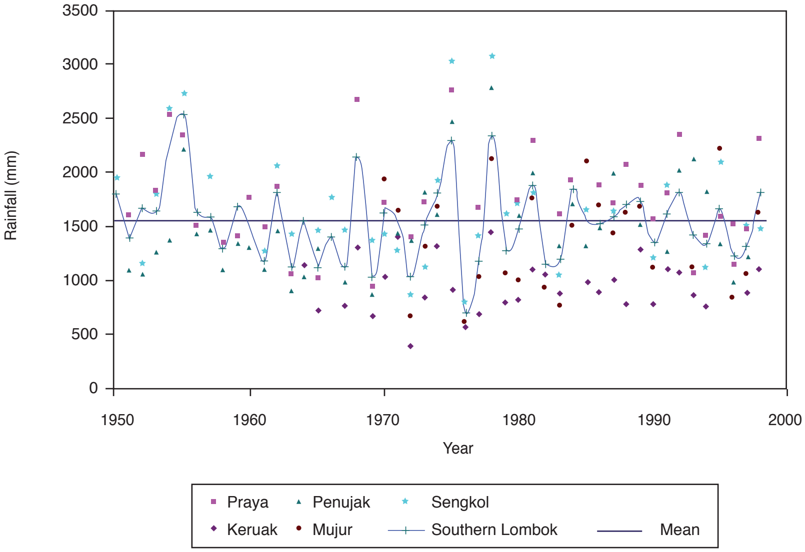

Figure 2. Annual rainfall in southern Lombok over 50 years (1950–2000).

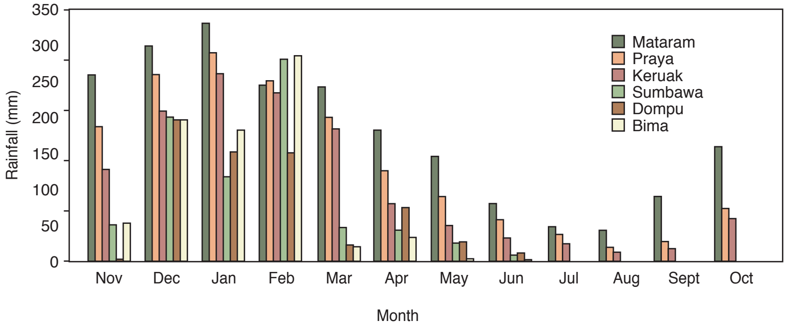

Figure 3. Average monthly rainfall at various sites in West Nusa Tenggara over 50 years (1950–2000).

farmers. Farms range from 0.25 to 0.35 ha, and families usually have more than three children to support.

Gogorancah

In the 1980s, to improve production and farmers' incomes, the government introduced and enforced the gogorancah system for rice and soybean on tilled flat land. In this system all labour is by hand; rice is direct seeded into hand-tilled soil early in the wet season when the water content of the soil is just sufficient to support germination (about 60 mm rainfall over 10 consecutive days). The land is then usually flooded from rain as it falls (when available). Gogorancah has been reasonably successful considering the erratic rainfall. Weeds are fairly well controlled on the tilled land, especially when there is enough rainfall to flood the land early in the wet season. However, much water evaporates from the surface when the land is flooded, and not enough water is stored in the soil for successful secondary crops. The land needs to be manually prepared for drainage just before the soybean seed is broadcast by hand; the soybean crop tends not to be carefully managed during the dry season. Because of the intensive hand-tillage needed and the shortage of available labour, farmers do not like gogorancah and have used the system less and less over the last 5 years.

Potential alternatives to gogorancah

A new sustainable system of management is needed for crop production in the semi-arid environment of rainfed southern Lombok, in particular to encourage better root growth in well-structured Vertisols. The soil, water and crops need to be better managed to improve the physical properties of the soil, increase the water supply for crops, and sustain the productivity of rice as well as some non-rice crops.

Permanent raised beds (PRB) have been successfully used for staple crops in the semi-arid tropics in Timor and Queensland, Australia (Borrell et al 1997, 1998; Borrell & Van Cooten 2000), and may be suitable for rainfed crops on Vertisols in southern Lombok. Another possible alternative to gogorancah for rice and soybean is flat land with no tillage, similar to a system already accepted by BPTP (Balai Pengjian Teknologi Pertanian, the government agricultural extension service) on Lombok.

Farmers will always want to grow some rice in the wet season, and most non-rice crops (including vegetables) cannot be grown on flat land in the wet season. However, PRB with good surface drainage may bring a better return if farmers can grow some non-rice crops (including vegetables) out of season in the wet season.

This paper addresses:

- the application and performance of crops on PRB and flat land in field experiments on rainfed Vertisols at two sites in southern Lombok over 3 years
- the collaboration between local farmers, researchers and a private seed company
- the adoption of PRB by the farmers.

PRB system for southern Lombok

Rationale

Some potential advantages of PRB with no tillage compared with the traditional gogorancah system are:

- decreased labour for tillage once the PRB are set up
- increased water harvested in the wet season, to be stored and used when needed in both the wet and dry seasons
- increased irrigation water-use index
- improved physical properties of soil
- increased crop diversity, including high-value vegetables grown in both the wet and dry seasons
- increased incomes for farmers.

On the other hand, some potential disadvantages of PRB with no tillage are the:

- high cost of initial establishment and maintenance
- difficulty in controlling weeds in unflooded soil with no tillage
- potential inability of fertilisers to reach the roots when they are applied at the surface of the soil during a dry spell.

Research approach to the proposed system

Two sites, Site 1 (Wakan) and Site 2 (Kawo), with extremes of rainfall were selected in southern Lombok (Table 1). At each site rice and soybean grown on PRB with no tillage were compared with rice and soybean grown on flat land with tillage (modified gogorancah) (Figure 4). Compared with true gogorancah as used by local farmers, modified gogorancah used certified rice seed, a better sowing rate and spacing, and better fertiliser management. Rice stubble was retained, and water was harvested during the wet season to be stored and used when needed during both the wet and dry seasons.

To encourage farmers to move towards our preferred system of PRB with no tillage, we included two other treatments with rice–soybean: PRB with tillage and flat land with no tillage. The latter treatment is similar to the current system being promoted by BPTP. Maize and soybeans were also grown on raised wavy beds in the wet season; and vegetables were grown on PRB with no tillage and on raised wavy beds in the wet and dry seasons (Figure 4).

Experimental design

In September 2001 experiments consisting of six treatments (replicated three times) were set up by hand at Wakan (Site 1) and Kawo (Site 2) in southern Lombok (Table 2; Figure 4). The yield of crops, physical properties of soil, water used and harvested, and economics were all assessed in each treatment in the experiment.

The raised wavy beds were included as a variant on the shape of raised beds. The width of beds (1.2 m) used for the PRB and raised wavy beds was based on the width of PRB in temperate crops in northern

Table 1. Rainfall (mm) during the experiments and the 50-year average.

	Year 1 (2001–02)	Year 2 (2002–03)	Year 3 (2003–04)	50-year average
Site 1 (Wakan)	709	1122	774	868
Site 2 (Kawo)	1084	1341	1221	1215

Table 2. Treatments used in the experiments at Site 1 (Wakan) and Site 2 (Kawo).

Treatment[a]		Soil management	First crop	Secondary crop
Permanent raised beds	T1	Preferred no tillage	Rice[c] (*Oryza sativa*)	Soybean[c] (*Glycine max*)
Permanent[b] raised beds	T2	With tillage	Rice[c]	Soybean[c]
Permanent raised beds	T3	Preferred no tillage	Onion (*Allium cepa*)	Chilli[d] (*Piper nigrum*)
Flat land[b]	T4	No tillage, herbicide	Rice	Soybean[e]
Raised wavy beds	T5	No tillage	Intercropped maize (*Zea mays*)/soybean	Intercropped[f] tomato (*Solanum lycopersicum*)/ mungbean (*Vigna radiata*)
Flat land[g]	T6	With tillage	Rice	Soybean[c]

[a] Figure 4 shows the land preparation of each treatment. The permanent raised beds (PRB) were renovated each year. T4 and T6 (but not other treatments) were flooded during the wet season.

[b] Precursors of the preferred system of PRB, with no tillage (T1).

[c] 6 rows of rice plants per bed; 620 soybean plants per plot, plant spacing 20 × 20 cm.

[d] Relay-cropped Year 3 (long bean sown 2 weeks after chilli sown).

[e] 960 soybean plants per plot (plant spacing 20 × 30 cm). Each year, before the soybean was sown, the land was set up by hand to drain any excess water from the surface.

[f] Intercropped Year 1 (2002); relay-cropped Year 2 (2003) and Year 3 (2004) (tomato transplanted 7 days before mungbean sown).

[g] Treatment closest to traditional gogorancah as used by local farmers, but T6 is a better system with certified seed and better crop and water management.

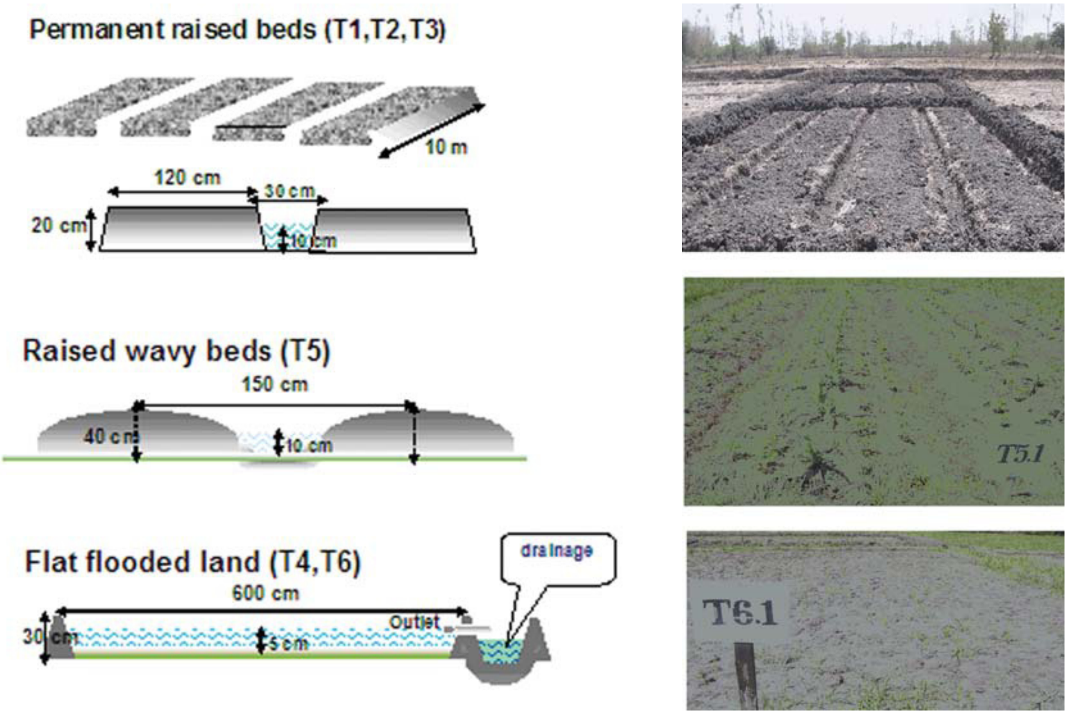

Figure 4. Design of the land and water in treatments with permanent raised beds (PRB), raised wavy beds and flat land (Table 2). All operations were by hand. Each year the PRB and raised wavy beds were renovated before the wet season. Each year before the soybean was sown on flat land, the land was set up by hand to drain any excess water from the surface.

Victoria, Australia (Tisdall & Adem 1988). Also, because crops in the wet season on Lombok receive most water directly from rainfall, they do not depend on lateral flow from the furrow to the centre of the bed, and wide beds enable a higher plant population than do narrow beds. However, in a complementary experiment at the drier Site 1 (Wakan), we also compared the performance of crops on narrow PRB 0.6 m and 0.9 m wide (not reported here).

The total growing season for rice was about 115 days. With rice under PRB (T1, T2; Figure 4), water in the furrows was maintained at 10 cm depth from the surface of the beds for 50–55 days during the growing season. When it dropped to 5 cm depth, water was applied to maintain the depth of water in the furrows at 10 cm. Excess water was drained into the channel via a bamboo pipe installed in the bund (a raised border around the rice crop) at 10 cm above the base of each furrow (Figure 5). With the non-rice crops in the wet season (T3, T5; Figure 4), no free water was allowed to remain in the furrows; excess water was again drained into the channel via a bamboo pipe and stored in the embung (water reservoir).

Because of low uncertain rainfall, on flat land (T4, T6; Figure 4) there was sometimes insufficient water to start flooding the land until up to 40 days after sowing. Even then water could only be kept at a depth of 5 cm above the soil surface for 35 days, probably because of higher evaporation from the larger surface area of water than that with PRB. When the level on the flat land dropped to a depth of 2.5 cm, water was applied (Figure 5). As with PRB, excess water was drained into the channel via a bamboo pipe installed in the bund at 5 cm above the flooded flat land. This excess water from each of the PRB, raised wavy beds and flat land areas was measured as water harvested (mm) and was stored in the embung.

Twice during the wet season, when the land was saturated but not flooded, fertilisers (N as urea; P as SP36) were banded alongside the seed (PRB; T1, T2) or broadcast on the surface (flat land; T4, T6).

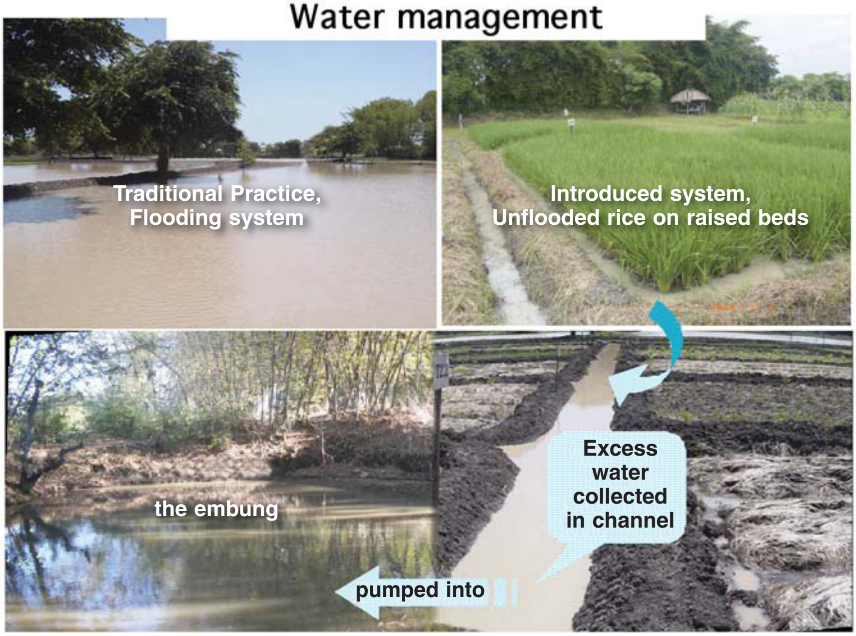

Figure 5. Water management of flooded treatments (T4, T6) and treatments with PRB (T1, T2, T3) or raised wavy beds (T5) (Table 2).

Performance of PRB systems

Yield

Rice and soybean (staple crops)

In general the rice yield was up to double the average yields produced by local farmers using traditional gogorancah (data not shown). However, the rice yield (Table 3) was generally lower under PRB with no tillage (T1) than on flat land with tillage (T6). The yield on flat land without tillage (T4) was similar to that on flat land with tillage (T6). The yields of rice and soybean in both T4 and T6 were higher than those on local farms, showing that, even without adopting PRB, farmers could increase their incomes. The best rice yield under PRB was at Kawo (Site 2) with an average monthly rainfall of at least 110 mm (data not shown) during the growing season. The complementary experiment at the drier site at Wakan (Site 1) in Year 2 suggested that PRB 0.6 m wide (6.1 t/ha) or 0.9 m wide (5.3 t/ha) (data not shown) may produce better yields of rice than would PRB 1.2 m wide. Rice on flat land with no tillage (T4) is therefore a good option for farmers.

The soybean yield was up to 150% of the average yields produced by farmers (data not shown). In Year 1 at each site the soybean yield as a secondary crop did not differ between treatments (Table 4). However, at Site 1 in the wetter Year 2 (Table 1), but not Year 3, the yield was higher on PRB (T1, T2) than on flat land (T4, T6). At Site 2 in Year 2 and Year 3, the yield was generally higher on flat land with tillage than in other treatments.

Crops other than rice and soybean

Onion is sensitive to pests and to poorly drained soil; hence, overall, onion was not successful on PRB in the rainy season (Table 5). Each year army worms attacked the onion at Site 1, and the soil was too wet during the high rainfall in Year 2 at Site 2 (Table 1).

Intercropped maize–soybean on raised wavy beds in the wet season was successful at both sites (Table 5), although the soybean yield was lower in Year 2 when rainfall was higher than the 50-year average (Table 1). Each year the yield of intercropped maize–soybean was less at the wetter Site 2 than at Site 1.

Long bean, mungbean and tomato on PRB or raised wavy beds in the dry season generally produced good crops at each site, but the yield of chilli was higher at the drier Site 1 than at Site 2.

One main advantage of PRB is that valuable vegetables can potentially be grown out of season in the wet season and bring a good return to farmers.

Table 3. Grain yield (t/ha) of rice in permanent raised beds (PRB) and flat land in the experiments at Site 1 (Wakan) and Site 2 (Kawo).

Treatment		2002	2003	2004	Mean
Site 1					
PRB with no tillage	T1	2.6	4.5	3.6	3.6
PRB with tillage	T2	2.9	5.0	3.1	3.7
Flat land with no tillage	T4	3.9	5.3	3.2	4.1
Flat land with tillage	T6	4.4	5.5	4.2	4.7
$LSD_{0.05}$		0.5	0.8	1.1	
Site 2					
PRB with no tillage	T1	4.1	5.4	4.8	4.8
PRB with tillage	T2	4.4	5.5	4.9	4.9
Flat land with no tillage	T4	4.8	5.7	5.8	5.4
Flat land with tillage	T6	4.7	6.2	5.5	5.5
$LSD_{0.05}$		ns	0.8	0.5	

Table 4. Grain yield (t/ha) of soybean in permanent raised beds (PRB) and flat land in the experiments at Site 1 (Wakan) and Site 2 (Kawo).

Treatment		2002	2003	2004	Mean
Site 1					
PRB with no tillage	T1	1.2	1.6	1.3	1.4
PRB with tillage	T2	1.1	1.6	1.4	1.4
Flat land with no tillage	T4	1.0	0.9	1.1	1.0
Flat land with tillage	T6	1.1	0.9	1.5	1.2
$LSD_{0.05}$		ns	0.02	0.2	
Site 2					
PRB with no tillage	T1	1.3	1.7	1.2	1.4
PRB with tillage	T2	1.4	1.6	1.3	1.4
Flat land with no tillage	T4	1.2	1.6	1.5	1.5
Flat land with tillage	T6	1.1	1.7	1.7	1.6
$LSD_{0.05}$		ns	0.1	0.1	

Because onion is sensitive to wet soil, it was not a good choice for the wet season. However, farmers have since successfully grown other vegetables on PRB in the wet season (see 'Adoption of PRB'). The PRB also provide more water for irrigation of the secondary crops than does flat land (see next section).

Water management and harvesting

Each year at each site the volume of water harvested from rice during the wet season (Table 6) on PRB (T1, T2) was generally about 1.5 times that on flat land (T4, T6), ie rice on flat land used more water than did rice on PRB (Marhup et al 2005). Therefore, PRB provided more harvested water, which could be used for irrigation of the soybean after rice, leading to more secure crops.

With vegetables, extra water was also harvested from PRB (T3) and from raised wavy beds (T5) in the wet season (Table 6). This was used as irrigation water in the dry season for the vegetables, which yielded well (Table 5).

These results show that rice and soybean grow better, and use less irrigation water, on flat land than on PRB. However, the better management of rice and soybean in the experiments at Site 1 (Wakan) and Site 2 (Kawo) led to higher yields than those on local farms. Hence, especially in years of low rainfall as in 2004–05 (data not shown), rice on flat land without tillage (T4) or flat land with tillage (modified gogorancah; T6) is less likely to fail than rice grown under true gogorancah, where crops are not well managed and water is not harvested and re-used (see 'Research approach to the proposed system' above).

Further research is planned in collaboration with the ACIAR climate project (SMCN/2002/033), to

Table 5. Yield (t/ha) of first crops other than rice, and of secondary crops, in the experiment at Site 1 (Wakan) and at Site 2 (Kawo).

Treatment		2002		2003		2004	
		Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
First[a]							
Onion	T3[b]	0.5	4.6	0.3	0.3	0.4	4.1
Maize	T5[b]	3.1	3.1	2.6	2.5	1.7	4.0
Soybean	T5	1.2	0.7	0.8	0.4	1.3	0.9
Secondary							
Chilli	T3	3.5	0.7	5.3	1.4	5.3[c]	1.4[c]
Long bean	T3	nd	nd	nd	nd	1.5[c]	1.5[c]
Mungbean	T5	1.0	1.4	1.1	0.9	1.4	1.6
Tomato	T5	3.4	1.7	12.3	12.7	13.1	10.2

[a] Crop grown out of season.
[b] T3 permanent raised beds; T5 intercropped on raised wavy beds.
[c] Relay-cropped chilli / long bean.

Table 6. Water harvested (mm) from each treatment (Table 2) at Site 1 (Wakan) and (Site 2) Kawo.

Treatment		2001–02	2002–03	2003–04	Mean
Rice, Site 1					
PRB with no tillage	T1	113	184	125	141
PRB with tillage	T2	114	159	125	133
Flat land with no tillage	T4	76	139	84	100
Flat land with tillage	T6	77	120	85	92
Rice, Site 2					
PRB with no tillage	T1	171	178	168	172
PRB with tillage	T2	172	179	169	173
Flat land with no tillage	T4	115	119	112	115
Flat land with tillage	T6	116	121	115	117
Crops other than rice, Site 1					
PRB with no tillage	T3	153	210	170	178
Raised wavy beds	T5	112	178	124	138
Crops other than rice, Site 2					
PRB with no tillage	T3	232	241	226	233
Raised wavy beds	T5	170	176	167	171

lessen the impact of uncertain rainfall on crops on Lombok.

Maintenance

Renovation of PRB

During the second year of the experiment at each site, the soil in the PRB and raised wavy beds slumped. Therefore, once a year, the beds needed to be renovated. The furrows between PRB or raised wavy beds were deepened by hand and the removed soil was put on the top of the beds.

Weed control

In each treatment weeds were cut with a knife only when they were severe. Rice was weeded twice on flat land with tillage (T6) and between one and three times on flat land with no tillage (T4) during the growing season. More weeding was needed at Site 1 (Wakan) than at Site 2 (Kawo) (data not shown). Weeds were best controlled on flat land with tillage (T6) and least controlled on flat land with no tillage (T4) (data not shown). T4 herbicide applied 1 day before the rice was sown controlled weeds early in the growing season, but later the weeds re-appeared

Table 7. Labour (man days/ha) used each year[a] in each treatment at Site 2 (Kawo).

Treat[b]	Set-up[c]	Tillage		Renovation		Drainage	Sowing	Weeding	Fertiliser	Herbicide	Harvest	Total		
	Yr 1	Yr 2	Yr 3	Yr 2	Yr 3	Yr 1,2,3	Yr 1,2,3	Yr 1,2,3	Yr 1,2,3	Yr 1,2,3	Yr 1,2,3	Yr 1	Yr 2	Yr 3
T1	167	0	0	125	100	0	167	167	167	0	50	717	675	650
T2	500	375	400	125	100	0	167	167	167	0	50	1050	1050	1050
T3	167	0	0	125	100	0	167	167	167	8	17	675	650	625
T4	0	0	0	0	0	20	167	250	13	2	50	502	502	502
T5	250	0	0	200	150	0	167	167	83	2	50	718	668	618
T6	417	417	417	0	0	20	167	83	13	0	50	750	750	750

[a] Yr 1 (2001–02); Yr 2 (2002–03); Yr 3 (2003–04).
[b] Treatment (Table 2).
[c] Initial land preparation.

in response to broadcast urea, especially before the land was flooded. On PRB with no tillage (T1) less weeding was needed than on flat land with no tillage (T4), possibly because the soil was drier and the banded urea in the drier T1 was less available for weeds (see ‘Experimental design’ above) (data not shown).

Labour requirements at Kawo

Each year the total labour used at each site (Table 7) was lower in PRB with no tillage (T1) than on flat land with tillage (T6), but both used more labour than did flat land with no tillage (T4). The big differences in labour were due to variations in initial land preparation, renovation, tillage, land preparation for drainage, application of fertilisers and weeding.

With PRB (T1, T2) in Year 1, furrows 30 cm wide and 20 cm deep were formed and the soil was moved from the furrows to the tops of the beds. In subsequent years similar tillage was needed to renovate the beds by hand. Hence, to decrease the cost of labour, a new machine is needed to set up and maintain PRB.

Tillage was expensive in T2 and T6 where the soil was tilled to a depth of 40 cm with a crowbar at the end of the dry season in preparation for rice. As with gogorancah as used by local farmers, on flat land (T4, T6) the land was graded by hand to improve surface drainage before soybean was sown.

In T4 and T6 fertilisers were broadcast on the surface of the soil (see ‘Maintenance’ above), but with PRB (T1, T2, T3) more labour was needed because the fertilisers were banded with a wooden stick to a depth of 5 cm.

Less labour was needed for weeding in PRB with no tillage (T1) than on flat land with no tillage (T4), in spite of herbicide use and flooding in T4. Differences were possibly due to differences in time until land was flooded, and application of urea (see ‘Maintenance’ above). Better methods of weed control are needed for all treatments without tillage.

Economic benefits of PRB at Kawo

In spite of more labour needed on flat land with tillage (T6; Table 7), the higher yields of rice (Table 4) led to a higher profit margin (Table 8) in T6 than that in PRB without tillage (T1). However, PRB 0.6 m or 0.9 m wide (see ‘Yield’ above) may produce a higher yield and profit margin that PRB 1.2 m wide. Overall, the profit margin was greatest on flat land with no tillage (T4), with generally high yields of rice and soybean and low cost of labour. Hence, flat land with no tillage (and not PRB) is a good option for the staple crops of rice and soybean.

Apart from the wet Year 2, the highest profit margin at Kawo was with T3 on PRB with no tillage (onion grown out of season in the wet season, chilli in the dry season) (Table 8). Onion is sensitive to wet soil and was unreliable in the wet season, with erratic returns even on PRB. Other vegetables, such as snake bean (*Vigna sesquipedalis)* long bean, pumpkin (*Cucurbita maxima*), watermelon (*Citrullus vulgaris* L) and cucumber (*Cucumis sativus* L), are less sensitive to wet soil and may give better returns on PRB in the wet season. Long bean, mungbean and tomato gave promising returns in the dry season at Kawo. One main advantage of PRB and raised wavy beds is that extra water can be harvested in the wet season and used for irrigation of high-value vegetable crops in the dry season.

Adoption of PRB

Current experience with farmers

Our field experiments showed that for rice–soybean, the highest profit margin and least labour were on

Table 8. Profit margin (million Rp/ha) of each treatment (Table 2) each year at Site 2 (Kawo) (1 million Rp = $A7,322)

Treatment		2001–02			2002–03			2003–04		
		Wet	Dry	Total	Wet	Dry	Total	Wet	Dry	Total
PRB with no tillage	T1	2.00	1.37	3.37	3.67	1.48	5.15	2.84	0.85	3.69
PRB with tillage	T2	2.06	1.31	3.37	3.57	1.37	4.94	2.83	0.90	3.73
PRB with no tillage	T3	7.82	4.33	12.15	–4.20	4.32	0.12	6.31	4.34	10.65
Flat land with no tillage	T4	3.03	1.11	4.14	4.12	1.99	5.31	4.21	0.77	4.98
Raised wavy beds	T5	2.00	2.21	4.21	1.75	4.30	6.05	0.21	5.03	5.24
Flat land with tillage	T6	2.93	1.20	4.13	4.75	1.20	5.95	3.28	0.94	4.22

flat land without tillage. However, vegetables grown on PRB with no tillage or on raised wavy beds were also promising. The farmers are reluctant to try new crops, especially vegetables, with unknown markets and returns. Hence in June 2003, to encourage farmers to adopt our new system, we started collaboration between the University of Mataram, PT.BISI (Benih Inti Subur Intani, a private seed company) and farmers. PT.BISI gave seed to the farmers and made a contract with them to produce seed of high quality of several vegetable crops (long bean, pumpkin, rockmelon (*Cucumus melo*), cucumber and bitter bean). Because these crops require well-drained soil, use of PRB was a pre-requisite for collaborating farmers to produce vegetables in the wet season. The local team from the University of Mataram, along with PT.BISI, facilitated and supervised the farmers. At present the farmers irrigate the vegetables by pouring water by hand.

At the beginning of the collaboration a formal ceremony (opened by the Governor of West Nusa Tenggara) celebrated the formation of the PRB farmer groups. The ceremony was essential to show the government's support for our new system and to encourage interest by farmers.

Because farmers in southern Lombok will always want to grow some rice, and we do not want to flood the market with vegetables, the local team encouraged the farmers to use the ACIAR cropping model (ACM) (Figure 6), where one-third of the farm land is converted to PRB with vegetables, and the rest of the farm is used for the staple rice and soybean crops on flat land with no tillage. In southern Lombok 45 farmers are now using the ACM to grow high-value vegetables on PRB with no tillage under contract with PT.BISI. The ACM suits the farmers who need to grow some rice for use by the family, but can also make a bigger profit with vegetables (especially out of season) than with rice only. The ACM looks promising so far. Farmers who adopted PRB in 2004 produced outstanding crops of snake bean (2.0 t/ha) in the wet season under contract with PT.BISI, and received a price of Rp 27 million/ha (almost $A4,000/ha). These returns were about twice that to other farmers who grew only rice in the wet season.

To stimulate widespread adoption of the system, over the next 2 years (2005–2007) we aim to establish collaborative work between the University of Mataram, La Trobe University in Australia, PT.BISI, the local government and farmers in southern Lombok.

Following the formation of farmer groups, the local team, together with PT.BISI and BPTP, will continue to supervise farmers in growing long bean, cucumber and pumpkin on PRB. Before buying the seeds from the farmers, PT.BISI will explain to them the need for seeds to be of high quality for good returns. The local team and BPTP will also run field days and provide brochures and calendars to disseminate information and encourage the farmers to adopt the practices. At the end of 2 years the local team will organise another formal ceremony (to be opened by the Governor of West Nusa Tenggara) to celebrate the successful PRB farmer groups. The ceremony will be essential to show the government's support for our new system and to encourage interest by other farmers.

Constraints to further adoption

To improve the ACM further for farmers, we need to develop a machine for forming and renovating the PRB, better methods for control of weeds, and better methods of harvesting, storing and re-using harvested water.

The fact that subsistence farmers have small farms (average 0.25 ha/family) and low capital discourages them from growing crops other than rice and from using PRB. To help overcome problems in the early stages, the local team, PT.BISI and BPTP will supervise farmers to produce vegetable seed of good quality on PRB. In the long term, farmers will be able to organise loans from the local bank (Bank NTB) through a microfinance scheme, and the University of Mataram will play a significant role as a bridge between the farmers and Bank NTB.

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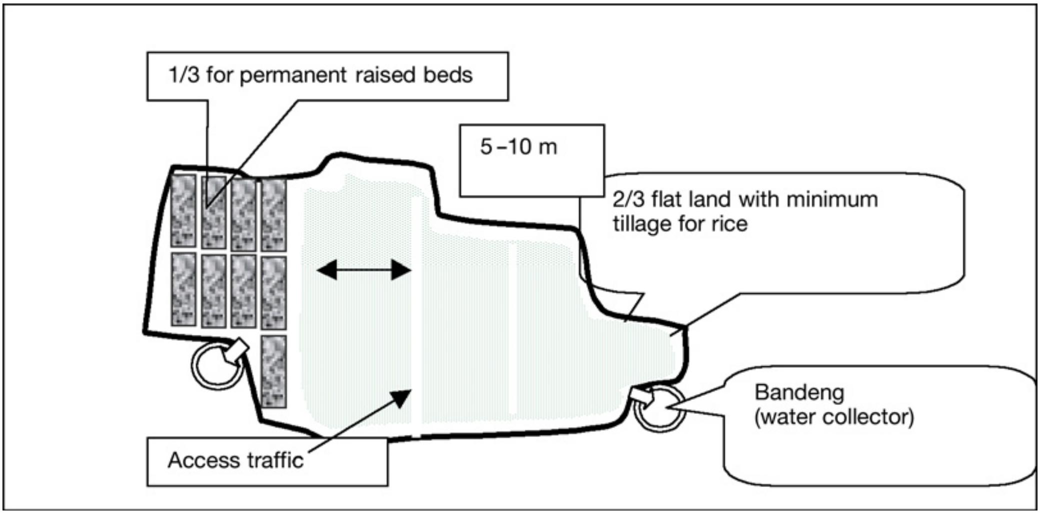

Figure 6. ACIAR cropping model (ACM) proposed by the local team at the University of Mataram for farmers on southern Lombok. Rice (wet season) and soybean (dry season) are grown on flat land with no tillage. Vegetables are grown in the wet and dry seasons on PRB under contract with the private company PT.BISI.

Conclusions

PRB with beds 1.2 m wide are not a good option for rice–soybean cropping in southern Lombok, although narrower beds (0.6 m, 0.9 m) may be suitable.

Flat land with no tillage could probably replace the traditional system of gogorancah, not only in rainfed Vertisols in Lombok, but also possibly in other regions in eastern Indonesia with similar soil and climate characteristics.

The ACM, including rice–soybean on flat land with no tillage and vegetables on PRB with no tillage, is a promising solution in southern Lombok, even though farmers would need to be encouraged to try the new system. Therefore, support from the government and private companies is essential to speed up adoption by farmers. Widespread use of the system could also be expected to alleviate poverty in southern Lombok.

To improve the performance and adoption of both the ACM and PRB for rice–soybean cropping, the following strategies are needed:

- development of simple equipment for making/renovating PRB and applying fertilisers on the PRB
- research on the best width of PRB for rice/soybean
- research on water harvesting, storage and re-use, and conservation of water in the soil, especially during the dry season for secondary crops
- research on better weed control in all crops
- provision of extension material and field days for farmers by local government through BPTP
- use of results and conclusions from ACIAR project SMCN/1999/005, combined with the ACIAR climate project (SMCN/2002/033), to reduce the risk due to uncertain rainfall in the region
- provision of financial assistance for poor farmers through soft loans from the local bank
- maintenance of a good relationship between the local government, the private company, the university (researchers) and farmers.

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Rice grown on raised beds: effect of water regime and bed configuration on rice yield, water input and water productivity

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Abstract

A system of growing rice on raised beds, where water is applied only in the furrows between beds, is hypothesised to reduce water input for rice. This study was carried out in the dry and wet seasons of 2002 and the dry season of 2003 at the International Rice Research Institute (IRRI) Experiment Station, Los Banos, Laguna, Philippines. The aim was to compare the effect of bed configurations (puddled flats, and beds with 65 cm and 130 cm centre-to-centre spacings) and water management on rice yield, water input and water productivity (rice yield per unit volume of water input). During the dry season water treatments used were well-watered; saturated; and irrigation when soil water potentials at 15 cm soil depth reached –10 kPa, –20 kPa and –50 kPa respectively. Water treatments used during the wet season were irrigated and partially rainfed. In each plot soil water potential and perched watertable depth were monitored near the edge and at the middle of the beds. Yield and yield components were taken at maturity.

Perched watertable depth and soil water potentials did not differ at the middle of the bed from those in the furrow or near the edge of the bed. This implies a similar water regime across the entire width of the bed. Well-watered flat fields had the highest grain yield and irrigation water input compared with other water treatments. Grain yield was also higher in flats than in beds, regardless of bed width. However, beds reduced irrigation water input by as much as 200–500 mm compared with puddled flats during the dry season. In flats increasing stress levels decreased grain yield and water input, while in beds no significant differences in water input were observed among the water treatments. Water productivity was generally higher in the stressed treatments (in both flat fields and raised beds) than in flooded flat fields. Raised beds with slight water stress can increase water productivity compared with flooded flat-field rice culture under water-short conditions, and may be an important option where crop diversification is considered.

Introduction

Rice requires very large amounts of water under the traditional continuously flooded irrigation method. However, due to growing demand in the domestic and industrial sectors, water is becoming increasingly scarce, and there is a need to develop ‘water saving irrigation (WSI) techniques’ that require less irrigation input than the traditional method. The need to produce more rice with less water is crucial for food security for many Asian countries where water scarcity for agricultural use is increasing (Guerra et al 1998).

One of the most studied WSI techniques is alternate wetting and drying (AWD) irrigation, which allows the soil to dry out to a certain extent before irrigation water is re-applied (Bouman & Tuong 2001; Cabangon et al 2004; Mao et al 2000). Under the AWD method, grain yield is similar to a continuously flooded system because the soil is not allowed to dry to a level that may cause water stress to the rice plants (Belder et al 2004; Bouman & Tuong 2001; Cabangon et al 2004; Tabbal et al 1992). Currently, other technologies to save water that are being studied involve a more radical change in production technique, eg the cultivation of rice on raised beds under soil saturation culture (SSC). This method involves growing rice on raised beds where water is maintained in 0.3-m-wide furrows at about 0.1 m below the bed surface (Borrell et al 1997, Ockerby & Fukai 2001), thus providing a saturated soil condition beneath the beds similar to that in AWD irrigation. It is hypothesised that water applied only in the furrows between beds can reduce water input and increase

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water productivity of rice without any decrease in yield. The objective of this study was to compare the effect of bed configuration and water management on rice grain yield, water input and water productivity (kg of rice produced per unit volume of water input).

Materials and methods

Experimental sites

The experiments were conducted at the International Rice Research Institute (IRRI) experiment station (14°11´N, 121°25´E), Los Banos, Laguna, Philippines. The experimental field was surrounded by rice fields in a relatively flat topography. The 25 cm topsoil layer has a clay texture, and the soil is characterised under the USDA textural classification as an Aquandic Epiaqualf. Other soil characteristics are shown in Table 1.

Experimental design and cultural practices

The experiments in the 2002 dry and wet seasons were conducted in a randomised complete block design (RCBD) in four replications with plot sizes of about 200 m^2.

In the 2002 dry season (DS) there were six treatments consisting of combinations of three water regimes and three land surface configurations. One water regime was well-watered (WW); for the other regimes the irrigation application timing depended on when the threshold soil water potentials of –10 kPa (W-10) and –20 kPa (W-20) at 15 cm soil depth were reached, at which time water application began. The land surface (or bed) configurations consisted of conventional puddled flat fields (B0), and beds of 65 cm centre-to-centre spacing (B65) and 130 cm spacing (B130) with furrows 35 cm wide. Thus, the bed width was 30 cm in B65 and 95 cm in B130. The bed heights were about 20–25 cm from the furrow bottom. Irrigation water is applied in flats (B0) until the water depth reaches 5 cm above the soil surface, and in beds (B65 and B130) until it reaches 1–2 cm below the bed surface. There were five treatments used in 2002 DS: (1) W-10 B0, (2) W-10 B65, (3) W-10 B130, (4) W-20 B65 and (5) W-20 B130. A control treatment (6) was added consisting of a well-watered conventional puddled flat (WW B0) located in a large field (of area = 1000 m^2) adjacent to the experimental area. In WW B0 irrigation commenced when the water depth in the field reached 1 cm and stopped when it was 5 cm above the soil surface. The treatments W-10 and W-20 are referred to as stressed treatments since the soil is unsaturated. In the stressed treatments, depending on the threshold soil water potentials, the depth of water in the furrows before the irrigation application varied from 0 to 10 cm.

In the 2002 wet season (WS) the water regimes were irrigated (IR) and rainfed (RF), while the bed configurations were the same as in the dry season. In beds under IR treatment the fields were irrigated when the water depth in the furrows was 10 cm below the bed surface and until the water depth reached 1–2 cm below the bed surface. The depth of water in the furrows varied from 0 to 10 cm before irrigation water was applied. In the RF treatment the fields were irrigated only when 50% of the plants showed a leaf score of 3 (using a scale of 1–5 to measure the level of stress experienced by the plants, in which 1 is unrolled and 5 is completely rolled under drought stress; O'Toole & Moya 1978). The six treatments used in 2002 WS were (1) IR B65, (2) IR B130, (3) RF B0, (4) RF B65, (5) RF B130 and (6) IR B0 (as the control treatment — similar to the WW B0 treatment in the dry season experiment).

During 2003 DS the use of varieties was included as another factor in the experiment. A split plot design was used where the main plots were water and bed treatment combinations while the subplots were varieties. Water treatments consisted of application of water when the soil matric potential at 15 cm depth reached 0 kPa (W0) or soil saturation, –10 kPa (W-10) and –50 kPa (W-50). In treatment W-50, the threshold value of –50 kPa was used as the threshold water potential only during the panicle initiation (PI) to heading period and from flowering to maturity. During the vegetative stage and heading to flowering

Table 1. Soil properties of the top soil layers in the experimental field at IRRI, Los Banos, Philippines

Soil properties	0–10 cm	10–25 cm
% clay	58	54
% silt	33	33
% sand	10	13
pH (1:1 H_2O)	6.9	7.0
Organic carbon (%)	1.6	1.0
CEC (cmol kg^{-1})	42	

Figure 1. Photos of (a) bed forming of dry-tilled soil using a bed shaper during the dry season and (b) bed forming in wet puddled soil in the wet season. Plant arrangement in (c) 95-cm-wide beds, B130 and (d) 30-cm-wide beds, B65. Widths of furrows are 35 cm. IRRI, Los Banos, Philippines.

periods, –20 kPa was used as the threshold water potential. Only B0 and B130 were used during the season. The six treatment combinations used in 2003 DS were: (1) W0 B0, (2) W-10 B0, (3) W-10 B130, (4) W-50 B0, (5) W-50 B130 and (6) WW B0 (as in the 2002 DS). The subplots consisted of two varieties: IR64 (modern lowland rice) and PSB-RC9 (an improved upland variety which has better drought resistance than lowland rice varieties). The treatments W-10, W-20 and W-50 are referred to as stressed treatments since the soil is unsaturated.

All main plots were surrounded by consolidated bunds and lined with plastic sheets installed to a depth of 0.3 m to minimise seepage among plots.

All plots during the dry season were cultivated dry with a roto-tiller to a depth of 20 cm. Beds of 30 cm width (B65) and 95 cm width (B130) with furrows about 35 cm wide and 20 cm deep were formed using a bed shaper attached to a 4-wheel tractor under dry soil conditions. There were 7 beds in B130 plots and 15 beds in B65 plots of 20 m length within each plot. Plots assigned as bed treatments remained dry while the flat fields were soaked 2 weeks before transplanting for puddling under wet soil conditions. One day before transplanting, the beds were flooded up to 10 mm, ponding water above the bed surface to facilitate transplanting. In the wet season all plots were puddled 2 weeks before transplanting because frequent rains prohibited land preparation under dry soil conditions. Beds were formed using a bed shaper under wet soil conditions (Figures 1a, 1b).

In all treatments standing water was maintained at 10–20 mm during the first 10 days after transplanting to facilitate seedling recovery. Afterwards, the ponded water layer in WW was kept between 10 and 50 mm before terminal drainage at 10 days before the harvest. In the other water treatments, water application was withheld depending on the soil water potential (Figures 1c, 1d).

The recommended fertiliser application rates for N, P and K were used. The rate of nitrogen application was 150 kg ha^{-1} during the dry season and 70 kg ha^{-1} during the wet season. Phosphorus was applied at a rate of 60 kg ha^{-1}, and potassium at 70 kg ha^{-1} during the dry season, while in the wet season 20 kg ha^{-1} P and 20 kg ha^{-1} K was applied. Zinc was applied at 5 kg ha^{-1} in both seasons. P, K and Zn were applied as basal dressings and incorporated in individual plots 1 day before transplanting. The cultivar used was IR64 in all seasons except in 2003 DS, when both IR64 and PSB-RC9 were grown in subplots.

Seedlings were grown in a seedling nursery for approximately 20–21 days. Transplanting was carried out by placing 2–3 plants per hill at a spacing of 20 cm × 20 cm in flats. In beds the row spacing was set at 15 cm, resulting in 7 rows in B130 (95 cm bed width + 35 cm furrow width) and 3 rows in B65 (30 cm bed width + 35 cm furrow width). The hill spacing along the rows was 21 cm in B130 and 18 cm in B65 to maintain a similar plant population (25 hills m^{-2}) among the bed treatments, and no plants were grown in the furrows (Figures 1c, 1d).

Water and climatic data measurements

The perched watertable depth was measured daily using 70 cm-long × 7.5 cm-diameter PVC pipes. The bottom 22 cm of the pipe was perforated with 1-cm-diameter holes at 2-cm intervals. A hole was dug using a soil auger, into which the pipe was installed to a depth of 50 cm below the soil surface in each plot. This allowed measurement of both above-ground and below-ground water levels. If the water level dropped below the ground or bed surface during the drying periods, it was recorded as 'negative field water depth'. In the beds the perched watertable depth was measured both in the furrow and in the middle of the beds to determine the variation in water level across the bed. Soil water potentials were measured using tensiometers installed at 15 cm depth in stressed treatments to determine the timing of irrigation in those plots. In B130 beds tensiometers were installed in the middle of the bed and near the edge of the bed at row 2. Groundwater tubes were 5 cm in diameter and perforated below a depth of 0.5 m, and were installed on the bunds to a depth of 1 m below the soil surface at 14 selected locations within the experimental field.

Each plot was irrigated separately. The volume of irrigation water applied in each plot was measured by a flow meter. The depth of irrigation water applied (I, measured in mm) over the plot surface was then computed from the volume of water applied and the area of the plot.

Daily rainfall, maximum and minimum temperatures, sunshine hours and Class A pan evaporation rates were recorded from a meteorological station located about 800 m from the experimental site.

Agronomic measurement and water productivity

At physiological maturity rice plants from the designated 16 (in B0), 18 (in B65) and 21 (in B130) hills were cut to ground level for yield component analysis (this was not done during the wet season experiment). At full harvestable maturity plants from an 8-m^2 (B0) and 8.2-m^2 (beds) area were taken for yield measurements. The harvest area for beds included the area occupied by the furrows. Total water productivity (WP) was calculated from grain yield (kg) divided by the volume (m^3) of total water input (irrigation + rainfall) during the crop season.

Data analysis

Data were analysed with standard analysis of variance (ANOVA) techniques for RCBD and split plot designs. The least significant difference (LSD) test, with the level of significance set at 5%, was used to compare significant differences between treatment means. The well-watered treatments WW B0 (dry season) and IR B0 (wet season) were not included in the statistical analysis because they were not part of the main experimental blocks, but served as control (reference) treatments (see 'Experimental design and cultural practices' above).

Results

Climatic conditions

The cumulative monthly rainfall, evaporation and solar radiation readings, and monthly average maximum and minimum temperatures, from transplanting to harvest in the three seasons studied are shown in Table 2. The dry seasons were characterised by low rainfall and high evaporation and solar radiation, compared with the wet season. There was no difference in seasonal mean temperatures among the three seasons. However, the dry seasons had low temperatures at the start, gradually increasing towards harvest. The wet season generally had constant temperatures during the rice-growing period. Solar radiation also increased with time during the dry seasons and decreased during the wet season. The daily evaporation rate was about 6 mm d^{-1} in the dry season and 4 mm d^{-1} in the wet season.

Agro-hydrological regimes

The watertable depth during the crop growth period ranged from –30 cm (at transplanting) to –70 cm in 2002 DS, and from –20 cm to –60 cm in 2003 DS. The watertable fluctuated according to the number of days with irrigation application, and was generally shallower in 2003 DS than in 2002 DS. The watertable depth in 2002 WS ranged from –10 to –40 cm due to frequent and heavy rains during the season (Table 2).

The mean subsurface water depths across the bed and in the furrows in B130 are compared in Figure 2a. Water depths were similar in the furrows and the middle of the beds, indicating that water was

Table 2. Monthly rainfall, evaporation, sunshine hours and mean maximum and minimum temperatures from transplanting to harvest (2002 and 2003 dry seasons) and from seeding to harvest (2003 wet season) at IRRI, Los Banos, Philippines.

Month	Rainfall (mm)	Evaporation (mm)	Radiation (MJ m^{-2} d^{-1})	Tmax (^{o}C)	Tmin (^{o}C)
2002 dry season (crop duration = 90 days)					
Feb (from 14th)	1	79	18.9	28.7	22.5
Mar	17	166	19.8	29.8	22.7
Apr	8	206	23.3	32.3	23.8
May (until 14th)	8	109	24.8	33.3	24.9
Total (mean)	**34**	**560**	**(21.6)**	**(31.0)**	**(23.4)**
2002 wet season (crop duration = 99 days)					
Aug (from 8th)	192	98	17.7	31.1	24.5
Sep	158	122	17.6	31.2	24.0
Oct	195	130	18.9	31.4	24.6
Nov (until 14th)	127	43	13.9	29.7	24.4
Total (mean)	**672**	**393**	**(17.5)**	**(31.0)**	**(24.4)**
2003 dry season (crop duration = 96 days)					
Jan (from 29th)	0	15	15.5	27.3	22.1
Feb	4	150	20.1	29.4	22.0
Mar	13	185	21.3	30.5	22.9
Apr	20	209	24.2	33.0	24.3
May (until 5th)	0	40	26.2	33.4	25.4
Total (mean)	**36**	**600**	**(21.9)**	**(31.0)**	**(23.2)**

able to infiltrate horizontally from the furrow towards the centre of the bed. This could be attributed to the loose soil structure due to tillage under dry soil conditions. Similar trends were observed in the narrower bed B65. There were also no clear differences observed in perched watertable depth between the B65 and B130 treatments (Figure 2a). Water depths among water treatments in 2002 DS are compared in Figure 2b, where a clear difference in water regimes between the WW and stressed treatments is shown. While ponded water depth was maintained in WW treatments, the stressed treatments had water depths below the bed surface, sometimes falling below the bottom of the furrow. In 2003 DS similar trends were also observed (Figure 2c).

In 2002 WS the water depth in the middle of the bed was generally similar to that in the furrows (Figure 3a). Irrigated flat (IR B0) treatments had higher water depths compared to other treatments (Figure 3b), and irrigated beds and rainfed flat and beds had generally similar field water depths. Irrigated beds had higher water depths than rainfed treatments only near the end of the season. In both water treatments the water depths between bed sizes were similar. Compared with the dry season, water stress in the wet season experiment was less due to frequent rainfall.

The water potentials measured at 15 cm depth in different treatments are shown in Figures 4a (2002 DS) and 4b (2003 DS). There were clear differences in water potential in the different water treatments. There was no difference in soil water potential between the middle and near the edge of beds in the B130 plots (data not shown). As with the perched watertable depth measurements, this indicated that there was a uniform water regime across the bed.

Grain yield

Rice yields ranged from 4.0 to 5.8 t ha^{-1} in dry seasons and from 3.0 to 3.7 t ha^{-1} in the wet season (Figure 5(a–c)). Higher grain yields in the dry seasons were attributed to higher solar radiation (Table 2). The lower yield in 2002 DS compared with 2003 DS was due to stem borer damage (12–16% damage in all treatments) in the 2002 DS experiment, which resulted in a 15–20% reduction in yield compared with similar treatments in 2003 DS. The higher yield in 2003 DS may also be partly explained by higher solar radiation and longer crop growth duration in 2003 DS than in 2002 DS (Table 2).

In 2002 DS increasing water stress reduced grain yield (Figure 5a). In flats decreasing water potential from saturation (flooded soil in WW B0) to –10 kPa (in W-10 B0) slightly decreased the grain yield, but increasing water stress (from –10 to –20 kPa) did not reduce grain yield. Despite different soil matric potentials between the two water treatments, the higher degree of water stress in –20 kPa treatments

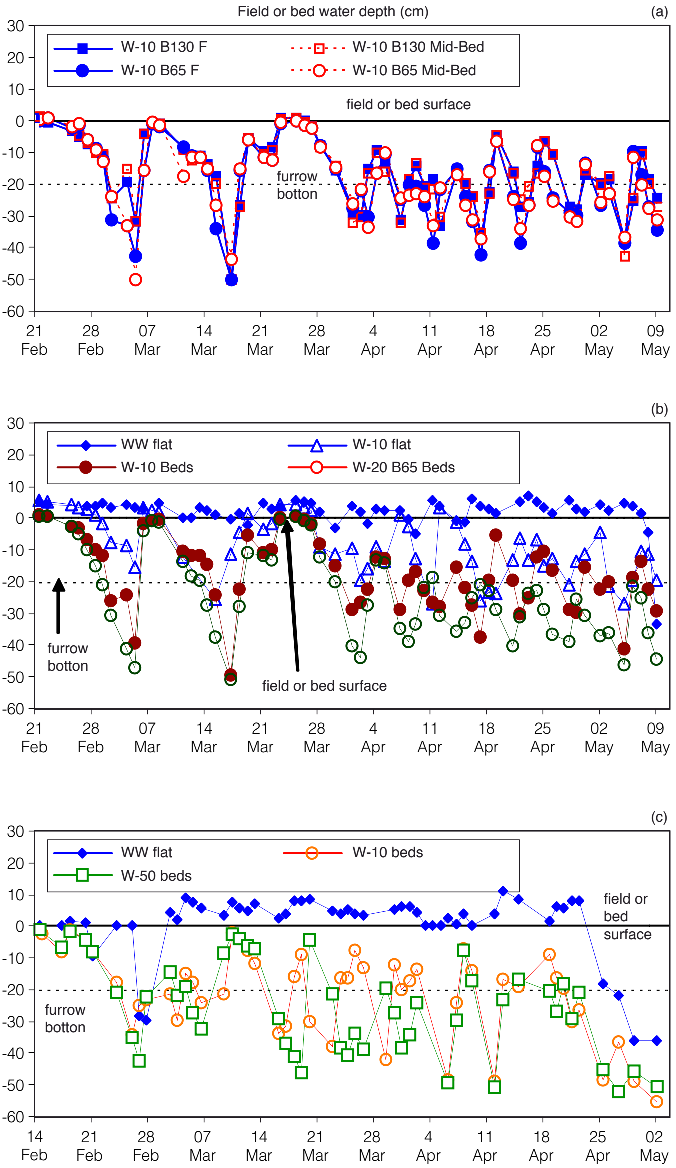

Figure 2. Mean of field or bed water depths (a) across 65 cm and 130 cm beds in 2002 DS and (b) among water regime and bed treatments in 2002 DS and (c) 2003 DS. IRRI, Los Banos, Philippines. (WW = well-watered; W-10, W-20, W-50 = irrigation at –10 kPa, –20 kPa and –50 kPa; B65 and B130 are beds with centre-to-centre spacing of 65 cm and 130 cm; F = furrow; Mid-bed = middle of bed)

was not enough to cause a reduction in yield. Due to shallow perched watertable depths (Figure 2b), the plants were probably able to extract moisture by capillary rise. There was no significant difference in grain yield between bed sizes (Figure 5a). This can be attributed to the similar water regimes (Figure 2a) and soil water potentials (Figure 4a) between the narrow and the wider beds, and a similar water regime across the bed regardless of bed width (Figure 2a). The difference in yield between WW-flat and beds may be attributed to the different water regimes (Figure 2a). Higher yield in the WW-

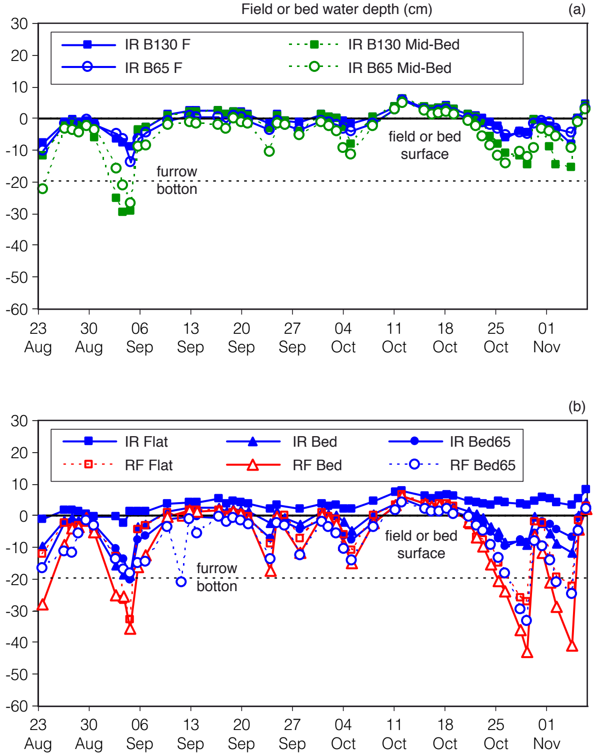

Figure 3. Mean of field or bed water depths (a) across 65 cm and 130 cm beds and (b) among water regime and bed treatments in 2002 WS. IRRI, Los Banos, Philippines. (IR = irrigated ; RF = rainfed; B65 and B130 = beds with centre-to-centre spacing of 65 cm and 130 cm; F = furrow; Mid-bed = middle of bed).

flat may also be explained by the particular variety used, ie a typical lowland variety suited to flooded and puddled soil conditions.

In 2002 WS the IR B0 treatment had higher grain yield compared with other treatments under irrigated conditions (Figure 5b) but the differences were not significant. Under rainfed conditions there were no significant differences among treatments. Rice grown on beds during the wet season performed similarly to rice grown in flats or beds under irrigated conditions, showing that rice can be grown on beds under rainfed conditions with minimal supplementary irrigation during the wet season.

In both varieties the WW B0 (control treatment) had a higher yield than other water treatments. Among water-stressed treatments there were no significant differences in yield. Under the same water treatment there were no significant differences in yield between beds and flats. There was no treatment × variety interaction on grain yield and no significant yield difference between the two varieties. The water stress was probably not high enough to reflect the upland variety's drought resistance.

In the two dry season experiments, grain yields in W-20 and W-50 were lower compared to the WW treatment. Mean water levels in these treatments were more than 20 cm below the bed or soil surface (Figures 2b, 2c), and water potential measurements at 15 cm depth were below –10 kPa (Figure 4). Belder et al (2004) and Lu et al (2002) reported that rice plants in conventional puddled systems did not suffer from water stress and grain yield was not affected if the soil water potential was not allowed to fall below –10 kPa. Our findings also confirmed the conclusions from a review by Bouman and Tuong (2001) that rice yields under unsaturated soil conditions were less than under flooded conditions. Tuong and Bouman (2002) indicated that the yield difference is determined by the level of stress the rice plant is exposed to during the drying cycles. Low yields in stressed treatments may also be due to differences in nutrient status compared with flooded conditions. The alternate wetting and drying of the soil could have led to gaseous losses of N and immobilisation of other nutrients (Wade et al 1998). Phosphorus availability may also be limited because the mobility

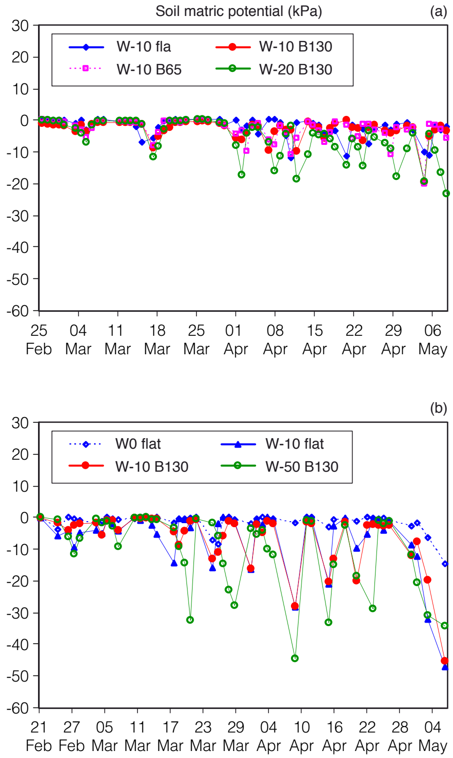

Figure 4. Mean soil water potentials among water regime and bed treatments in (a) 2002 DS and (b) 2003 DS. IRRI, Los Banos, Philippines. (WW = well-watered; W-10, W-20, W-50 = irrigation at –10 kPa, –20 kPa and –50 kPa; B65 and B130 = beds with centre-to-centre spacing of 65 cm and 130 cm).

of P decreases as soil dries (Cheng et al 2003; Kirk et al; Wade et al 1998).

Under the same water treatment, yields in beds were slightly lower than in the flats. The lower yields in beds can be attributed to differences in growth of the plants across the bed. We observed that the plants in the middle of the bed were shorter and had less tillers compared with plants near the edge of the bed (data not shown). The plant density in the middle of the beds was 37 hills m^{-2} in B65 and 32 hills m^{-2} in B130, compared with 25 hills m^{-2} in flats. This could have caused competition among the plants (Tuong et al 2000) in each bed. Low yields in beds may also be due to differences in nutrient status compared with flooded flats; or to the loss of area (15% in B130 and 30% in B65) which was occupied by the furrows.

The two varieties performed similarly and there was no treatment × variety interaction on grain yield. There was, however, an indication that the upland variety is more tolerant of water stress than the lowland variety. When stressed treatments were compared with the WW (control) treatment, the decrease in yield of the upland variety was only 8–15%, compared with a reduction of 12–24% in the lowland variety. The moisture potentials applied in the experiment (–10 to –50 kPa) may not have been high enough to clearly express the lowland variety's drought tolerance.

Water input and water productivity

The water input from rainfall and irrigation is shown in Figure 6. Wet seasons had very low irrigation water inputs due to frequent and high amounts of rainfall and low evaporation and radiation, compared with the dry season (Table 2). During the dry season rainfall was only about 35 mm in both years; thus, most of the total water input came from irrigation. Lower water input in 2003 DS compared with 2002 DS may be due to the shallower watertable in 2003 DS.

In 2002 DS irrigation water input in WW B0 was higher compared with other treatments. More than 200 mm of water was saved under W-10 B0 treatment and as much as 500 mm under bed treatments, compared with the WW B0 treatment. This amounts to about 30–40% savings in irrigation water input. There was no significant difference in total water input among bed treatments regardless of water regime (Figure 6a). In 2002 WS irrigation water input was highest by a significant margin in IR B0 (96 mm) compared with other treatments (average of 28 mm). There were no significant differences in water input among other water treatments (Figure 6b) due to the high amount of rainfall.

There was no significant difference in 2003 DS in water inputs between varieties (data not shown). Irrigation water input was higher in WW B0 compared with other treatments (Figure 6c). Stressed treatments reduced irrigation water input by about 15–25% in flats and 20% in beds compared with the WW treatment. The reduction in water input in W-50 was low compared with the highest stress level (–20 kPa) in 2002 DS (Figure 6a). The low differences in irrigation water input between W-50 treatments and other treatments may be due to the formation of cracks in W-50, which increased water losses in both beds and flats. The crack depths may be less in beds since these were tilled under dry soil conditions without puddling, but this did not result in significant differences in water input in beds compared to flats with the same water treatment.

Water productivity in terms of total water input ranged from 0.45 to 0.70 kg m^{-3} (Figure 7). In the 2002 DS experiment WP in bed treatments gave significantly higher results compared with the WW-flat treatment (Figure 7a). However, there was no significant difference in WP between the flats under

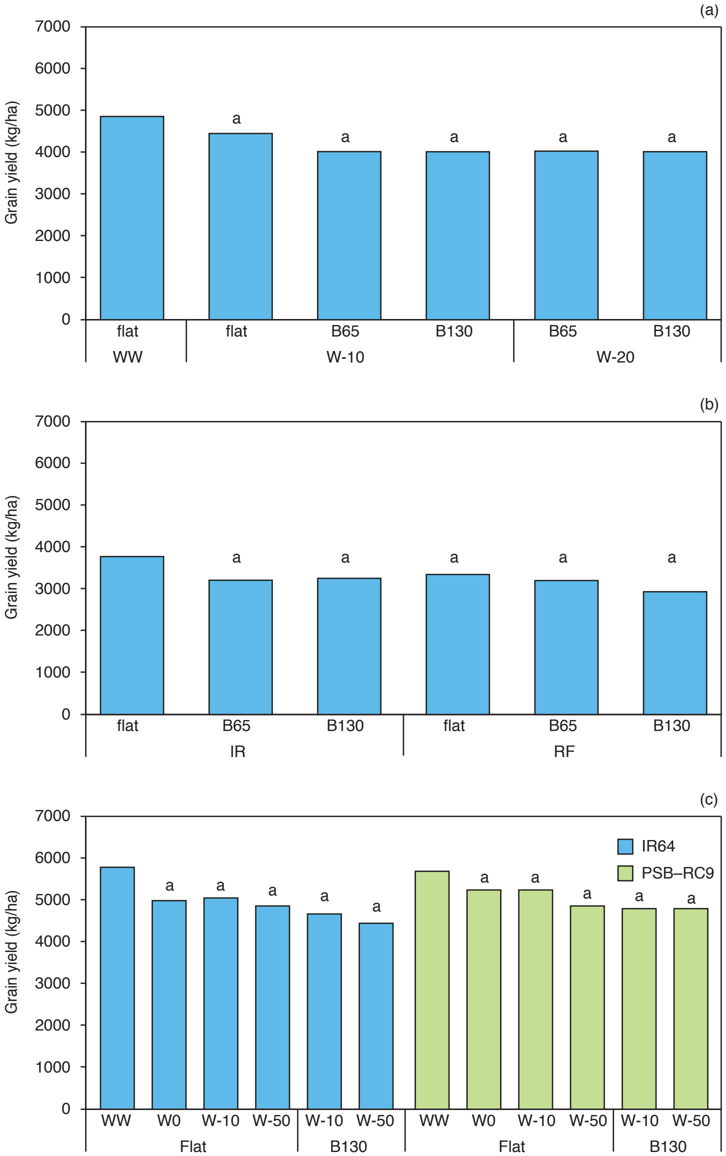

Figure 5. Mean grain yield of rice among water regime and bed treatments in (a) 2002 DS (b) 2002 WS and (c) 2003 DS. IRRI, Los Banos, Philippines. WW = well-watered; W-10, W-20, W-50 = irrigation at –10 kPa, –20 kPa and –50 kPa; IR = irrigated; RF = rainfed; B65 and B130 are beds with centre-to-centre spacing of 65 cm and 130 cm. Bars (in Figures 5a and 5b; and under the same variety in 5c) with the same letter are not significantly different at 5% level by LSD (WW treatment was not included in the statistical analysis).

W-10 treatment compared with bed treatments. In 2002 WS there were no significant differences in WP between flats and beds (Figure 7b). Similar WP among treatments may be attributed to relatively similar grain yields and water inputs among the treatments. In 2003 DS the lowest WP was obtained in the WW treatment. Beds under low water stress (W-10 B130) had higher WP compared with other treatments but the differences were not significant at the 5% level. Beds under W-50 treatment had low WP due to low yields and relatively high water input due to water losses through cracks. Compared with

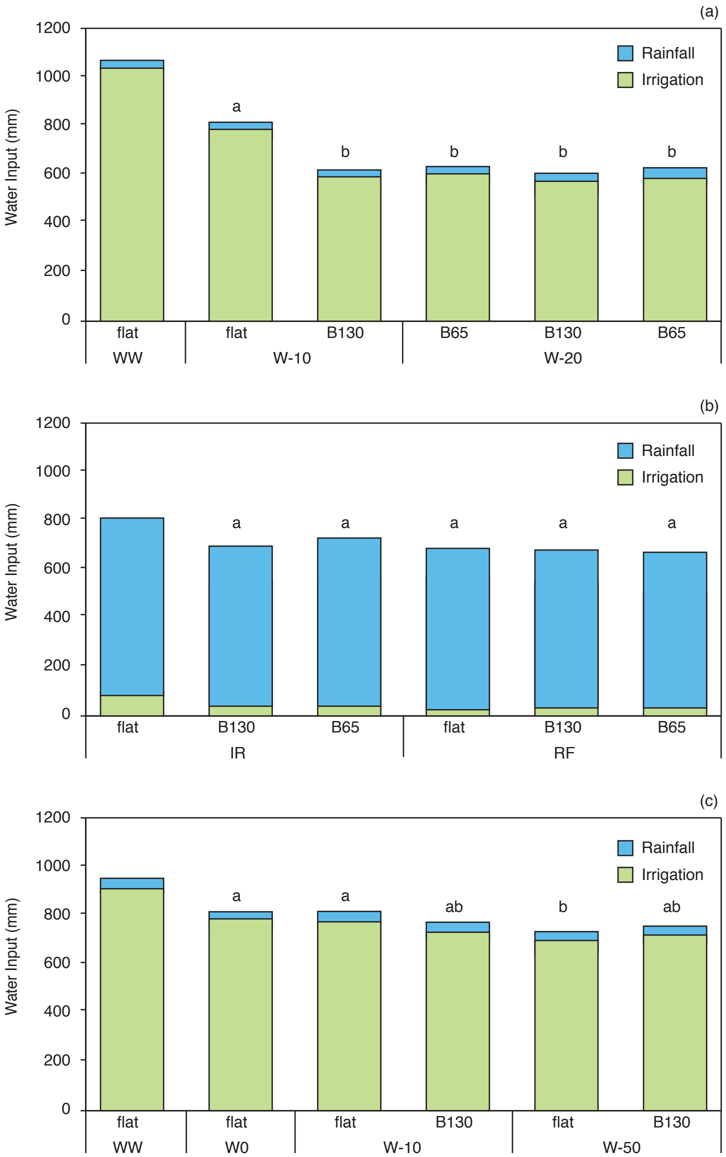

Figure 6. Mean water inputs from irrigation and rainfall among water regime and bed treatments in (a) 2002 DS (b) 2002 WS and (c) 2003 DS. IRRI, Los Banos, Philippines. WW = well-watered; W-10, W-20, W-50 = irrigation at –10 kPa, –20 kPa and –50 kPa; IR = irrigated; RF = rainfed; B65 and B130 are beds with centre-to-centre spacing of 65 cm and 130 cm. Bars with the same letter are not significantly different at 5% level by LSD (WW treatment was not included in the statistical analysis).

other studies (Bouman & Tuong 2001), the WP of this study was in the middle of the range according to the moderate yields and water inputs obtained in the experiments. The higher WP in beds offers an opportunity for water savings in rice cropping systems.

Issues and concerns in raised bed systems

Beds that were formed at the start of the plot preparation were about 20 cm high. However, irrigation during the dry season and rainfall during the wet season eroded both the bed surface and the sides of the

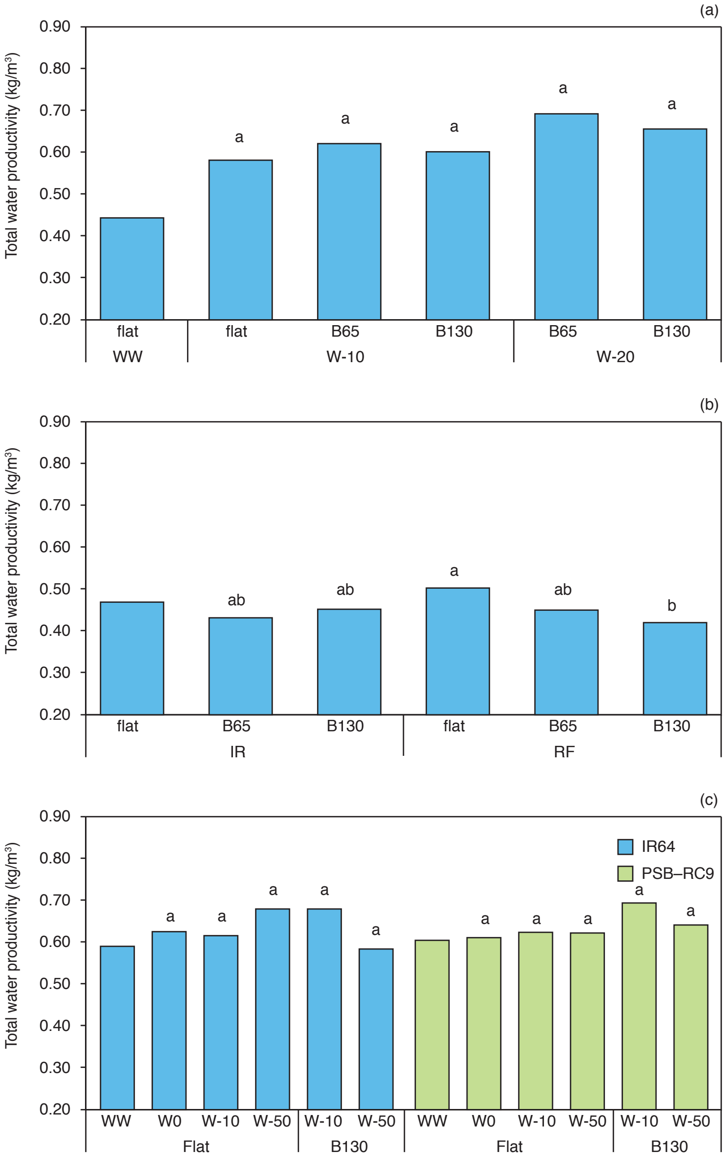

Figure 7. Mean water productivity in terms of total water input among water regime and bed treatments in (a) 2002 DS (b) 2002 WS and (c) 2003 DS. IRRI, Los Banos, Philippines. (WW = well-watered; W-10, W-20, W-50 = irrigation at –10 kPa, –20 kPa and –50 kPa; IR = irrigated; RF = rainfed; B65 and B130 are beds with centre-to-centre spacing of 65 and 130 cm. Bars (in Figures 7a and 7b; and under the same variety in 7c) with the same letter are not significantly different at 5% level by LSD (WW treatment was not included in the statistical analysis).

beds, and deposited the soil in the furrows. At the end of the season we observed that the height of the beds had been reduced to about 10–15 cm. This problem of soil erosion may be rectified by planting rice on the edges of the bed, and by direct seeding rice on beds with profuse root systems. In terms of crop establishment, transplanting of rice on raised beds is a disadvantage because measurements of the time required for transplanting in beds showed higher man-days than in flats. Thus, mechanical transplanting or other crop establishment methods such as direct seeding are important options to consider.

Good bed levelling is also an important criterion in bed systems because uneven levels will lead to non-uniform plant growth along the bed. Uniform bed levels across the field are also important to facilitate uniform water application among beds. Thus, a good land levelling procedure prior to bed forming must be undertaken.

Weeds also posed a problem in the raised bed system since the beds are often under aerobic conditions, which promotes weed growth, especially grasses. Using micro-plots we studied weed growth in the bed treatments. We tested four methods of control: pre-planting glyphosate (PPG); PPG and thiobencarb (TBC) after transplanting; PPG+TBC and hand weeding at mid-tillering stage; and no weed control (NW). Applying only PPG reduced weed weights at mid-tillering stage by only 20% compared with NW (from 40 g m^{-2} to 32 g m^{-2}). However, results showed good control of weeds under the combination of PPG+TBC, with weed weights reduced by 80% (from 40 g m^{-2} to 8 g m^{-2}). An additional hand weeding did not further reduce the weed population at the mid-tillering stage.

Discussions and conclusions

Water was able to infiltrate the beds horizontally from the furrows. However, during the drying cycle of rice in beds, the soil water potential attained values of –20 kPa to –50 kPa (measured at 15 cm soil depth), and the beds in our experiment were irrigated only when these water potentials had been reached. At that time, the soil moisture potential within the rootzone reached low values which gave resistance to extraction of water. Grain yield decreased in both tested varieties with increasing stress levels.

Our dry season experiments were characterised by the existence of a perched watertable within the rooted depth of the soil profile, and the maintenance of low soil moisture potentials in the root zone (at 15 cm depth) during the drying cycles of the stressed treatments. Thus, our bed treatments were not always under 'soil saturation culture' (SSC) conditions. Lower grain yields in bed treatments can also be attributed to loss of productive area (15% in B130 and 30% in B65). Higher yields could have been obtained if the area occupied by the furrows had been planted, as in the experiments of Borrell et al (1997). Few reports in the literature show similar yields in raised beds compared with continuously flooded rice. Results of experiments by Borell et al (1997) showed lower yields in beds under SSC compared with permanent flooding. However, the differences were significant only in one of the two seasons studied. Conventional paddy rice culture gave slightly higher yields than rice on raised beds, as reported by Ockerby and Fukai (2001). Under aerobic soil conditions, rice yield is generally decreased compared with continuously flooded conditions when soil water potentials drop below –30 to –50 kPa (Belder et al 2005; Bouman et al 2005; Tuong & Bouman 2002).

Despite lower rice yields in beds compared with flats, higher water productivity in bed treatments offers an option in irrigated rice farming systems where rice is grown in sequence with other upland crops. Rice can be grown in the wet season and non-rice crops in the dry season or vice versa. Under raised bed systems the furrows can promote good soil aeration for the non-rice crop by facilitating drainage.

Beds reduced irrigation and total water input by as much as 200–500 mm, which amounts to a 20–45% reduction in total water input compared with well-watered treatments. In Asia lowland rice is grown on more than 30% of the irrigated land and accounts for 50% of irrigation water used (Barker et al 1999). These savings could have a significant impact on the total amount of water saved when extrapolated to the whole rice ecosystem.

Acknowledgments

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Raised bed planting system for irrigated spring wheat in the Hexi Corridor

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Abstract

The Hexi Corridor is a moderate altitude (1000–2300 m), low rainfall, irrigated region in Gansu province of northwestern China. It is representative of irrigation areas in western China and thus is an important window to regional development. Water scarcity is the major issue facing the irrigated cropping system, causing many environmental problems and resulting in a poor output to input benefit ratio. To resolve this issue it is necessary to establish new cropping systems with increased water use efficiency, thereby reducing groundwater degradation and negative environmental impacts. The raised bed cropping system is one advance which may help achieve this goal.

Preliminary research on raised beds, including factors such as planting density, fertiliser application rate, bed width, water allocations per irrigation, number of allocations and suitable varieties, suggest that a 25–30% saving in water is possible without yield loss for spring wheat. The yield on raised beds increased by 34–46% over that on flats under irrigation amounts of 2100–2850 m^3/ha, but when the irrigation amount exceeded 3600 m^3/ha the yield difference was not significant. For equal yields beds saved 750 m^3/ha of water compared to flats. Because the differences in yield are not statistically significant among 60-cm, 75-cm and 90-cm beds, the 75-cm bed should be selected as the most suitable dimension for bed planting systems in the Hexi Corridor. Results showed that grains per spike and weight per 1000 seeds for edge rows in beds increased by 14.1 seeds and 0.8 g, respectively, over those in the middle rows.

Refinement of the raised bed planting system appears to be a promising way to resolve the key issues and maintain food production in northwestern China. However, to establish a system of permanent raised beds in the Hexi Corridor, further research is needed. New varieties with bigger spikes, more kernels, higher weight per 1000 seeds, larger leaf area, more tillers and higher lodging resistance should be selected for bed planting. New cropping systems and methods of residue management should be researched, and suitable small farm machinery should be developed for zero-till and relay planting methods, and residue and weed management.

Introduction

The Hexi Corridor is located in western Gansu province between latitudes 36°30´–41°31´N and longitudes 104°43´–92°21´E, adjacent to Xinjiang province in the west, Qinghai province in the south and Inner Mongolia province in the north. It is traversed by the Old Silk Road and is a typical irrigated area in northwestern China. At 1000–2300 m above sea level, it has a cold and arid climate (40–200 mm annual rainfall, 1900–3000 mm evaporation) with dry air and abundant sunshine. The average annual temperature is 5–10°C, with a mean maximum of 45.1°C and a mean minimum of –33°C. The mean temperature in March, when wheat is planted (on 20 March), is –1 to –4°C. The Hexi Corridor has a population of 5.25 million people and approximately 535,400 ha of irrigated cropping, producing not only wheat (mostly spring planted) and maize grain, but also vegetables, high-quality malting barley and flowers. It is also the most important location for producing hybrid maize seed in China. The areas of grain crops, industrial crops and vegetables account for 56.9%, 17.0%, 9.9% of the total crop area respectively. Production is 2.23 million t of wheat and maize, 0.28 million t of malting barley, 0.13 million t of oilseed and 69,000 t of seed cotton. Thus the Hexi Corridor is an irrigated oasis of vital regional economic importance and is representative of other such agricultural areas in western China.

Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico
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Lately, shortage of water and low output have become the main limiting factors for agricultural production in the Hexi Corridor. The highest priorities in finding a solution are to maintain and enhance yields while reducing irrigation water consumption and decreasing groundwater degradation and negative environmental impacts. A new cropping system must be developed that includes greater efficiency in water and fertiliser use, increased yields, lower mechanical inputs, and decreased impacts on regional ground water. The raised bed planting system, which incorporates developments in crop growing methods, water consumption, tillage, the soil structure, movement of soil water, fertiliser management etc, may be one such system. The bed planting system needs to be studied as a promising option to improve cropping and water use efficiency (WUE) in the Hexi Corridor and in similar irrigated areas of western China.

Issues facing the irrigated cropping system in the Hexi Corridor

Water scarcity is the major issue

In the Hexi Corridor there are three rivers, the Heihe River, Shiyanghe River and Shulehe River. In the past, reliable irrigation water from the Qilian Mountains snow melt to the south of Hexi gave rise to and sustained this relatively rich agricultural area of north-western China. In more recent times, especially from the 1980s onwards, reduced snow melt (the snowline in the Qilian Mountains has risen by 30 m during the last 45 years) and rainfall and low river flows have led to significant water restrictions. The annual river water resource (from the Shiyanghe, Heihe and Shulehe rivers) is 7.48 billion m^3 and the groundwater resource is 0.51 billion m^3 (Shen 2003). The utilisation rate of the total water resource is 103.9%, but its net utilisation rate after accounting for transport losses is only 55.3% (Chen & Qu 1992). Compared to the measured run-off in the 1950s, river flow has decreased by 1.5 billion m^3. Especially critical is the Shiyanghe River, where the run-off was 594 million m^3 in the 1950s but was reduced to 230 million m^3 in the 1980s and 150 million m^3 in the 1990s. In 2000 it was only 110 million m^3 (Li et al 1994).

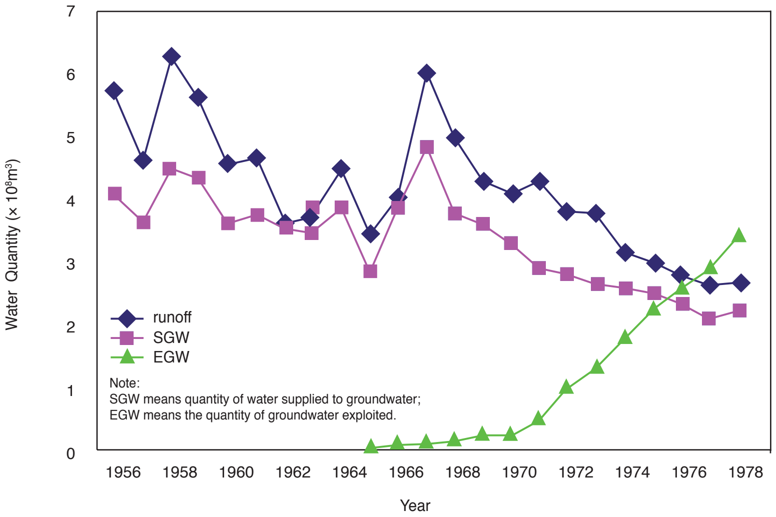
Another issue is the mismatch between the distribution of the water resource and the requirements of the wheat and maize crops. From April to June the supply of irrigated water is 22–27% of the total amount, but the crops need 50–60% of their water requirement at that time. Competition for water is becoming much sharper between industry and agriculture, upstream and downstream users, and within the agricultural departments, although agriculture still uses 92.6% of the water and industry only 5.6% (Li & Ma 1993).

Environmental problems related to water shortage

The shortage of water has caused environmental problems, especially in the downstream areas, and the eco-environmental balance is becoming more threatened. Watertable rise, salinisation, land desertification, wind erosion and groundwater degradation are all increasing. In recent years there has not been enough surface water to irrigate crops so farmers have pumped groundwater. The increased use of groundwater in turn has caused its level to drop by 0.5–1.0 m per year (Figure 1), resulting in the death of trees and grassland, and consequent desertification, in large downstream areas previously fed by groundwater. Measurements have revealed that the total dissolved solids concentration has increased by 0.20–0.35 mg/L per year for shallow groundwater and 0.24 mg/L for deep groundwater (Lin 2003). The frequency and intensity of dust storms has increased year by year as a result of both the desertification and frequent tillage. The period in which the soil is uncovered is 265–275 days for single cropping of spring wheat, 210–220 days for single cropping of maize and 195–205 days for intercropping of wheat and maize. Research on the diameter of the dust particles (0.005–0.063 mm) has shown that most comes from farm fields rather than from the desert. Nevertheless, in downstream areas, desert sands are moving into the oasis at the rate of 3–4 m per year. So the shortage of water resources, in combination with uncontrolled and excessive development of surface water upstream and groundwater downstream, has led to a vicious circle of environmental degradation.

Higher inputs but lower benefits

For current cropping systems, inputs (seeds, fertiliser, labour and irrigation water) have increased but outputs have not, leading to decreases in factor productivity and farmers' incomes. For example, in the wheat cropping system the planting rate is 6–6.75 million seeds/ha (600–675/m^2) and the fertiliser application rates are 180–225 kg/ha N and 150–180 kg/ha P_2O_5. The irrigation amount is 1200–1800 m^3/ha for winter storage irrigation and 2750–3000 m^3/ha for irrigation from sowing to harvesting (total is around 400–450 mm). Yet the average yield remains around 6–7.5 t/ha (Ma et al 2004). Analysis shows that both input energy and output energy have increased, but the energy ratio of output to input has decreased, over the last 50 years (Table 1).



Note:
SGW means quantity of water supplied to groundwater;
EGW means the quantity of groundwater exploited.

Figure 1. The changes of water resource in Minqin County located in downstream area of Shiyanghe River from 1956 to 1978.

Small farms and low levels of mechanisation are also constraints

In the Hexi Corridor farmers own about 1 ha of land each, and their mechanisation level is quite low. Generally, farmers do not buy tractors and other machinery because of the small farm size, but rely on contractors for tillage and planting operations. Existing tractors are less than 20 hp and many are single axle tractors. Although farmers and officials aspire to larger machinery, and the central government provides subsidies for 50 hp tractors, plainly they are not suitable for small farm plots. This has become a constraint on the adoption of new techniques and increased benefits.

Preliminary work on the raised bed planting system

Preliminary work on the raised bed farming system in the Hexi Corridor has confirmed that this will probably be a method by which water use efficiency and land management can be improved. Research results on bed planting in the Hexi Corridor have indicated that a 25–30% saving in water without yield loss for spring wheat, a 30% saving in water with 12% increase in yield for malting barley, and a 30–35% saving in water without yield loss for maize, are possible. These results justify further research on the bed planting system in northwestern China.

Effect on yield of raised bed planting for spring wheat

One experiment (2002–03) looked at planting method × seeding rate, in which wheat on beds comprised 4 rows per bed 15 cm apart (with a bed spacing of 75 cm centre-to-centre) while wheat on the flat was spaced at the traditional 20 cm between rows. Results (Table 2) showed that the yield of bed planted spring wheat increased with higher seeding rate, from 4.5 to 6 million seeds/ha, while the highest yield

Table 1. Input–output benefit analysis of total energy (in 10^{10} J/ha) for wheat cropping systems in the Hexi Corridor.

Period	Total input	Inorganic energy*	Organic energy**	Total output	Grains energy	Residue energy	Output/ input
1949–60	20.78	1.42	19.36	48.66	21.25	27.41	2.34
1961–70	33.87	11.21	22.66	73.20	32.01	41.19	2.16
1971–80	65.31	42.72	22.59	141.50	62.06	79.44	2.17
1981–90	81.43	53.09	28.34	203.66	88.89	114.77	2.50
1991–2000	110.31	72.13	38.18	218.64	92.93	125.70	1.98

Note:
* Inorganic energy input includes fuel, machinery, farm tools, insecticide and pesticide, fertiliser, electricity for farm etc;
** Organic energy input includes manure, labour, animal power, seeds etc.

Table 2. Yield and its components of raised bed and flat planted spring wheat with different seeding rates (2002–03).

Seeding rate (10^6seeds/ha)		Grains per spike	Grain weight per spike (g)	1000-grain weight (g)	Yield (kg/ha)
4.5	Bed	39.1	2.0	51.4	6460
	Flat	37.7	1.9	50.5	7837
5.25	Bed	41.1	2.2	53.9	7365
	Flat	35.1	1.8	52.1	7590
6.0	Bed	41.5	2.2	52.5	7912
	Flat	37.9	1.8	47.2	7440

Note:
The bed spacing was 75 cm centre-to-centre and 4 rows were planted per bed 15 cm apart; on the flat, rows were spaced at the traditional 20 cm apart.

of flat planted wheat was in the treatment with the lowest seeding rate; importantly, highest yields were the same for beds and flat. Statistical analysis showed that the differences in yield between planting methods as well as between seeding rates were significant at the level of 0.05, and the interaction of seeding rate × planting method was statistically significant at the 0.001 level. As a result, a rate of 6 million seeds/ha ($600/m^2$) is recommended for bed planting. Analysis of the yield components showed that grains per ear and 1000-grain weights in bed planting were always greater than those in flat planting.

Mulching crops with plastic film has been shown to decrease the evaporation of soil water and increase soil temperature, leading to a wheat germination date 7–9 days earlier than that without plastic film. An experiment in 2000 (Table 3) showed that the yield in BPF (bed planting with plastic film mulching) was markedly greater than in FPF (flat planting with plastic film mulching) and FPN (flat planting without plastic film mulching). The yield in BPF was 8.1% higher than in FPF and 32.7% higher than in FPN; again, wheat in beds performed as well as or better than wheat on the flat. The results also showed that the spikelets/spike, grains/spike and 1000-grains weight of BPF were increased by 2.7 spikelets, 10.9 grains and 1.5 g over FPF, respectively; and by 2.9 spikelets, 11.9 grains, and 2.4 g over FPN, respectively. Spikes/m^2 were not counted.

The effect of edge rows is obvious in bed planting, as shown by results of an experiment in 2003 on a bed width of 75 cm (centre-to-centre) with 4 rows 15 cm apart planted on it; this means that the 'gap', ie the distance from the last (edge) row on one bed to the first (edge) row of the next bed, was 30 cm. The ear length, number of grains per spike and weight of grains per spike all increased in the edge rows compared with the middle rows. The average increases were 0.21 cm for ear length, 4.1 for number of grains per spike, 1.91 g for weight of grains per spike and 104.3 for spikes per m^2.

The results in another experiment, in 2000, with the same bed dimensions showed that the yield of the two edge rows was 1.05 kg/m^2 (allowing only 15 cm for the row width), the grains per spike were 38 seeds, and the 1000-seeds weight was 46.0 g. The yield for the two middle rows was 0.65 kg/m^2 (again allowing 15 cm per row), the grains per spike were 23.9 seeds, and the 1000-seeds weight was 45.2 g. Thus, the grains per spike and 1000-seeds weight for edge rows increased by 14.1 seeds and 0.8 g, respectively, over those in the middle rows. The effect of edge rows is therefore very important to overall yield in beds. These results show the extent to which the edge row can compensate for the 'gap' in the planting layout, such that for modest gaps there is no per hectare yield loss. This is largely because the edge rows

Table 3. Yield effects of bed and flat planting for spring wheat with and without plastic film mulching.

Treatment*	Spikelets per spike	Grains per spike	1000-seeds weight (g)	Yield (kg/ha)
BPF	15.3	42.2	43.6	8845
FPF	12.6	31.3	42.1	8180
FPN	12.4	30.3	41.2	6665

* BPF = bed planting with plastic film mulching; FPF = flat planting with plastic film mulching; FPN = flat planting without plastic film mulching.

Table 4. Yield and WUE of bed and flat planted spring wheat with different irrigation regimes.

Irrigation (m^3/ha)	Yield (kg/ha)		Water consumption (mm)*		WUE (kg/mm/ha)	
	Bed	Flat	Bed	Flat	Bed	Flat
2100	5169	3543	258	239	20.1	14.8
2850	6363	4753	324	334	19.6	14.2
3600	6327	6102	395	410	16.0	14.9
4350	6372	6556	452	502	14.1	13.1

* Water consumption exceeded irrigation because it included the pre-sowing winter storage irrigation..

receive extra solar radiation which they use in additional photosynthesis.

Water-saving effects of bed planting system

An experiment in 2003–04 looked at irrigation amounts in bed planting, varying the amount of water per irrigation for a fixed irrigation schedule of three post-sowing irrigations. The results (Table 4) showed that on raised beds the yield, water consumption, and WUE changed with different irrigation amounts. The irrigation amounts in Table 4 included only the quantity of irrigation from sowing to harvesting and not the quantity of winter storage irrigation, which was included in the water consumption. The yield was highest, but the WUE lowest, with the greatest irrigation total, namely 4350 m^3/ha. although the yield differences between the irrigation amounts of 4350, 3600 and 2850 m^3/ha were not remarkable, the yield fell substantially with an irrigation amount of 2100 m^3/ha. WUE is higher with less irrigation. Measurements on the 7th day after irrigation revealed that the soil water content in the bed was 0.24–3.15% lower than in the furrow (Table 5), and this difference declined with increasing irrigation quantity.

Under irrigation amounts of 2100 m^3/ha and 2850 m^3/ha, the yield on raised beds increased by 46% and 34%, respectively, compared to that on the flat, but when the irrigation amount exceeded 3600 m^3/ha the yield difference was not significant. The differences in water consumption between beds and flat with different irrigations were not remarkable, and therefore the differences in WUE were similar to those in yield. The results (Table 4) also revealed that the differences in yield are not significant between 2100 m^3/ha on beds and 2850 m^3/ha on the flat, or 2850 m^3/ha on beds and 3600 m^3/ha on the flat, or 3600 m^3/ha on beds and 4350 m^3/ha on the flat. Thus, irrigation water of 750 m^3/ha can be saved with no yield loss by using raised beds.

Suitable bed width for spring wheat

In 2003 an experiment compared different bed widths and rows per bed, with a 15 cm spacing between rows. The results (Table 6) revealed that the yield of the 75-cm bed was highest, but the differences in yield between the 60-cm, 75-cm and 90-cm beds were not statistically significant. To establish permanent raised bed cropping systems using existing tractor widths, the 75-cm bed should be selected as the most suitable dimension for bed width in the Hexi Corridor.

Selection of spring wheat varieties for bed planting

Out of 32 spring wheat varieties, 4 have been selected by comparing the yield potential on beds

Table 5. Soil water content* of 0–120 cm of bed planted spring wheat under different irrigation regimes.

Irrigation (m^3/ha)		0–10 cm	10–20 cm	20–30 cm	30–40 cm	40–60 cm	60–80 cm	80–100 cm	100–120 cm	Average
2100	Bed	8.06	9.08	12.36	13.80	12.78	14.58	13.64	14.05	12.29
	Furrow	14.87	15.68	18.94	15.54	17.02	16.32	14.45	13.98	15.80
2850	Bed	13.03	13.66	12.24	16.44	14.33	14.59	14.15	14.03	14.05
	Furrow	17.24	17.70	17.66	18.53	16.64	14.89	14.44	14.18	16.41
3600	Bed	15.82	15.84	16.16	15.91	14.47	15.80	14.13	13.98	15.19
	Furrow	16.46	17.91	17.87	19.38	18.87	18.26	16.40	14.43	17.45
4250	Bed	18.22	18.33	17.22	17.91	19.25	18.48	15.11	14.87	17.42
	Furrow	15.19	17.70	17.84	18.57	17.53	19.00	16.66	18.77	17.66

* determined on 7th day after irrigation, % gravimetric.

Table 6. Edge row effects of raised bed planting for spring wheat with different bed width.

Bed width	Determined rows	Grains per spike	Grain weight per spike (g)	1000-grain weight (g)	Yield (kg/ha)
60 cm, 3 rows	Edge rows	29.62	1.74	58.17	5524
	Middle rows	20.37	1.22		
75 cm, 4 rows	Edge rows	29.05	1.79	58.80	5752
	Middle rows	24.82	1.53		
90 cm, 5 rows	Edge rows	30.12	1.81	58.56	5502
	Middle rows	21.12	1.36		

(Table 7). These varieties gave more grains per spike and higher weight per 1000-grains. This appears to be advantageous for increasing yield on beds because wheat planted in cold areas has few tillers and less seedlings per ha than on the flat. The spring wheat variety Ning 210 is the best among the four varieties.

Future research on bed planting in the Hexi Corridor

Bed planting technologies have been researched for many years in Mexico, Pakistan, India and Turkey. The technologies have been demonstrated and extended successfully, and the effect on water use efficiency has been reported to be positive. Although bed technologies could be introduced to the Hexi Corridor, as the preliminary results show, there are differences in the Hexi situation that need to be considered. These particular factors include the soil type, cold winter, reliance on many spring crops planted into cold soil, use of plastic mulch to save water, and relay planting of maize into wheat to gain time. Nevertheless, the potential benefits that raised beds offer, especially water saving, justify further research on the system. The following aspects of raised bed planting systems should be researched and perfected according to the specific situation in the Hexi Corridor.

New varieties

In northwestern China most demonstrated varieties, especially for spring wheat, have been developed for flat planting with very high seeding rates, such that their tiller rate is low. The seeding rate is 225 viable seeds/m^2 in northwestern Mexico compared with 600 viable seeds/m^2 in the Hexi Corridor, and field investigation has shown that tiller production reached 5–6 per plant in Mexico and only 1–1.5 per plant in the Hexi Corridor. Varieties with bigger spikes, more kernels, higher weight per 1000 seeds, larger leaf area, more tillers and higher resistance to lodging may perform better on beds in Hexi than current varieties, and need to be sought.

Irrigation technologies

CIMMYT scientists have conducted experiments on the best irrigation regime for bed planted crops, while much research on water-saving technologies has been conducted in the Hexi Corridor on flat systems. What is missing is the comparison of these technologies on beds. Research should focus on new irrigation regimes related to soil moisture, flow speed of irrigation water and water-saving irrigation techniques, and especially include testing where winter storage irrigation is withheld.

Residue management

The cold and arid climate in the Hexi Corridor exacerbates the issues of residue management because the lower temperature makes it difficult for residues to decompose. Mulching residues on the soil surface also reduces the soil temperature, which then rises more slowly in spring. Measurements at wheat planting (20 March) showed that the soil tem-

Table 7. Yield comparisons of 4 spring wheat varieties selected for raised bed planting.

Variety	Number of ears	Grains per spike	Grain weight of spike (g)	1000-grain weight (g)	Yield (kg/ha)
Ning210	16.74	31.60	1.78	51.51	5643
00J26	15.86	35.44	1.72	45.38	5112
Ning32	15.80	38.16	1.86	45.96	5235
00J4	20.70	40.46	2.04	47.20	5463

perature at 0 cm and 5 cm was lower by 4.5°C and 3.2°C, respectively, and the germination rate was lower by 15–20%, on a mulched crop compared to a treatment without residues (Ma & Lan 2003). Surface residues have other obvious advantages but the cooling disadvantage warrants further research; perhaps plastic mulching has a role to play in resolving this issue.

Permanent raised bed planting for different cropping systems

The Hexi Corridor is a high-yielding region with single cropping of spring wheat and of maize, but further yield gains are possible with intercropping and relay cropping (eg relay of maize into wheat), grain crops and industrial crops, and grain crops and green manures, under different rotation systems. Use of raised beds in this region is expected to be very different from the planting systems in warmer regions such as northwestern Mexico. While permanent beds may facilitate intercropping, the soils will initially be harder in permanent beds, which could create problems.

Machinery for small–scale farms

The machinery necessary for implementing conservation tillage and permanent raised bed systems needs to be adapted to the existing small low-powered tractors of the Hexi Corridor. Existing tractors are less than 20 hp and many are single axle tractors. Thus a significant opportunity exists to develop suitable small farm machinery for bed shaping, zero-till and relay planting, and residue and weed management on permanent raised bed systems.

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Raised bed planting for wheat in China

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Abstract

China is the most populous country in the world and the largest producer and consumer of food. In terms of planted area and output, wheat (*Triticum aestivum* L.) (including both winter wheat and spring wheat) is the most popular crop in northern China. Shortages of both water and arable farmland are becoming more and more serious as a result of the growth in population and increase in economic development. At the same time, China needs to produce even more agricultural products to satisfy the requirements of the growing population. Most cereal crops (such as maize, wheat and rice) are normally flat planted with flood irrigation. But overseas experience has shown that the use of raised beds with furrow irrigation not only saves water, but is also convenient for water management. Therefore, in order to increase water use efficiency, we started a research and demonstration program of raised bed planting for wheat, with support from CIMMYT, in 1998. Experimental results in northern China indicating reduced irrigation water use, higher yields and greater water use efficiency were most promising, and are reported here. Increased yield with wheat on raised beds may be due to less dynamic fluctuations in soil water, and reduced disease and lodging. We have been cooperating with an agricultural machinery factory to develop a bed-planter pulled by a small 4-wheel tractor, suitable for the very small scale of Chinese farms (0.3–0.5 ha per family). To date, raised bed planting for wheat has not only been extended widely in Shandong province, but has also been introduced to Henan, Hebei, Shanxi and Ningxia provinces, reaching a total of 40,000 ha. A program of permanent raised beds for wheat–maize double cropping is now being tested in farmers' fields.

Introduction

Current status of water resource and wheat production in China

China is the world's most populous nation. Although its water resource is about 2800 billion m^3, there is less than 500 m^3 per capita in northern China (Dai & Li 2000; Figure 1) and the shortage of water is becoming the most important limiting factor for Chinese development. Ancient Chinese people started to plant wheat 2500 years ago (770–220 BC). Now wheat is the second crop after rice in China, but it is still the most popular crop in northern China in terms of area and output. More than 23 million ha of wheat, much of which is irrigated, were planted in 2004, and it is estimated that the output will reach 90 million tons. Traditionally, where irrigated, almost all of the wheat was conventionally planted on the flat, and water management was by flood irrigation with low water use efficiency (Ren et al 2001). For example, 1 m^3 of water can produce 2.32 kg of grain in Israel, but only 0.8–1.0 kg of grain in China, on the average (Kang & Li 1997; Figure 2). The flat planting of wheat, maize and rice contrasts with

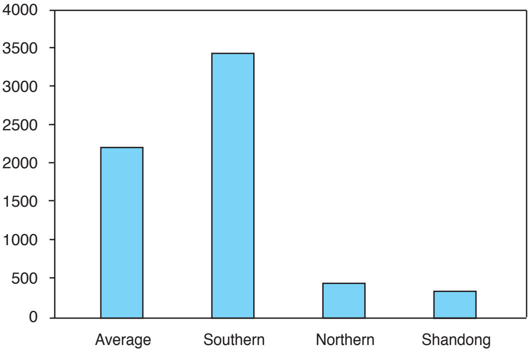

Figure 1. Current status of water resource in China.

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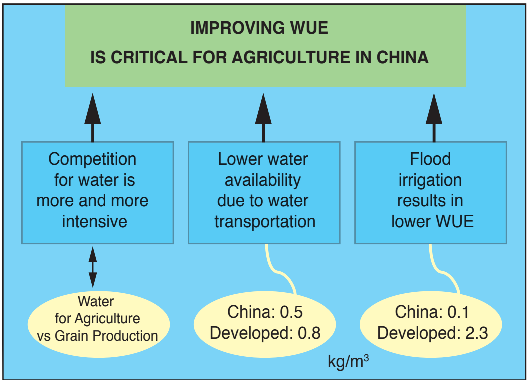

Figure 2. Current status of water use efficiency (WUE) in China and in developed countries.

methods used for most cash crops in China. Many crops, such as peanut, cotton, tobacco, sweet potato and other vegetables are planted on raised beds with furrow irrigation, a method which not only has the potential to save water but is also convenient for water management (Bouaziz & Chekli 1999; Sayre & Moreno Ramos 1997; Wang et al 1999). Given the importance of water-saving techniques for Chinese agriculture, investigation of raised bed cropping for field crops was therefore initiated in Shandong province several years ago.

Introduction and extension of raised bed planting for wheat

Raised bed planting for wheat with furrow irrigation was introduced in 1998 to Shandong province with the help of Dr Ken Sayre, CIMMYT (International Maize and Wheat Improvement Centre). There were eight locations (Changqing City, Qingzhou City, Zhucheng City, Gaomi City, Rushan City, Zouping county and Zoucheng City) for the demonstration of raised bed planting in 1998. We made use of very simple available equipment for planting because of the lack of suitable machinery (Figure 3). We held several field days in different locations before harvesting, and invited officers and agronomists from agricultural administration as well as farmers to visit the bed-planted fields. Most of them believed that the raised bed planting system was very successful since it not only saved water by 30–40%, but also improved output by 10%. In almost every year since 1998, we have sponsored demonstrations and field days in order to extend the adoption of raised bed planting and have achieved good results. During this time an experimental program was also begun.

Materials and methods

The first experiments were conducted at Jinan, Qingzhou and Zouping for four crop cycles (1998–2002). The soil was a light loam, with a 1.2% concentration of organic matter, 21 mg/kg of rapidly available phosphorus, 120 mg/kg of rapidly available potassium and 65 mg/kg of rapidly available nitrogen. The winter wheat varieties used for experiments, Jimai 19 and Yannong 19, are currently the two most widely planted commercial varieties. These varieties were planted using both flat planting with flood irrigation and raised bed planting with furrow irrigation. The amount of irrigation water applied to each treatment from a tube well was carefully monitored. The planting date varied between 4 and 10 October and a constant seedling density of 180 plants per m^2 was used. Fertiliser was applied at the rate of 140 kg/ha P and 36 kg/ha N at first node stage. In addition, to assess nitrogen use efficiency, there were two control treatments, one where no N

Figure 3. Left – The planter for raised bed planting; Right – Making bed, applying fertiliser and sowing wheat at same time.

was applied and one where 207 kg/ha total N was applied, half at planting as basal and the other half at first node stage. The design of the experiment each year was a randomised complete block with four replications.

The height of the bed was 13–15 cm from the furrow bottom to the bed top, and the width was 75 cm from furrow bottom to furrow bottom. Three rows of wheat were planted on the top of each bed with 15 cm spaces between each row. The control treatment for comparison was flat planted (conventional method), with a row spacing of 22 cm (the most popular practice used by farmers (Yu 1990)). Planting was carried out with a small bed planter. Irrigation and fertilisation was applied in the furrow for raised bed planting, and uniformly applied over the surface for flood-irrigated flat planting.

Research into water use efficiency (WUE) was conducted in the fields for both raised bed planting with furrow irrigation and flat planting with flood irrigation. There were three irrigation applications during the growth period, in winter (600 m^3/ha), at the jointing stage (750 m^3/ha) and at the filling stage (600 m^3/ha). WUE = wheat grain production per ha (kg/ha) / water transpiration quantity (kg) per m^3. The water transpiration quantity (mm) = precipitation quantity + irrigation quantity + decrease in soil water quantity from sowing to harvest (Hanks 1974).

Results

Improved water use efficiency

According to measurements across the four crop cycles, wheat planted on raised beds with furrow irrigation produced 1.96–1.99 kg of grain per m^3 of water, but only 1.34–1.41 kg of grain on flat planting in the underground well irrigation area, and 0.8–1.0 kg of grain on flat planting in the Yellow River flood irrigation area (Table 1, Figure 4). WUE, based on the amount of grain produced per m^3, increased by 40–90% on raised beds, largely because more water was used by flat planting with flood irrigation.

Figure 4. Irrigating through the furrow.

Figures 5 and 6, from one year of the Jinan experiment, indicate that the soil water of raised bed planting changes gradually, that is the ratio of gain and loss is balanced. The soil water of flat planting, however, changes more markedly and does not increase as much with increase in soil depth. Traditional flat planting requires better conditions for smoothing/levelling of the field, while raised bed planting has the benefit of better distributing the limited water in the soil and thus creating a more stable soil water environment for the growing root system. The change with time of the soil moisture content in different layers of the soil (Figures 7, 8) shows that the two planting methods display similar characteristics in the 0–20 cm layer, where the soil moisture content fluctuates greatly. But in the 20–40 cm layer, the extent of soil moisture changes for flat planting is greater than that for raised bed planting. The soil moisture at 20–40 cm at jointing stage for flat planting was only 10% or so, while that of raised bed planting was kept at 14%. We can conclude that an increase in water consumption led

Table 1. Comparison of yield and water use efficiency for raised bed versus flat irrigation/planting methods (Jinan, 1998–2002).

Variety	Planting method	Grain yield (kg/ha)	Rainfall (m^3/ha)	Irrigation water applied (m^3/ha)	Total water available (m^3/ha)	Water use efficiency (kg/m^3)
Jimai 19	Bed	6900	2043	1500	3543	1.96
	Flat	6415	2043	1800	3843	1.67
Yannong 19	Bed	7065	2043	1500	3543	1.99
	Flat	5799	2043	1800	3843	1.51
Mean	–	6544	–	–	–	1.78
LSD (P=0.05)	–	375	–	–	–	0.29

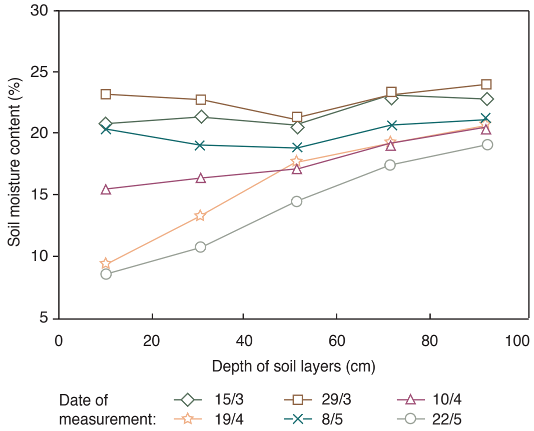

Figure 5. Vertical changes of soil moisture content at different stages of bed planting.

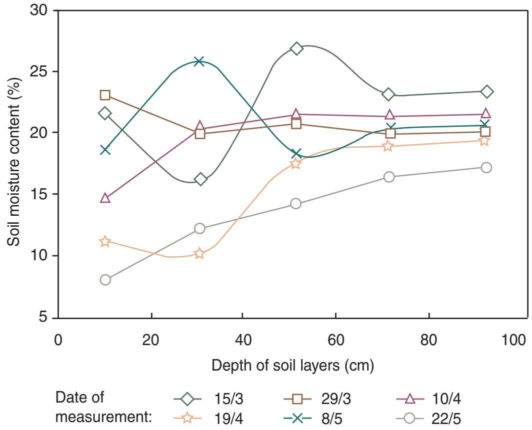

Figure 6. Vertical changes of soil moisture content at different stages of flat planting.

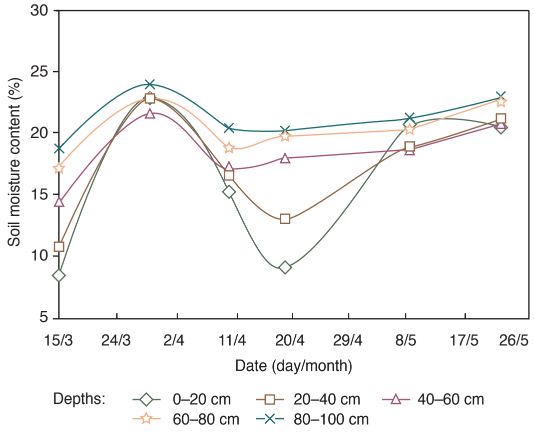

Figure 7. Dynamic change of soil moisture content in different layers of soil in bed planting.

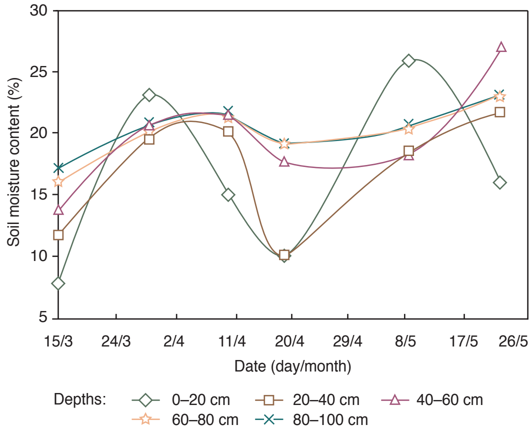

Figure 8. Dynamic change of soil moisture content in different layers of soil in flat planting.

to a decrease in soil moisture in the flat planting, and that the range in soil water content of traditional flat planting is greater than that of raised bed planting.

The experimental results at the other locations in Shandong also showed that raised bed planting not only increased production by 8.8–13.6% but also saved water by 32.7–37.1%, and WUE was obviously improved (Table 2).

Increase in nitrogen use efficiency

Chinese farmers have a habit of using more nitrogen but less phosphorus and potassium than developed nations. Therefore, the nitrogen use efficiency is relatively low, which not only increases production costs but also pollutes the environment (Elmi et al 2002; Jaynes et al 2001; Li & Lin 1999; Limon-Ortega et al 2000; Raun et al 2002; Stites & Kraft 2001; Xiao et al 2002). Under flat planting conditions with flood irrigation (Table 3), post-emergence nitrogen fertiliser is normally broadcast on the soil surface, which leads to a low nitrogen use efficiency (about 20%). With raised bed planting, nitrogen use efficiency can reach 23% by band applying nitrogen fertiliser (urea) into the furrows with machinery to deepen the fertiliser placement. Thus, nitrogen fertiliser uptake efficiency can be improved by 15%.

Decreased humidity within the crop canopy and increased lodging and disease resistance

The humidity within the crop canopy for raised bed planting is consistently lower than that for flat planting because raised bed planting is better ventilated (Table 4). This is beneficial for decreasing the incidence of some important diseases, such as sharp eye spot and powdery mildew (Table 5, Figure 9).

Planting on beds shortened the height of the wheat plant by 4.0–7.5 cm, with the length of the basal first and second nodes being shortened by 1.7–4.4 cm (Table 6). The field microclimate was improved with raised bed planting, giving the wheat a better growing environment. In beds the wheat basal internode grew thicker, the internode length was shorter, and the weight of dry matter produced per cm increased, thus noticeably increasing the lodging resistance (Table 5).

Table 2. Effects of raised bed versus flat irrigation/planting methods on irrigation water saving and yield of wheat at different locations (Jinan, 1998–2002).

Location	Year	Variety	Planting method	Area (m^2)	Water used (m^3/ha)	Water saved (%)	Grain yield (kg/ha)	Yield increase (%)
Qingzhou City	1999	Jimai 19	Bed	0.433	2042	37	7518	8.8
			Flat	0.12	3246		6912	
Qingzhou City	2002	Jimai 19	Bed	6.67	2283	32	9158	13.6
			Flat	6.67	3393		8064	
Zouping City	2002	Yannong 19	Bed	20	1837	37	8129	12.1
			Flat	20	2896		7254	

Table 3. Comparison of nitrogen use efficiency for the different irrigation/planting methods (Jinan, 1999–2002).

Variety	Treatment		Biomass (kg/ha)	Biomass N (%)	Biomass N (kg/ha)	N uptake efficiency (NUpE) (%)	NUpE increase (%)
	Planting method	N use (kg/ha)					
Jimai 19	Bed	207	16438	1.52	250	23.1	12.7
	Bed	0	14851	1.36	202	–	
	Flat	207	15156	1.44	218	20.5	–
	Flat	0	12283	1.43	176	–	
Yannong 19	Bed	207	16750	1.56	261	21.6	13.7
	Bed	0	15039	1.44	217	–	
	Flat	207	15621	1.42	222	19.0	
	Flat	0	13132	1.39	183	–	

Table 4. Canopy relative humidity (%) at different dates for the different irrigation/planting methods (Jinan, 1998–2002).

Variety	Planting method	Position	23 April	2 May	9 May	16 May	23 May
Jimai 19	Bed	Bed-top	65	71	76	79	84
		Furrow	59	62	65	73	73
		Average	62	67	71	76	79
	Flat	Average	71	79	84	85	93
Yannong 19	Bed	Bed-top	67	72	87	88	83
		Furrow	62	65	67	78	74
		Average	65	69	77	83	79
	Flat	Average	72	77	84	86	88
LSD (P=0.05)			3	4	4	3	3

Table 5. Effect of different irrigation/planting methods on plant height, sharp eye spot and powdery mildew incidence, and crop lodging (Jinan, 1998–2000).

Variety	Planting method	Plant height (cm)	Sharp eye spot (%)	Powdery mildew (%)	Lodging (%)
Jimai 19	Bed	73.0 c	7.9 c	7.7 d	0 d
	Flat	77.0 b	32.6 b	19.6 b	10 b
Yannong 19	Bed	76.0 bc	1.8 d	9.2 c	5 c
	Flat	83.5 a	51.2 a	22.8 a	60 a

Table 6. Dry matter accumulation of the first and second internodes of wheat as affected by irrigation/planting method (Qingzhou, 1998–2001).

Variety	Plant method	First internode						Second internode			
		Length (cm)	Water (%)	Dry matter (mg/cm)	Stem diam. (mm)	Wall thickness (mm)	Length (cm)	Water (%)	Dry matter (mg/cm)	Stem diam. (mm)	Wall thickness (mm)
Jimai 19	Bed	3.8d	62.2b	22.6a	3.63a	0.65a	8.9c	44.0c	18.9a	3.76a	0.49a
	Flat	5.6b	70.3a	18.4b	3.41a	0.46c	10.4b	55.9a	15.7b	3.58a	0.37b
Yannong 19	Bed	4.4c	58.6c	21.3a	3.30a	0.54b	9.8b	38.1d	18.1a	3.72a	0.47a
	Flat	6.9a	69.7a	17.4b	3.14b	0.39c	12.2a	50.2b	15.0b	3.55a	0.31b

Increased grain yield and improved grain quality

From the experiments over four crop cycles at different locations, it was observed that the grain yields of raised bed planting were at least 10% higher compared to those of flat planting (Table 7, also Tables 1 and 2). This was associated especially with significantly more grains per spike and larger grains. These yield and yield component increases could be explained by the improved microclimate within the crop canopy in raised bed planting, resulting in a reduction in disease and lodging.

Future trends: permanent beds

In terms of planting area, wheat and maize account for more than 70% of cropped farmland in northern China, and the double cropping rotation of maize–wheat is the most popular rotation system. Currently, maize is relay planted before harvesting wheat or planted directly after harvesting wheat, in both cases in flat seedbeds. There are several disadvantages associated with this common practice. First, because relay-planted maize is usually harvested in early September, there is a period of about 30 days between harvesting the maize and planting the next winter wheat crop in which climatic resources (sunlight and temperature), which are very suitable for grain filling of maize during this period, are wasted. Second, it is very difficult for maize to maintain density, which is an essential factor for achieving high yields in maize. Third, relay planting is inconvenient for mechanisation and decreases efficiency. Finally, waterlogging of maize seedlings often takes place when the maize is directly planted after harvesting wheat if the wet

Table 7. Canopy relative humidity (%) at different dates for the different irrigation/planting methods (Jinan, 1998–2002)

Variety	Planting method	Spikes per m	Grains per spike	Grain weight (mg)	Grain yield (kg/ha)	Yield increase (%)	Harvest index (%)
Jimai 19	Bed	453	43.1	38.7	6195	10.0	0.40
	Flat	448	39.8	36.0	5629		0.40
Yannong 19	Bed	633	36.1	36.3	6765	13.4	0.42
	Flat	616	32.2	34.1	5965		0.41
LSD (P=0.05)		28	2.0	1.8	312		0.15

Figure 9. Powdery mildew occurs more in flat planting (left) than in bed planting (right).

season begins early, reducing the growth of maize and decreasing its yield.

We found that using permanent raised beds was a good option to overcome the above disadvantages. After first planting wheat on raised beds, we planted maize by machine without tillage on the same beds between the wheat rows soon after harvesting the wheat. The furrows helped guide the planting operation. This procedure reduces the waterlogging risk, makes better use of natural resources, increases the grain yield of the maize and reduces the production costs. We have now done this experiment of using permanent raised beds based on the wheat–maize rotation system for 2 years. The maize can be planted on the same bed after harvesting wheat, but we cannot yet plant wheat on the same bed after harvesting maize without tillage because of the lack of appropriate machinery for planting amongst the strong maize stalks.

Adoption of raised beds for wheat in China

In order to extend adoption of the raised bed planting technique for wheat, we have made use of newspaper, television and broadcasting services to disseminate information. The Chinese Agricultural Ministry sponsored a very important meeting to promote raised bed planting at Jinan, the capital of Shandong province, in May 2004. More than 200 agronomists from different cities and counties, and from different provinces, attended this meeting, which further promoted the technology. To date, bed planting for wheat has not only extended widely in Shandong province (Figures 10, 11) but has also been introduced to Henan, Hebei, Shanxi and Ningxia provinces, and the area of raised bed planting for wheat now accounts for more than 40,000 ha. The Chinese Agricultural Ministry has accepted raised bed planting for wheat as a major technology for increasing wheat productivity and improving water use efficiency.

Figure 10. Left – Raised bed planting wheat at the beginning of grain filling; right – harvesting.

Figure 11. Location of raised bed planted wheat in Shandong province.

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Early work on permanent raised beds in tropical and subtropical Australia focusing on the development of a rice-based cropping system

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Abstract

In northern Australia permanent raised beds (PRB) were first used as a means by which soybeans could be grown in the field using saturated soil culture (SSC), a technique which originated from earlier work investigating genetic and physiological variation in zinc deficiency among soybean lines. This early work was not focused on developing PRB, but more on water management in soybean cropping systems. Subsequently, the concepts of PRB and SSC were extended from soybeans to rice in the Burdekin River Irrigation Area (BRIA) of North Queensland, initially with the aim of reducing water use. Collectively, the studies undertaken in the BRIA suggest that the development of a rice-based cropping system, in which rice and field crops are double cropped in rotation, is feasible and may provide additional synergistic and logistic benefits over those found in the traditional rice–fallow system. These benefits include improved water, nitrogen and phosphorus economies; energy savings; greater timeliness of operations; and reductions in soil compaction. Further, in practical terms, such a system is only feasible if based on PRB. It is suggested that it has substantial potential as a preferred system in high rainfall and/or irrigated areas in the tropics and thus would appear ideally suited for much of the rice-growing land in South East Asia.

Introduction

This review will be restricted to the early work that led to the development of permanent raised beds (PRB) as a cultural practice in tropical and subtropical cropping systems in Australia. Early studies on PRB in southern Australian cropping systems (eg wheat) will be covered elsewhere in this workshop. The research on PRB was primarily undertaken in Queensland over a 20-year period between 1971 and 1991, with some work also being conducted in Western Australia and Victoria. The key organisations involved were the University of Queensland, CSIRO, Queensland Department of Primary Industries, Western Australia's Department of Agriculture and Victoria's Department of Agriculture and Rural Affairs. Significantly, this early work was not focused on developing PRB, but more on water management in soybean cropping systems. Permanent raised beds were first used as a means by which soybeans could be grown in the field using saturated soil culture (SSC), a technique which originated from earlier work investigating genetic and physiological variation in zinc deficiency among soybean lines.

In this review a chronological approach is taken in discussing the original research that led to the development of PRB in tropical Australia; the realisation that PRB, once established, had real potential for the development of a cropping system based on a soybean–rice rotation; and the application of the concept to double-cropping systems using PRB as a means of controlling traffic and improving timeliness of operations. In addition, the extension of this work to rice-based cropping systems in South East Asia is reported, including how some specific factors important in crop production are influenced by PRB.

Initial glasshouse studies (1971–78)

Dr Don Byth and his team at the University of Queensland were the early innovators of raised bed technologies between 1971 and 1978, pioneering the

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irrigation strategies known formerly as ‘controlled watertable’ (CWT) and subsequently as ‘saturated soil culture’ (SSC).

Waterlogging of soybeans in southeastern Queensland, together with associated symptoms of zinc deficiency as first reported by Mungomery and Byth in 1976, provided the initial background for the subsequent development of PRB. Initially, genetic variation in zinc deficiency was observed in 1971 within breeding populations of soybeans that were waterlogged for several weeks following emergence (Mungomery & Byth 1976). Genetic and agronomic approaches were investigated to overcome the constraints of waterlogging.

The initial agronomic approach to these production constraints was adopted in a 1977 glasshouse study at the University of Queensland (Hunter et al 1980). A range of soybean lines was grown on raised beds in the glasshouse under controlled watertables maintained at 3 and 15 cm (CWT 3 and CWT 15) below the soil surface, and under conventional overhead irrigation (OHI), in an attempt to produce differential zinc deficiency. Zinc deficiency was not produced but at harvest (36 days after planting) results showed higher above-ground and nodule biomass with CWT, particularly CWT 3, compared with OHI. From this study Hunter et al (1980) suggested the potential for ‘paddy’ soybean culture — a radical concept at the time!

An innovative watering system for pot studies was developed by Hunter et al (1981) to further examine the effects of a controlled watertable on soybean growth under varying rates of applied zinc. In this system water transpired by the plants was continuously replenished by water from a reservoir (an upturned bottle in the centre of each pot), maintaining the controlled watertable. The CWT technique accentuated zinc response through stimulation of growth in plants supplied with zinc, not because of intensified zinc deficiency. Nodule production was also higher in plants grown under CWT compared with those regularly ‘watered to weight’. Dr Mal Hunter and his colleagues discovered some fascinating aspects of soybean growth under controlled watertables. Indeed, biomass production and nodulation of soybeans were greater under saturated conditions (following an acclimation phase) compared with standard irrigation practices.

The final experiment in these early studies at the University of Queensland was undertaken in 1978 by Nathanson, a visiting fellow to CSIRO with Dr Bob Lawn. It was during this study that the term saturated soil culture (SSC) was first coined. Nathanson, in conjunction with Dr Don Byth, decided to further investigate the positive response to CWT measured in the glasshouse by Hunter et al (1980, 1981). Nathanson et al (1984) grew two soybean lines of different maturity on raised beds in the University of Queensland glasshouse with CWT imposed at 3 and 15 cm below the soil surface. Increased yields under CWT, particularly in the case of the longer duration line, were due to higher growth rates sustained during an extended reproductive period. They concluded that the higher growth rates following an initial acclimation phase were due in part to greater photosynthetic potential resulting from improved plant water status under saturation. However, the physiological basis of the sustained root, shoot and nodule growth observed in CWT plants remained unclear.

Original field studies (1978–85)

Solving this puzzle was the lure for future researchers. In particular, a series of very detailed studies on the irrigation management of soybeans by Dr Alan Garside (1978–80) and Dr Robert Troedson (1981–83), both students of Lawn and Byth, investigated the main issues raised by Nathanson et al (1984). The initial two field experiments were conducted in the Ord Irrigation Area (OIA) of far northern Western Australia in 1978 and 1979 to study the effect of irrigation frequency on the growth, development and yield of soybeans (Garside et al 1992b,c). These experiments were conducted on Vertisols under furrow irrigation with the soybeans established on raised 1.5-m-wide beds with irrigation applied to the furrows between the beds. In the 1978 experiment each bed was 1.82 m wide (mid-furrow to mid-furrow) with 8 rows of soybeans 15 cm apart established on the bed top. In the 1979 experiment the bed width was 1.5 m (mid-furrow to mid-furrow) with 6 rows of soybeans 15 cm apart. Irrigation frequencies were based on Class A pan evaporation and involved irrigation after every 30, 60, 120 or 240 mm of cumulative pan evaporation. An additional treatment, SSC (water continually trickled down the furrows between beds), was included in the 1979 experiment as a follow-up to Nathanson’s 1978 experiment on SSC. Grain yield was enhanced under SSC and was highly correlated with water use in both experiments. Hence, no differences in water use efficiency were observed among irrigation treatments. As expected, plant water status was higher in the more frequently irrigated treatments.

Two further experiments were conducted in the OIA in 1980 to examine responses to SSC in more detail (Garside et al 1992d; Figure 1). In the first study the effects of SSC on 14 genotypes were compared with conventional irrigation after every 60 mm of pan evaporation in an early wet season sowing. On average, grain yield was 21% higher under SSC compared with conventional irrigation, with the advantage

Figure 1. Soybeans grown on raised beds under saturated soil culture in the Ord River Irrigation Area (Garside et al 1992d).

Figure 2. Soybeans exhibiting chlorosis during the acclimation period when grown on raised beds under saturated soil culture (Troedson et al 1989a, b).

ranging from 2% to 49% depending on genotype. In the second study the effects of SSC on growth and yield of three cultivars of different maturity were evaluated in a late wet season sowing. Irrigation method and cultivar interacted strongly. Compared with conventional irrigation, SSC was advantageous for the late maturing genotype, neutral for the intermediate maturing genotype, and disadvantageous for the early maturing genotype. Overall, these studies suggested that substantial yield increases are possible with SSC in this environment, the extent of the increases being dependent on genotype, crop duration, and timing of treatment application as it related to the duration of the acclimation period after SSC application.

The research by Dr Robert Troedsen, carried out in southeastern Queensland, sought to build on the work of Garside et al (1992b, c, d) in the OIA. Soybean was grown on raised beds in successive years (1981–82) at Lawes (Troedson et al 1989a,b), with irrigation applied either continuously (SSC) or after 60 mm of cumulative open-pan evaporation (conventional irrigation, CI). Shoot growth in SSC was greater than in CI during grain filling, although early shoot growth was less under SSC due to the acclimation period (Figure 2). Root and nodule growth, nitrogenase activity and leaf conductance were all greater in SSC. Grain yields were 24% and 52% higher in SSC in the 2 years, respectively. Troedson et al (1989a, b) concluded that the beneficial response to SSC was primarily due to enhanced leaf water status, enabling increased photosynthesis and, in turn, nitrogen fixation, rather than a direct positive effect of the wet-soil environment on the symbiosis. An additional study by Troedson et al (1991) found that *Phytophthora* root and stem rot is not a limitation to using SSC in soybean provided resistant cultivars are available.

At a similar time Dr Graeme Wright, who had been working in the OIA when the Garside studies were undertaken, carried out some SSC research with soybean in Victoria at the Irrigation Research Institute at Tatura. Wright et al (1988) compared the growth of two soybean cultivars grown on raised beds with continuous water applied in furrows (called 'wet soil culture' in this study, WSC) with conventional furrow irrigation applied at soil water deficits of 35 mm (frequently irrigated) and 70 mm. Overcoming the constraint of waterlogging was also an objective of this study. Interestingly, plants grown under WSC did not yield more than those grown under the frequently irrigated treatment. Severe lodging of one of the cultivars also occurred under WSC.

A summary of these research studies over a 21-year period is provided in Table 1.

The development of rice-based cropping systems (1986–92)

In the conclusion to their third paper on the SSC work in the OIA, Garside et al (1992d) said:

'Taken together, the studies support the contention (Lawn and Byth, 1989) that SSC provides a unique opportunity for expanding the adaptation of soybean. That opportunity is likely to be the greatest in the subtropics and tropics, where warm temperatures contribute to high evaporative demand, and enable soybean production to be contemplated year-round. It is likely to be especially relevant in rice-based agriculture, where present irrigation practice has some similarities with that used in the SSC treatments herein. Indeed, recent work in the Burdekin

Table 1. Key results from soybean studies undertaken between 1971 and 1992 with the aim of developing saturated soil culture (SSC) on permanent raised beds.

Experiments in chronological order	Key results from soybean studies
Mungomery & Byth (1976)	Genetic variation in zinc deficiency was observed among soybean lines that were severely waterlogged. This observation led to further studies on the response of soybeans to soil moisture conditions close to saturation.
Hunter et al (1980)	Plants grown with a controlled watertable (CWT) maintained at 15 cm below the soil surface accumulated 37% more dry matter and 35 times more nodule dry matter than did plants grown with overhead irrigation.
Hunter et al (1981)	A novel watering technique was developed to examine plants grown under CWT. Nodule production was greater in CWT-treated plants than in those regularly watered to weight.
Nathanson et al (1984)	In the first study to coin the term 'saturated soil culture' (SSC), soybeans grown under SSC initially exhibited N deficiency compared with plants grown under conventional irrigation (CI), although after acclimation SSC plants showed improved nodulation and subsequent growth rates.
Wright et al (1988)	Lodging was identified as a potential constraint on soybeans grown under SSC (called 'wet soil culture' in this study).
Garside et al (1992a)	In a comparison of CI and SSC strategies in soybeans, seed yields increased linearly with increasing irrigation frequency, with the highest yields being obtained under SSC.
Garside et al (1992b)	Efficiency of water use under SSC was comparable to that from furrow irrigation after cumulative open-pan evaporation losses of 30, 60, 120 and 240 mm.
Garside et al (1992c)	Averaged across 14 soybean genotypes, seed yields with SSC were increased by 0.74 t ha^{-1}, or 21% above the mean yield of 3.47 t ha^{-1} with CI (60 mm) treatment. Among genotypes, the advantage of SSC ranged from 2% to 49%.
Troedson et al (1989a)	Root and nodule growth, nitrogenase activity and leaf conductance to water vapour were all greater in soybeans grown under SSC compared with CI. Seed yields were 24% and 52% higher in SSC than in CI in the 2 years examined.
Troedson et al (1989b)	Hypothesised that the response of soybeans to SSC is primarily due to enhanced leaf water status, which enables increased photosynthesis and, in turn, nitrogen fixation, rather than a direct positive effect of the wet-soil environment.
Troedson et al (1991)	*Phytophthora* root and stem rot is not a limitation to the use of SSC in soybean provided resistant cultivars are available.

Irrigation Area in north Queensland (Borrell et al, 1991; Garside et al, 1992a) suggest that there may be advantages in exploiting SSC to grow both soybeans and rice in an integrated cropping system.'

Garside moved from the OIA to the Burdekin River Irrigation Area (BRIA) in 1985 and provided a strong link between the earlier studies investigating SSC in soybean and the subsequent pioneering work on SSC in rice.

Technologically, the step from growing soybeans under SSC to growing rice under SSC was a relatively small one. However, in terms of mindset, stepping from conventional paddy production to rice under SSC was more of a quantum leap, requiring a paradigm shift for growers. Rice growers in the BRIA were keen to reduce water and nitrogen fertiliser costs since they accounted for 40% and 25%, respectively, of the variable cost of growing a rice crop. In some ways it was a logical extension for Garside and rice agronomist Andrew Borrell from the Queensland Department of Primary Industries (QDPI) to investigate the growth of rice under SSC on permanent raised beds. In other ways the progression from soybean under SSC to rice under SSC was more of an intuitive leap than a logical progression, since the conventional wisdom was that high rice yields could only be produced under flooded (paddy) conditions. The topic became the subject

Table 2. Water use (mm), grain dry mass (g m^{-2}) and efficiency of water use for grain production (WUEg, g m^{-2} mm^{-1}) for two seasons and five methods of irrigation (Borrell et al 1997).

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	0.82
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 b
PF-3L	1228 c	456 b	0.37 a
PF-PI	1075 b	421 ab	0.39 a
SSC	833 a	402 ab	0.48 b
II	873 a	363 a	0.41 ab
Mean	1059	451	0.43 ab
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 ($P > 0.05$).

of Borrell's PhD (1989–92) through the University of Queensland (UQ), supervised jointly by Garside (QDPI) and Professor Shu Fukai (UQ).

Experiments were established to study different strategies for irrigating rice (Borrell et al 1991, 1997; Table 2). Comparisons were made between applications of permanent flooding at three different stages: sowing (PF-S), the 3-leaf stage (traditional, PF-3L), and prior to panicle initiation (PF-PI), with two unflooded methods: SSC and intermittent irrigation (II), at weekly intervals (Figure 3). SSC consisted of growing rice on raised beds of height 0.2 m and width 1.2 m, with water maintained in the furrows (0.3 m wide) some 0.1 m below the bed surface. The SSC treatment was sown into both beds (generally 7 rows) and furrows (generally 2 rows) in rows of width 0.178 m.

These studies challenged the existing paradigm, showing that it is not necessary to flood rice to obtain high grain yield. The expectation was for yield to increase with water supply, but there was no significant difference in yield or quality between SSC and

Figure 3. Rice grown on raised beds under saturated soil culture in the BRIA: immediately after sowing (left) and during the seedling stage (right) (Borrell et al 1997).

traditional flooded production, even though SSC used about 32% less water in both seasons. Therefore, the efficiency of water use for grain production was higher in SSC than in traditional flooded production. Borrell et al (1991, 1997) concluded that because of increasing water scarcity, there was an urgent need to develop irrigation methods encompassing both improved efficiency and lower water use. Based on these dual criteria, SSC was the optimal treatment in these experiments (Table 2). In addition, there were obvious other advantages of PRB emerging that could be used in the BRIA.

Broader-scale farming systems based on PRB

The development of the BRIA as an expanded irrigation area was to proceed without the new areas having the capability to grow sugarcane because of assignment restrictions and industry regulations. The charter given to the scientists employed to investigate other potential crops was to develop a system that would provide comparable economic returns to sugarcane. At that time this would only have been achievable with a double cropping system, so the primary focus was on developing a system that would allow rapid turnover from one season to the next. Permanent raised beds were to become the cornerstone of the system. They not only allowed a soybean–rice rotation under SSC, but also enabled a range of upland and traditional crops to be grown together in a controlled traffic system, thus facilitating a rapid turnaround time between crops.

Hence, the focus of studies by the QDPI team of scientists in the BRIA between 1986 and 1991 was based on double cropping of rice, maize and soybean on PRB in a rotational system (Garside et al 1992a). Studies within this system involved nitrogen dynamics (Borrell et al 1998a, b, 1999; Ockerby et al 1999a, b), water management (Borrell et al 1997), phosphorus dynamics (Dowling 1995) and the benefits of controlled traffic (Braunack & McPhee 1991; Braunack et al 1995; McPhee et al 1995a, b, c). All this research was conducted on a cracking clay soil at Millaroo Research Station. The double cropping system that was developed, based on PRB, had recognisable advantages of improved water, nitrogen and phosphorus economies, energy savings, greater timeliness of operations and reductions in soil compaction.

Specific effects on crop growth factors

Raised bed stability

The studies by McPhee et al (1995a, b, c) and Braunack et al (1995) found that PRB facilitated controlled traffic, improved timeliness of operations, saved energy, reduced soil compaction and minimised weed problems. The beds remained stable after establishment, requiring only a furrow cleaning operation between crops. These results suggested that there were no obvious limitations preventing the combination of SSC, permanent beds and traffic lanes (Garside et al 1992a), and that a short break between double crops was feasible.

Nitrogen

Initially, studies were undertaken between 1986 and 1988 in the BRIA to improve the efficiency of nitrogen (N) use for flooded rice production (Borrell et al 1998a, b, 1999). Subsequently, N dynamics associated with alternative irrigation strategies in rice were examined at the same location in 1989 and 1990 (Borrell 1993; Borrell et al 1993). The soil water status of these treatments ranged from anaerobic (250 mV) to largely aerobic (500 mV). Hence, the activity of microbial groups would have differed between treatments, resulting in considerable variation in N transformations between treatments (Borrell 1993).

Low apparent N recoveries under SSC suggests that denitrification was also relatively high in this treatment (Borrell 1993). The aerobic status of the beds (redox potentials above 400 mV) indicate that sufficient oxygen existed for the nitrification of ammonium to nitrate, promoting subsequent denitrification of nitrates when the water level was increased. Significantly, the practicalities of running these experiments meant that although SSC was maintained with PRB, the water depth fluctuated between 6 and 14 cm below the soil surface. This was probably the reason for considerable nitrification and subsequent N loss through denitrification. In previous SSC studies the watertable was maintained at a constant depth (Garside et al 1992b), and it is envisaged that commercial production of rice on PRB under SSC would also use a controlled watertable. Tissue N concentrations in rice produced on PRB under SSC indicated N deficiency during the grain filling period in the dry season, supporting N loss. In the wet season, however, the N concentration of organs in SSC plants was comparable with the control, possibly reflecting the deep placement of N fertiliser (urea) into the anaerobic zone in all treatments in the wet season. Hence N nutrition, more than likely, provided a yield limitation under SSC (Borrell et al 1993).

Phosphorus

Phosphorus (P) deficiency has been shown to cause poor growth and yield in crops grown after flooded rice (Brandon & Mikkelsen 1979; Willett 1979). Hence, P requirements for other field crops increase after flooded rice. A series of field and glasshouse studies (Dowling 1995) were carried out in conjunction with the irrigation studies of Borrell et al (1997) to determine the magnitude and direction of changes in P requirements for field crops after rice. Dowling (1995) found that these P requirements increased with the number of days under flood, with the traditional flood at the 3-leaf stage requiring 60% more P relative to unflooded soil. However, similar increases in P requirement were not found following rice grown under SSC on PRB, suggesting that an increase in P requirement for upland crops in this rice-based cropping system is unlikely. Subsequent field studies examined the effect of five methods of irrigating rice on the responses of soybeans and maize to P and zinc fertilisation. These studies found that differences in P fixation due to method of irrigation in the previous rice crop did not occur (Borrell 1993). The reasons for these results are unclear.

Extension of Australian technology to West Timor (1993–99)

A fortuitous meeting of two ‘like-minded’ scientists resulted in the extension of SSC rice technology from North Queensland to West Timor, Indonesia, between 1993 and 1999. Don Van Cooten, an Australian agriculturalist working in Indonesia, visited Borrell on his way back to Indonesia in 1991. After viewing Borrell’s experiments he quickly realised that SSC technology should provide similar benefits for rice production in the semi-arid tropical environment of West Timor. Subsequently, a series of experiments were undertaken in West Timor (Figure 4), commencing in 1993 (Borrell et al 1998c; Borrell & Van Cooten 2001, 2003; Van Cooten & Borrell 1999).

In turn, these studies laid a foundation for the current ACIAR project (Figure 5) on the island of Lombok, Indonesia (Improved Soil Management on Rainfed Vertisols in Nusa Tenggara) (Mahrup et al 2004; Mansur et al 2003). This project is managed jointly by the University of Mataram, Indonesia, and La Trobe University, Australia, with Van Cooten and Borrell as consultants. This collaboration highlights the capacity of knowledge to spread quickly from one region to another, particularly if clear benefits are realised by the adopters of the technology.

Conclusion

Permanent raised beds were the common factor linking research on SSC in the early 1970s involving high watertable soybean with more recent work in the 1990s on rice-based cropping systems in West Timor. Although not an original focus of the early soybean work, the practical application of SSC technology was only ever likely to be feasible with PRB. Subsequent intensive studies carried out in the BRIA have clearly demonstrated the practicalities of a rice-based cropping system based on PRB. Collectively, the complementary studies undertaken in the BRIA between 1986 and 1991 suggest that the development of a rice-based cropping system in which rice and field crops are double cropped in rotation is feasible, and may provide additional synergistic and logistic benefits over those found in the traditional rice–fallow system (Garside et al 1992a). Further, in practical terms, such a system is only feasible if based on PRB. It has substantial potential as a preferred system in high rainfall and/or irrigated areas in the tropics and thus would appear ideally suited for much of the rice-growing land in South East Asia.

Figure 4. Experiments on rice-based cropping systems near Kupang in West Timor, Indonesia (Borrell et al 1998c; Van Cooten & Borrell 1999).

Figure 5. Australian and Indonesian agricultural science students examine raised beds in the ACIAR project on the island of Lombok, Indonesia.

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Successful permanent raised beds in the irrigated farming systems of the Murrumbidgee and Murray valleys of New South Wales, Australia

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Abstract

The need to increase the water productivity of irrigated winter and summer crops in the irrigated areas of southern New South Wales (NSW), Australia, has seen the development and adoption of raised bed cropping systems, an approach which better addresses rootzone limitations caused by both seasonal and irrigation waterlogging and soil compaction. Raised bed farming systems have become part of the irrigated agricultural scene in the Murrumbidgee and Murray valleys over the past 25 years. The adoption of these systems continues to expand as growers seek to increase water use efficiency and cropping flexibility.

Permanent raised beds are the recommended irrigation design to achieve high yields in many irrigated crops on heavy clay soils, including maize, soybean, faba bean, canola and winter cereals. The incorporation of lateral (ie placed across the main slope of the field) raised beds into a bankless channel style design provides the opportunity to produce selected crops in sequence on raised beds within an unaltered irrigation design.

In this paper changes over time from contour basin designs to raised beds, permanent raised beds and now raised beds in bankless channel irrigation designs (drain-back level basins) are discussed. A field experiment that has been in progress since 2002 at Coleambally, southern NSW, is described, where the production, productivity and water use of a range of crop sequences in rice-based farming systems are being evaluated across a series of irrigation methods.

Introduction

Raised beds are a farming system where the crop and traffic zones (furrows) are distinctly separated. The flat top of the bed is constructed by moving soil from the traffic lane to the crop zone. The furrows act as traffic zones or tramlines to which wheels are confined, and also as conduits for irrigation water supply and drainage. Permanent raised beds (PRBs) remain in place with minimal renovation or reworking for several years.

The use of PRBs for the production of summer crops other than rice in the heavy clay soils of the irrigation areas of southern New South Wales (NSW) (Figure 1) was pioneered by Martin Maynard at Hay, NSW, in the mid 1970s in order to control irrigation water, drainage, soil structure and water infiltration. He began seeding winter crops directly into the previous summer crop's raised beds (Maynard et al 1991), and eventually a number of winter and summer crops were grown consecutively without reforming the raised beds. These raised beds are typically irrigated down the slope.

Now, virtually all non-rice summer crops (maize, soybeans, sunflowers, sorghum) and considerable areas of winter crops (100% of faba beans, chickpeas and safflower; 50% of canola and in excess of 25% of cereals) are grown on raised beds. These beds are typically constructed to be 1.5–2 m wide, depending on soil type and machinery constraints.

A series of experiments with double cropping on raised beds was undertaken in the 1980s at Tatura in central Victoria (Tisdall & Adem 1986a,b,c; Tisdall & Hodgson 1990). Tisdall and Adem (1988) developed a system of double cropping on furrow-irrigated permanent beds referred to as 'Tatura permanent beds'. Tisdall and Adem (1990) investigated the opportunities for relay cropping summer crops with winter crops on permanent beds, aiming at increasing cropping intensity.

Tisdall and Hodgson (1990) reported ridge tillage (including PRBs) being used successfully on poorly-

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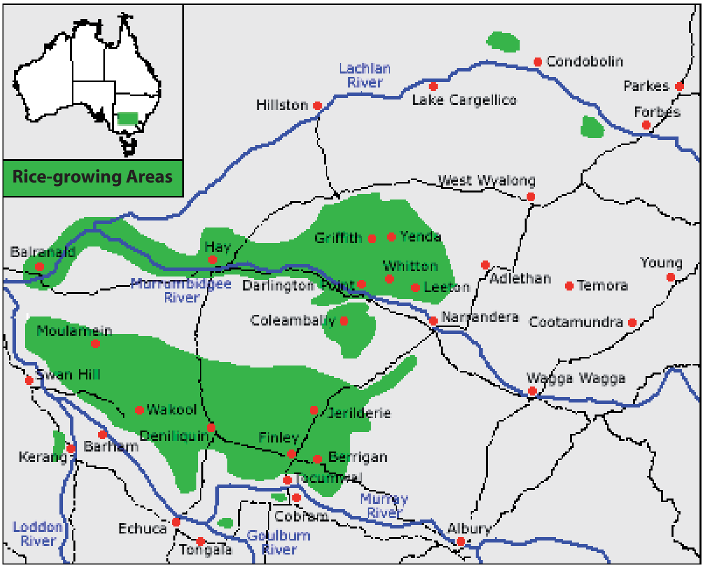

Figure 1. Location of rice-growing areas in southeastern Australia.

drained and poorly-structured Vertisols and Alfisols of southeastern, central-eastern and northern Australia, mainly for growing vegetables and irrigated cotton, sorghum, maize, wheat, sugarcane, pastures and grain legumes. They identified higher yields for crops grown on raised beds compared with those on the flat due to better soil aeration. Prolonged ponding of irrigation water in the furrows decreased yields of wheat, maize, cotton, sorghum and most grain legumes, but not of soybean.

In southern NSW a series of experiments pointed to the yield advantages of PRB designs over border irrigation designs in wet winter/spring conditions (Thompson & North 1994). They demonstrated the opportunity to have a high cropping intensity on PRBs (Thompson 1995; Thompson et al 1991, 1992). Beecher et al (1994) showed that PRBs could be successfully integrated within rice-based farming systems.

Successful rice production in southern NSW requires a continuous water supply and the ability to pond water. The ability to manage both supply and depth means that water can be controlled to deal with agronomic issues such as effective weed control, maintenance of shallow water depth at rice establishment, uniform coverage of fields, and provision of increased water depth at the low-temperature-sensitive rice reproductive stages to achieve high yields. Rice yields are protected in the cooler southeastern Australian rice growing environment by the adoption of deep water (20–25 cm on the high side of bay) during the reproductive period when ambient temperatures down to 10°C can occur. The occurrence of low temperature events during early pollen microspore development can affect pollen viability and resultant yields. Continuously ponding water on rice fields also provides a buffer against widely fluctuating evaporative-demand conditions and interruptions, or restrictions to irrigation supply.

Although the irrigation supply flow rates, basin sizes and grades are designed to accommodate other crops grown in rotation with rice, the irrigation field designs used for conventional rice culture are generally not well suited to many other crops. This is due to the combination of fine-textured soils, poor surface and internal soil drainage, and soil structural damage resulting from prolonged ponding and machinery traffic during rice harvest. Therefore, the range of crops that can be grown in rotation with rice is limited, and their productivity is generally less than desired. There is potential to increase the yield and water use efficiency of crops grown in rotation with rice through the adoption of PRBs, which provide improved surface drainage and reduced compaction due to controlled traffic. Such irrigation designs will also allow production of higher value commodities (ie crops that cannot be grown in conventional rice irrigation designs such as vegetables, soybeans and other grain legumes), thus increasing flexibility in response to market opportunities and unpredictable weather.

Laser-graded contour irrigation designs (Doneen 1972) using bankless channel supply/drainage

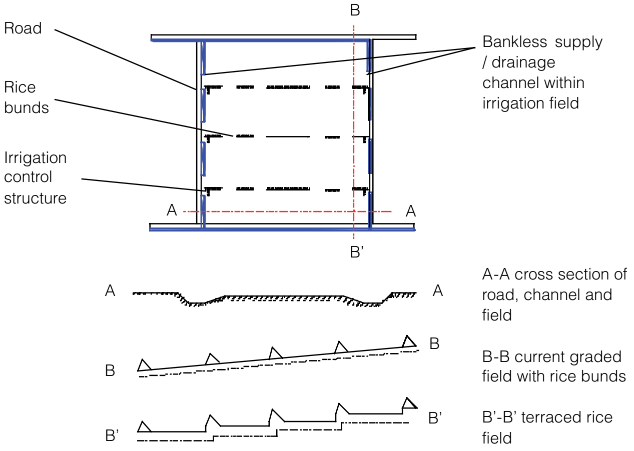

Figure 2. Diagrammatic representation of a bankless channel irrigation design showing surface elevations across and down the field for graded and terraced fields.

systems have been widely adopted in the Murrumbidgee Valley to suit both rice and winter cereal production. They are comparable to border irrigation designs in terms of irrigation efficiency and crop yields, and similar to the drain-back level basin or self-drain level basin designs used in the western USA (Dedrick et al 1982). Most bankless channel irrigation designs used within the Murrumbidgee and Murray valleys of southern NSW do not have level basins (or bays) but use a grade that is constant across the entire field (ie there are no terraces or benches) (Figures 2–5).

Some maize producers are using raised beds within bankless channel field designs but with slopes down the length of the irrigation bay. They cite advantages of decreased labour requirement, faster water-on/water-off periods, reduced waterlogging and decreased opportunity for excessive infiltration.

Raised beds are also increasingly being used for production of both winter and summer crops in the Murrumbidgee Valley. These farming systems allow improved soil structure, reduced soil compaction, reduced tillage, more timely operations, greater cropping flexibility and improved crop yields (Beecher

Figure 3. Rice growing on raised beds within a bankless channel design, where rice was sown into the furrows. Irrigation supply/drainage channel in foreground, borrow ditch and rice bund at left.

Figure 4. Commercial wheat crop on raised beds in a bankless channel design. Note concrete water control structure at left.

Figure 5. Commercial crop of adzuki beans on raised beds following wheat harvest (see Figure 4). Note irrigation supply/drainage channel in foreground.

et al 1998). The management and design of irrigated PRBs have generally been well defined (Beecher et al 1998). The use of level basins is increasing in the Murrumbidgee Valley, particularly when raised beds are incorporated into the irrigation design. It should be possible to retain the same irrigation design and grow an increased range of high-yielding crops.

Main reasons for promoting permanent raised beds in southern NSW

Soil limitations for crops on flat contour basin irrigation designs

Transitional red-brown earth soils and non-self-mulching clay soils are frequently poorly structured, sodic at depth and, consequently, poorly drained under surface irrigation. Limitations of these soils include physical conditions such as poor tilth, inadequate infiltration, shallow hard-setting or crusting surface horizons, dense subsoils, waterlogging and soil compaction (Beecher et al 1998). Surface irrigated soils are unable to support machinery traffic for an extended time after irrigation without being subject to compaction. These soils have a narrow non-limiting water range and remain too wet to cultivate after irrigation. They also have a relatively small window in which soil moisture and strength are suitable for field operations, and tend to become too dry to cultivate, resulting in poor tilth and pulverisation of the soil structure.

Irrigation field design limitations

Natural grades in these areas of southern Australia are frequently flat to very flat (1:1500 to 6000), especially in rice-growing areas. Such low grades mean that the fields have poor surface drainage. The soils used for irrigation generally also have poor internal soil drainage, so soil waterlogging is a serious issue for crop production following prolonged rainfall or surface irrigation. Such conditions can reduce crop growth and yield.

Generally, the contour basin irrigation field designs predominately used for rice growing in these areas can severely limit establishment and growth of other irrigated crops. Non-landformed fields used for conventional rice culture are generally not well suited to other crops, as a result of a combination of clay soils, poor surface drainage and soil structural damage due to prolonged ponding and machinery traffic during rice harvest. In these situations crop choice is limited to wheat and subterranean clover pastures grown in rotation with rice, and their productivity is generally poor, especially during high rainfall conditions.

Permanent irrigated raised bed farming systems allow improved soil drainage and structure, reduced soil compaction, reduced tillage, more timely operations, greater cropping flexibility and improved crop yields (Beecher et al 1998).

Humphreys et al (2001) showed that growing winter crops immediately after rice harvest allows use of stored water in the soil profile and creates the capacity to capture and use winter rainfall instead of losing it as run-off or deep percolation. This increases the irrigation and total water productivity of rice-based cropping systems. Crop water use from upward flux from the watertable can be significant, varying between 10% and 36% of total evapotranspiration for well-irrigated wheat with a shallow (1.5–2.1 m) fresh watertable (Meyer et al 1987).

In the Murrumbidgee Valley, growers rotating crop sequences between rice and alternative summer crops use one of two options. They either employ different field irrigation designs on different parts of their farms, or they change rice irrigation systems (contour or lasered contour) to furrow irrigation designs (down the slope) for summer crops. The ability to use residual soil moisture following rice growing may be enhanced in irrigation field designs which incorporate PRBs within rice fields (bankless channel or drain-back level basin designs), and this may provide an improved opportunity to double crop after rice.

The possibility of combining irrigated raised beds within a terraced bankless channel irrigation design for use in rice-based farming systems negates the need to convert irrigation designs between different phases of a cropping rotation. Current research is investigating the potential for using lateral PRBs (beds placed laterally across the main slope of the field) within the banks used to pond water for rice cultivation in rice-based crop rotations (Figure 2).

Main features of permanent raised bed irrigation systems

Irrigation designs

Permanent beds are being used in two types of irrigation designs (Figures 6a, 6b):

- standard beds using down-the-slope furrow irrigation (predominant)
- lateral beds within bankless channel rice field designs (innovative growers).

A square or rectangular field is preferred where landforming and laser levelling is possible. In many cases a square field cannot be achieved and a parallelogram is adopted to allow a constant running length. Alternatively, raised bed irrigation designs may be adapted to irregularly shaped fields using variable running lengths. However, this type of design may mean increased labour requirements due to variable irrigation time intervals along beds.

Raised bed dimensions and configurations vary with soil type and available machinery. The ability of the soil to 'sub' (ie allow the lateral movement of irrigation water into the centre of the bed) is a key determinant of bed dimensions. For grey self-mulching clay soils that sub easily, growers use bed widths at 1.84 m centres for all crop types. Where soils do not sub as well, narrower beds at 1.50 m centres are frequently used. Bed height may also vary with soil conditions and field slope. Higher beds are frequently used on soils that sub well and have flatter grades and longer run lengths, while beds of a lower height are used on more difficult soils or on steeper graded fields. The flat top of the bed varies from 1.0 to 1.4 m in width.

Growers prefer run lengths in the order of 600–800 m, where possible, for lower-value, large-

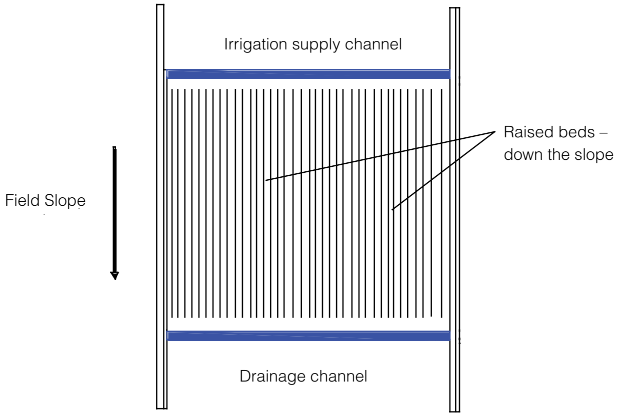

Figure 6a. Irrigation design for field using standard beds down the field slope.

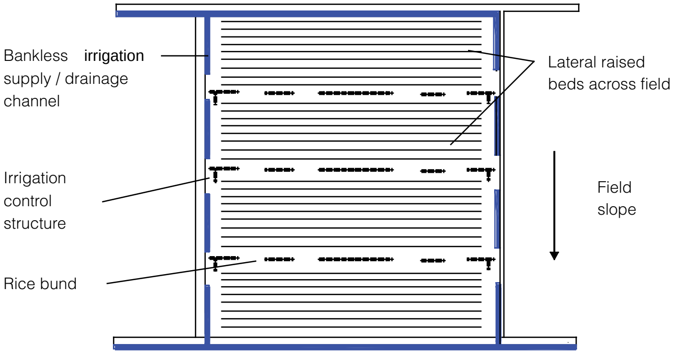

Figure 6b. Irrigation design for field using lateral raised beds within a bankless channel design.

scale cropping operations, although this is limited by existing field and farm dimensions and shapes. Where vegetables and other high value crops are grown on beds, run lengths are shorter to prevent transient waterlogging.

Furrow irrigation used with raised beds requires growers to adopt a whole-farm planning approach to deal with drainage waters and the integration of on-farm drains and drainage water recycling systems, to increase both water use efficiency and drainage water quality control.

Crop agronomy and sequencing

A range of row spacings and sowing widths are used across the flat top and shoulder of the bed. For a summer crop such as maize, 2 rows are generally planted near the bed edges. Where good subbing to the centre of the beds occurs, 3 to 6 rows can be spaced across the beds for crops such as soybeans. Increasing the number of rows leads to earlier canopy closure and suppression of weeds. Winter crops are normally established at conventional combine row spacings, with rows placed into the shoulder of the bed, thus minimising the unplanted space between outside rows on adjacent beds.

Water and nutrient management

Most growers irrigate beds prior to sowing, especially where the beds may not sub well. Watering up (ie irrigating after sowing to germinate the seed) can be undertaken where the soils sub well but not in crops that are prone to seed bursting during germination, such as soybeans. Watering up might be considered a more viable option in the future for lateral raised beds where the water depth in the furrows can be managed without inundating the seed. It is important that crops should be watered up only on previously irrigated raised beds where the soil has been consolidated to some degree (ie double-cropped beds), not on newly constructed raised beds where there is the chance that the soil may slump on wetting and inundate the seed line.

Once the crop has germinated, lateral beds also provide the opportunity to flood and then drain the beds in situations where the soil conditions may not allow water to sub adequately to the centre of the beds from the furrow. On PRBs, particularly in double-cropped or minimum tillage situations, fertiliser management needs to be considered over a longer time. Application of the less mobile nutrients (phosphorus, zinc, sulphur and molybdenum) is frequently managed by using a luxury level of these nutrients to provide for the needs of a number of successive crops during construction of the raised beds (Figure 7).

Generally, a starter fertiliser (eg diammonium phosphate) is applied with the seed. Nitrogen (as urea) is broadcast before rainfall or irrigation at the appropriate time in the crop development (eg node formation during the stem elongation growth stage for wheat and barley, stem elongation in canola, panicle initiation for rice). For maize, applications of anhydrous ammonia are injected into the bed prior to final bed shaping, and further N is applied by water-run urea (ie fertigating the nitrogen by dissolving urea in water and metering it into the irrigation supply). There may be the opportunity to water-run urea on other crops, eg wheat and canola.

Figure 7. Fertiliser being applied during bed shaping (in a one-pass operation) in construction of raised beds.

Figure 8. Anhydrous ammonia fertiliser being injected into renovated raised beds following incorporation of wheat crop residue prior to establishment of a maize crop.

Tillage operations and bed maintenance

Tillage operations are generally restricted to sowing, inter-row weed cultivation and refurrowing with furrow sweeps (tools). Shallow cultivation and reshaping of beds may sometimes be necessary to reflatten the top of the beds or allow for physical destruction of potential insect pests (eg heliothis pupae, *Helicoverpa armigera* and *H. punctigera*). Periodically, major renovation of the beds may be necessary in order to allow re-lasering of the field following soil movement due to soil swelling, or bed damage resulting from wet harvesting conditions.

Where maize is grown, the stubble residue is frequently burnt following harvest, and the beds are ripped and allowed to recondition over winter. Anhydrous ammonia is then injected into the beds, and the field is refurrowed and the beds reshaped. Several of these operations may occur in the same tractor pass. Winter cereal and rice stubble residues are burnt to allow successful establishment of following crops (Figure 8).

Bed-planting and harvesting machinery

Equipment requirements vary with the level of adoption of raised bed farming practices. Initially, growers often adapt existing conventional farming equipment to use on raised beds. Future equipment purchases are then directed toward specialised bed-farming equipment.

Once the initial development phase of levelling and laser grading are completed, the tractor and heavy equipment can be reduced to smaller tractors and implements. Bed construction requires the use of toolbars fitted with furrow sweeps at appropriate spacing, and bed-shapers to create the flat-topped bed. For seeding, appropriately modified conventional combines have been developed. Alternatively, specialised row-cropping planters can be used, especially for crops such as maize or sunflowers where interplant spacing in the plant row is important. Specialist bed-farming contractors have developed businesses aimed at providing all bed-farming field operation requirements from initial landforming, bed construction and shaping, seeding, fertilising, inter-row cultivation and spraying, through to harvest (Figure 9).

Figure 9. High powered tractor using a toolbar equipped with furrow sweeps to create furrows and beds.

Performance to date of permanent raised beds

Level of adoption

Virtually all non-rice summer grain cropping in the Murrumbidgee/Murray valleys is undertaken using PRBs. Thompson (1995) reported an estimated 35,000 ha of raised bed cropping occurring in these regions. Current estimates of the area of PRBs presently cropped, derived from discussions with district agronomists and irrigation officers, suggest that there may be up to 35,000 ha of land using irrigated permanent raised bed farming systems in the Murrumbidgee and 5,000 ha in the NSW Murray Valley. The area of land developed to PRBs is probably much higher but recent historically low water allocations have perhaps reduced the use of established areas and slowed further development of raised bed farming systems.

In the Murrumbidgee Valley use of raised bed farming systems has expanded to virtually all maize and soybean plantings; all irrigated faba bean, adzuki and chickpea plantings; more than 30% of irrigated canola plantings; and 25–30% of irrigated wheat plantings.

In the Murray Valley, after an initial interest, only limited areas maintain the use of raised beds, predominantly wherever land has minimal slope in the eastern part of the irrigation district. Thompson (1999) concluded that if the soil type has good internal drainage and/or sufficient surface slope, then raised beds are unlikely to offer much advantage. However, any advantages attributed to controlled traffic or better opportunities to double crop would still be applicable and favourable for raised beds. There are also growers investigating the use of wider 'bed' configurations in the western Murray Valley, where very flat grades exist.

Problems encountered

Under double-cropping rotations

Maynard and Muir (1984) comment that soybeans grown after barley have reduced yields compared to a single-season soybean crop, due to a later than optimal sowing date. Although no obvious agronomic limitations were identified with double-cropped soybean–barley rotations on raised beds, soybean yields were lower than desired when sowing was undertaken in mid–late December following the barley harvest rather than in the optimum mid-November period of soybean sowing (Thompson et al 1992) (Figure 10).

At Yanco, NSW, on a red-brown earth soil, double cropping on PRBs has been successful, although summer crop yields were reduced by delayed sowing dates. Where rotated with barley, dense stubble reduced plant establishment numbers, resulting in reduced yield compared to stubble burnt plots (Beecher 1992).

Stubble management

Highly productive crops produce significant quantities of crop residue. Within the Murrumbidgee Valley the majority of producers remove both summer and winter crop residue by burning. In the Murray Valley the inability to gain fire permits during summer means that growers cannot double crop on PRBs by burning wheat/barley stubble and planting a summer crop such as soybean directly afterwards. This also reduces the attractiveness of using raised beds for winter field crops and crop rotations in the Murray Valley. Stubble burning is of major concern due to greenhouse gas emission and public health issues. The development of suitable machinery that can direct drill into large amounts of crop residue and subsequently high crop establishment following sowing is required.

Non-straight furrows

Part of the advantage of PRBs comes from restricting machinery traffic into consistent locations, ie the furrows, hence isolating compaction zones to the wheel tracks. Where furrows are not straight or where beds need to be reconstructed, there is the possibility of furrows being relocated over time as a consequence of bed maintenance activities and thus increasing the zone of soil compaction. However, the advent of satellite guidance systems and contract farming operations has helped to reduce this issue. With this new technology, furrows remain in the same position throughout many years.

Matching machinery (particularly harvest machinery) to bed dimensions

Initially, there were issues concerning typical harvesting machinery wheel spacings not fitting the furrow spacings (1.8 m) used by other machinery. However, recent tractor wheelbase spacing modifications by tractor companies and growers have standardised on wheelbases of 3 m, spanning two beds of 1.5 m width and an intervening furrow. This means that harvesting equipment appropriate to this bed arrangement can operate in the furrows without compacting the beds (Figure 11).

Figure 10. Soybeans (4 rows per 1.84-m-wide bed) double cropped immediately following burning of barley crop residues.

Figure 11. Level and smooth seeding surface being created on raised beds by use of a rotary hoe and rotary harrows.

Weeds

Rotations that alternate broadleaf and cereal crop types allow for ready weed control of most weeds through the use of different herbicide treatments. Also, growing rice in rotation with these other crops on PRBs allows for inundation and death of many weed seeds that can infest non-rice crops.

Water penetration into beds

Thompson and North (1994) used a transitional red-brown earth soil type in the Murray Valley to compare border and conventional raised beds irrigation designs for growing wheat or barley. They reported that lateral penetration of irrigation water into the centre of the 1.6-m-wide PRBs was poor due to poor soil structure. This meant that grain yield in the centre of the beds was probably reduced by water stress The soil type was such that it was unlikely that adequate subbing would have occurred even using 1.5-m-wide raised beds. Using flooding irrigation over the top of lateral beds in bankless channel irrigation designs, then quickly draining, would eliminate this problem.

Benefits of permanent raised bed systems

A range of benefits from the use of PRBs have been recorded/observed, including increased production, reduced costs, better soil conditions and organic carbon levels, less compaction in the root zone, reduced cultivation and increased opportunity to double crop.

Yield improvements

Thompson and North (1994) showed that crops grown on raised beds averaged 26% higher yields than those on border irrigation designs. They concluded that in all 4 years of winter cereal growing, raised beds produced increased crop yields compared to the border irrigation design because of the removal of transient winter/spring waterlogging. Growing triticale during 1994 and wheat in 1996 (both drier seasons) at the same experimental site, when there was no waterlogging, produced no yield advantage for the raised bed irrigation design (Thompson 1999).

With minor exceptions, all summer crops of maize and soybeans are grown on raised beds. In most situations these crops would not be considered suitable for growing in border irrigation designs unless the grade was greater than 1:800. Cropping of maize and soybeans would not be undertaken without the use of raised beds or at least hills. Best management practice cropping guides for irrigated faba beans, canola and adzuki beans recommend the use of raised beds. McCaffery et al (2005) state that raised beds are the preferred irrigation method for growing canola in the Murrumbidgee Valley. Raised beds allow the crop to be irrigated without soil crusting, and to be fully irrigated to schedule in spring without waterlogging reducing yields.

Opportunity to double crop

Previous research by Thompson et al (1992) has investigated double cropping of a range of crops on PRBs in a traditional down-the-slope furrow irrigation design. Soybeans were successfully continuously double cropped with wheat, canola and barley, starting with soybeans in 1984. They consistently achieved yields of 3 t/ha in stubble burnt treatments when double cropped with winter cereals/canola. Five crops of soybean, two of wheat, one of canola and two of barley were successfully grown on permanent raised beds over 5.5 years on untilled, burnt treatments on a self-mulching clay soil (Thompson & Beecher 1988; Thompson et al 1992).

Opportunity to delay decisions on crop type

Growers consider that raised bed irrigation designs allow them to make delayed decisions on crop choice, subject to changing market opportunities, on the basis that a favourable irrigation design for numerous crop types and variable weather conditions is available.

A level of precision farming in terms of fixed furrows/traffic lines

The positioning of fixed traffic lines by the furrows mean that fertiliser and spraying operations are undertaken with a high degree of accuracy/repeatability. This minimises ‘misses’, and double applications (overlapping) are avoided, thus reducing costs.

Decreased soil compaction within crop area

Confining traffic to the furrows means that beds are not trafficked, resulting in reduced soil compaction and improved soil conditions for water entry, root growth, and surface and internal drainage.

Ability to use smaller machinery (tractors)

For large-scale dryland farming, Murray and Tullberg (1986) reported that by using controlled traffic approaches (which could include PRBs), the energy requirement at crop establishment could be reduced by approximately 50% while still enhancing crop production. Maynard et al (1991) reported that although heavy equipment (perhaps contracted) is needed for initial land preparation, a permanent bed farming operation could be managed with smaller tractors and hence reduced capital and running costs.

Increased opportunity to use residual soil moisture

Humphreys et al (2001) showed that growing winter crops immediately after rice harvest on conventional rice fields increases irrigation and total water productivity of rice-based farming systems. This increase in efficiency is the result of using stored water in the profile and creating the capacity to capture and use winter rainfall instead of losing it as run-off or deep percolation. Better drainage of rice grown on raised bed irrigation designs potentially allows better establishment of winter cereals or other crops in more seasons than can be achieved on a conventional flat contour basin irrigation design.

With a rice-based rotation using a lateral PRB irrigation design, there are perceived weed control benefits within other summer crops, better 'incorporation' of herbicides, improved water infiltration into difficult-to-'sub' soils (since the beds can be flooded if necessary), and the ability to water up dry-sown crops in a dry year and have better drainage in a wet year.

Economic and environmental benefits and risks

Economic analysis of PRBs has been undertaken by McKenzie (1989) and Maynard et al (1991). Both studies showed positive financial outcomes from the adoption of permanent raised bed farming systems.

Environmental benefits include reduced groundwater accessions, as discussed by Humphreys et al (2001). Adoption of raised bed farming systems requires the development of whole-farm plans and on-farm drainage recycling systems in order to manage irrigation drainage. These on-farm works are seen by regional planning strategies (Land and Water Management Plans) as of environmental benefit in terms of reduced off-farm movement of nutrients, soil, salt and pesticides (insecticides and herbicides). These planning approaches seek to improve drainage water quality in irrigation districts and to protect and enhance natural resources and biodiversity in downstream environments.

Farmer experience and/or constraints to adoption

Many growers perceive that the adoption of permanent beds will require significant financial resources to change from border or contour irrigation designs, involving landforming, channels and drains, irrigation stops etc. Growers have commented that changing from contour basin rice designs to a raised bed farming system is expensive in terms of whole-farm design, landforming and laser levelling; and also necessitates significant investment in machinery to undertake the change on a large scale. Raised beds are an essential part of vegetable growers' irrigation designs, where vegetable cropping may form about 20% of the cropping program and a complete range of other crops are grown in rotation/sequence (including winter/summer cereal and oilseeds, and rice on the flat).

A majority of growers in the Murrumbidgee Valley are shifting toward raised beds even if only for one field per farm. Yet, as experience is gained in the management of these systems, some growers have converted their entire holdings to raised bed farming in a very short time. The high machinery requirement has encouraged the development of extensive contracting services, not just for landforming and laser levelling but also for raised bed construction, sowing, spraying and harvesting.

Yield improvements not realised

Some growers have been unable to realise the yield advantages that typically accrue from using bed style irrigation designs over flat contour or border irrigation designs. This suggests that further education and training in advanced crop agronomy and irrigation management needs to be undertaken. A series of relatively dry seasons have also occurred since the mid 1990s, and during this time advantages of improved drainage from raised bed systems have not been observed.

Water: a limiting resource

Other issues such as low irrigation water reliability/security have not been conducive to some growers adopting PRBs. Infrastructure impediments such as low flow rates and the timing of irrigation water access during crop growth have also contributed. Limited water availability means limited irrigation, making it more lucrative to use flat irrigation designs without the high capital cost of permanent raised bed infrastructure.

Lack of promotion

Raised beds were vigorously promoted in the Murrumbidgee Valley by John Muir (District Agronomist, Hay) in the 1980s, both within established irrigation areas and districts and to irrigators accessing surface water or groundwater resources. This promotion has been a significant driver of the adoption of PRBs in the Murrumbidgee Valley. However, promotion of beds has not been as effective in the Murray Valley.

High cost of bed farming machinery

Some growers perceive that entry into PRBs requires a complete change of farming machinery. This may be the case for growers making the change to raised bed designs over a short timeframe. However, basic furrowing equipment is relatively inexpensive and if current machinery can be modified to fit the beds, the expense may not need to be very large.

Marketing

For major crops such as rice, wheat and barley, significant marketing and grain handling organisations exist to purchase or 'pool' market the crop produced. With less significant crops (in production terms) such as maize, soybean and canola, the productivity of which is favoured by cultivation on raised beds, growers have to store and market the crop themselves. Many growers do not possess the skills or inclination to undertake such marketing, and so tend not to produce these crops and therefore do not use raised beds.

Innovative irrigation field designs using lateral permanent raised beds

Rice irrigation designs used in Australia can be natural contour basins, laser graded within contour basins, landformed and laser graded basins, or terraced and laser landformed within bankless channel basin systems.

When growing winter crops in sequence with rice, the contour basin design is still frequently used; however, this design has a negative impact on the growth and yield of winter crops. For summer crops the irrigation design is frequently radically changed from the contour basin design to border irrigation or furrow irrigation using raised beds down the field slope. This necessitates removal of the rice banks (bunds/dikes), re-lasering of the field and, possibly, construction of raised beds.

In the western USA level basin irrigation (using drain-back level basins) is used, where a controlled amount of water is applied to level soil surfaces (flat or bedded) within dikes (Erie & Dedrick 1979; Dedrick et al 1982). This irrigation design aims to achieve high irrigation water use efficiency and uniformity by irrigating the basin as rapidly as possible without causing soil erosion.

Drain-back level basins and the bankless channel design have the advantage of improved water supply and drainage compared to other irrigation designs, as the channel acts as both a supply and drain and there are fewer water control structures required compared to other designs. The development of terraced, landformed bankless channel designs potentially allows crop sequences that include rice, winter crops and summer crops on raised beds without any change of irrigation design.

With a minimal side slope within each bay or level basin, rice can be satisfactorily grown on lateral PRBs (Thompson et al 2003). Growing rice on beds with saturated soil culture in the southern NSW environment reduces irrigation water use, but gives no change in water productivity due to lower yields (Thompson et al 2003). Research during the past 4 years in southern NSW has shown irrigation water savings of about 14% using raised beds compared to flat irrigation designs, but at a cost of 12% yield decline (Thompson et al 2003). This contrasts with Tracy et al (1991), Borrell et al (1997) and Vories et al (2002), who report the use of raised beds for the cultivation of rice in semitropical environments and varying soil/stratigraphic conditions. In all these studies reductions in rice crop water use were reported for rice grown on beds without any yield loss.

Figure 12. Rice establishment (2002) on raised beds (left) and on flat (right) in field experiment at Coleambally investigating crop performance under a range of irrigation designs and crop sequences.

Table 1. Irrigation designs and crop sequences used for Coleambally field experiment.

Irrigation design	Summer 2002–03	Winter 2003	Summer 2003–04	Winter 2004	Summer 2004–05
Flat	Rice	Wheat	Fallow	Wheat	Fallow
Flat	Rice	Fallow	Fallow	Wheat	Fallow
Bed	Rice	Wheat	Fallow	Wheat	Fallow
Bed	Rice	Barley	Soybean	Barley	Soybean
Bed–drip	Rice	Barley	Soybean	Barley	Soybean
Bed	Rice	Fallow	Rice	Fallow	Rice
Bed–drip	Rice	Fallow	Rice	Fallow	Rice

Current permanent raised bed experiment at Coleambally, southeastern Australia

A field experiment has been in progress at Coleambally in southern NSW since September 2002. The production, productivity and water use of a range of crop sequences in a rice-based farming system are being evaluated across a series of irrigation methods including lateral PRBs (Beecher et al 2006). (Figure 12).

The replicated field trial consists of three irrigation treatments – conventional flat rice contour basin, and PRBs with furrow and with subsurface drip – all inside a bankless channel type design. Plots are 150 m long by 12 m wide (with 6 × 1.84 m beds). Rice was grown in all treatments in the first season and then a range of cropping rotations has been established over the irrigation treatments (Table 1).

Rice 2002–03

Rice was sown at 140 kg/ha, using a modified double-disc seeder with row spacings of 15 cm for all treatments. Eight rows were sown on the top of the beds. Five irrigation designs/treatments, as follows, were applied following a germination irrigation and three further flush irrigations (Figure 13):

(i) Flat — permanent flood was applied with an initial water depth of 15 cm for weed control. Water was maintained between 3 and 5 cm after permanent flooding until 10 days after panicle initiation (PI), when it was raised to a minimum depth of 15 cm until the completion of anthesis.

(ii) Bed 15 — the water was ponded at the same time as the flat received permanent flood, to assist weed control and promote transport of N fertiliser into the soil. After ponded water had been used by the crop, water was maintained in the furrows until 14 days prior to PI, when the soil was allowed to dry. A second application of N was applied 10 days prior to PI and the bays flooded to 10 cm above bed surface. After the crop had used this water, it was maintained at 3–5 cm above the bed until 10 days after PI, when the water depth was increased to a minimum of 15 cm for the reproductive period.

(iii) Bed 5 — as for bed 15 except that the water level was retained at 3–5 cm above the bed surface during the reproductive period.

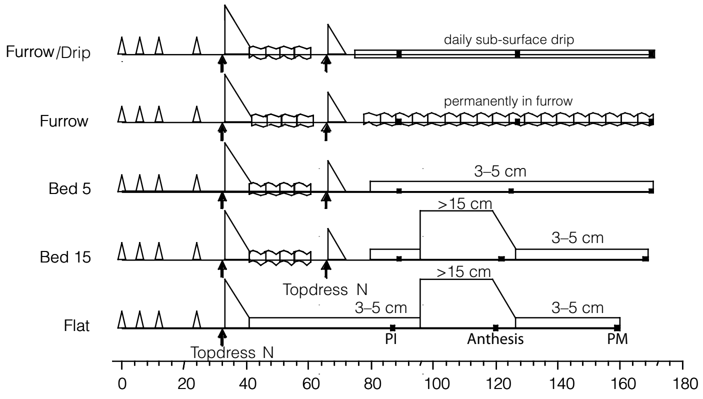

Figure 13. Graphical representation of the five irrigation designs/treatments applied during the 2002–03 rice crop.

Table 2. Effect of irrigation designs/treatments (mean of N rates) on rice crop (2002–03 and 2003–04) establishment, grain yield (at 14% moisture), irrigation water use and input water productivity.

Season	Irrigation design/ treatment	Estab. plants/m^2	Grain yield (t/ha)	Input water use (ML/ha)	WP[a] (t/ML)
2002–03	Flat	279	12.7	18.7	0.68
	Bed 15	384	10.2	18.1	0.56
	Bed 5	389	10.1	18.2	0.55
	Furrow	366	9.4	17.2	0.55
	Furrow–drip	269	8.3	15.1	0.55
2003–04	Furrow	100	7.66	13.6	0.56
	Drip	91	8.07	14.3	0.56

[a] These values do not take into account soil moisture remaining in the profile at sowing or harvest

(iv) Furrow — as for bed 15 until after the water had receded into the furrows, and water was then maintained only in the furrows until physiological maturity (PM).

(v) Furrow–drip — as for bed 15 until PI, then water was supplied by the drip system following the second ponding prior to PI until physiological maturity.

Water applications and drainage were measured into and from individual bays using flumes equipped with water depth loggers. Input irrigation water productivity (Table 2) was calculated using the grain yield at 14% moisture averaged over the N rates for each treatment, and divided by the sum of irrigation and rainfall minus surface runoff.

The unplanted furrows of the raised bed plots contributed to reduced yield and water use efficiency when compared to the conventional flat plots. High yields, greater than 10 t/ha, were still achieved on the raised beds. Unponded rice on beds was delayed in maturity.

Rice was only sown on raised bed treatments in 2003–04. Establishment was poor and grain yields (Table 2) were reduced in all treatments, due to poor plant numbers and cold damage as deep water was not imposed during early pollen microspore.

Wheat–barley

In 2003 wheat and barley crops were direct drilled after the rice crop residues had been burnt. Wheat was grown either on furrow-irrigated PRBs or surface-irrigated basins, while barley was grown on drip- or furrow-irrigated PRBs. Establishment was poor due to shallow seed placement into dry and hard soil conditions with unsuitable equipment and no rain for a long period of time after sowing. Large furrows with no plants reduced yields in the bed treatments, and stripe rust (although treated with fungicide) may have contributed to lower wheat yields (Table 3).

In 2004 wheat and barley were dry sown (at 100 kg/ha) with 185 kg/ha diammonium phosphate fertiliser on 12 May. Nine rows were sown on the bed and two rows on the bed shoulders. Rainfall on 25 May initiated germination and establishment, which was excellent in both the wheat and barley (Table 3). Nitrogen

Table 3. Winter crop (2003 and 2004) establishment, grain yield (at 12% moisture), input water use and input water productivity.

Season	Crop	Treatment	Estab. (plants/m^2)	Yield (t/ha)	Water use[a] (ML/ha)	WP[a] (t/ML)
2003	Wheat	Bed	122	4.8	5.1	0.95
	Wheat	Flat	96	5.0	5.1	0.98
	Barley	Bed	100	5.3	4.6	1.14
	Barley	Bed–drip	97	5.4	3.7	1.47
2004	Wheat	Bed	166	7.36	5.04	1.46
	Wheat	Flat	196	7.60	5.34	1.42
	Wheat	Flat fallow	196	7.32	5.41	1.35
	Barley	Bed	125	6.56	4.47	1.47
	Barley	Bed–drip	130	6.50	4.58	1.42

[a] These values do not take into account soil moisture remaining in the profile at sowing or harvest

Table 4. Soybean crop (2003–04 and 2004–05) establishment, grain yield, input water use and input water productivity

Season	Treatment	Estab. plants/m^2	Yield (t/ha)	Water use (ML/ha)[a]	WP (t/ML)[a]
2003–04	Furrow	33	3.68	9.5	0.39
	Drip	33	3.05	5.6	0.55

[a] These values do not take into account soil moisture remaining in the profile at sowing or harvest

topdressing of 100 kg N/ha as urea was applied at the second node stage of stem elongation, immediately prior to the first irrigation. Yields were acceptable and much better than in the previous season. There was little difference in grain yield between the irrigation treatments. This can possibly be attributed to minimum waterlogging in the basin design due to dry conditions and relatively small crop areas compared to the commercial situation.

Soybeans 2003–04

Soybeans were sown at 4 rows per bed (2 rows either side of the drip tape for the drip-irrigated treatment). Crop establishment was satisfactory and yields were impressive given the relatively late sowing date. Grain yield for the drip treatment was reduced compared to the furrow treatment due to a premature crop senescence, which was induced by an automated irrigation system failure late in the season and not due to the overall lower water use (Table 4).

Conclusions

Raised bed farming systems have become part of the irrigated agricultural scene in the Murrumbidgee and Murray valleys over the past 25 years. The adoption of these systems continues to expand as growers seek to increase water use efficiency and cropping flexibility. Raised beds are the recommended irrigation system to achieve high yields of many irrigated crops on clay soils including maize, soybean, faba bean, canola and winter cereals. The incorporation of PRBs running laterally across the slope as a new rice-based farming system offers many potential advantages.

High-yielding rice, winter cereals and soybean crops were successfully grown on raised beds experimentally. The incorporation of raised beds into a bankless channel style design provides the opportunity to pond water, assisting weed control at crop establishment. Savings in irrigation water use are related to the amount of time a crop is intermittently irrigated. The longer ponding occurs (eg for weed control or to increase N application efficiency, or for protection of the crop against cold temperatures during the reproductive period), the less the water saving. The potential gains from growing rice on raised beds are considered to be associated with the overall farming system. They include greater flexibility in the crops that can be grown in rotation, double cropping and increased water use efficiency of the cropping system. Rice not ponded during the growing season is delayed in crop development, potentially negating some of the savings in water use and delaying harvest into autumn.

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Permanent raised bed farming in Western Australia

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Abstract

In the late 1980s seasonal waterlogging was recognised as the cause of substantial losses in crop and pasture production in Western Australia (WA). Waterlogging affected approximately 1 million ha of crop and 1 million ha of pasture annually, with resultant productivity losses in the order of 25–40%. This paper presents the results of Western Australian research that was undertaken to develop permanent raised bed (PRB) technology to prevent winter waterlogging. It also provides an insight into new work that adapts this technology in an effort to overcome the combination of winter waterlogging and mild salinity.

Water balance and drainage modelling is used to illustrate the relative importance of the environmental conditions that cause waterlogging, as well as to identify the soil conditions and engineering works required to drain and aerate the surface layers of soils. PRB combined with sound soil management practices are shown to have been successful in creating and maintaining soil conditions that allow sufficient infiltration, drainage and aeration to prevent waterlogging and improve plant production.

Adoption of raised bed technology has been rapid on farms that suffer frequent waterlogging over significant proportions of their cropping area. Raised bed farming is currently estimated to cover about 35,000 ha in WA, mostly along the south coast. Adoption has been facilitated through a combination of theoretical modelling, allowing simplified paddock-scale field experimentation, and the use of commercial farm machinery. Research results and practices have thus been immediately useable by farmers.

Farmers in turn have demonstrated that PRBs produce significant yield improvements and are a highly profitable investment, particularly where large areas require treatment. Farmers have obtained larger yield increases than those from research sites. Their average yield increases are 0.85 t/ha, which equates to an average addition to farm income of $184/ha/yr. Investment analyses based on research and farmer data show internal rates of return of 20–106% over 10 years.

Modelling and recent field research data are presented from a new project that seeks to adapt this technology to reclaim waterlogged and mildly saline land in WA. These data illustrate the soil conditions required to minimise capillary rise and maximise leaching. They show moderate yield increases and salinity decreases that illustrate why there is confidence that PRB technology can be successfully adapted to reclaim waterlogged and mildly saline land.

Introduction

Several factors combine to predispose the agricultural landscape of Western Australia (WA) to winter waterlogging: the unimodal winter dominant rainfall; the low-slope-low-relief topography; and the extreme texture contrast soils consisting of shallow topsoils and dense, poorly permeable subsoils. In the late 1980s winter waterlogging was recognised as the cause of substantial losses in crop and pasture production in WA (Anon. 1988). This research revealed that waterlogging affected approximately 1 million ha of crop and 1 million ha of pasture each year, and caused productivity losses in the order of 25–40% (Anon. 1988, McFarlane et al 1992). While there have been no studies specifically linking the widespread occurrence of winter waterlogging to groundwater recharge and increasing salinity, it is assumed that these factors make a substantial contribution. In fact, the predicted 1.8 M ha expansion of salt-affected land over the next decade or so (Ferdowsian et al 1996) includes most of the area affected by winter waterlogging, substantial proportions of which are already mildly saline.

Until the mid 1990s the only available technology to alleviate waterlogging was shallow surface drains, which have a limited impact because they only remove surface water. In an environment with cool temperatures coinciding with many wet days and flat topography, widely spaced surface drains do not draw water from or aerate poorly structured A-horizons, which can remain saturated for days. This paper sum-

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marises the results of Western Australian research work undertaken since 1996 to specifically adapt permanent raised bed (PRB) technology to overcome winter waterlogging. It also provides an insight into more recent research to further adapt this technology to reclaim land afflicted by the combination of winter waterlogging and salinity.

Methods

Waterlogged land

Extent and severity of waterlogging

A daily water balance model for two-layered soils was used to assess the waterlogging risk of various climate–soil combinations and to provide insights on how best to manage excess winter water. Daily water balances were computed for the April to November period using records from 1906 to 1996 for 39 locations in the agricultural area of WA. These computations predicted the changing soil-water content in the surface layer of a range of texture contrast soil profiles. The range of profile conditions included sand- and loam-textured A-horizons 10 cm, 20 cm and 30 cm deep over clayey B-horizons. Frequencies of daily waterlogging (ie when soil-water content ≥ 92% total porosity, or when air-filled pore space ≤ 8%) were derived, and maps with lines of equal frequency of daily waterlogging were produced.

Drainage properties

Drainage modelling was undertaken (i) to predict the time for perched watertables to fall from the surface to 30 cm depth, and (ii) to identify the soil conditions and drain spacings that produce the drainage and aeration necessary to prevent waterlogging. This modelling used the Glover equation (van Schilfgaarde 1974, p 250) with a range of soil hydraulic and aeration properties.

Experimental design and treatments

Five experimental sites were initially installed in 1996, located across the southern portion of the Western Australian wheatbelt from Beverley to Esperance. All had a history of frequent, severe waterlogging and average annual rainfalls in the range 450–650 mm. One site, Cranbrook, was intensively instrumented and the other four less intensively monitored. All were large, with tri-replicated treatment plots of > 2 ha. Another three sites were installed later, two in 1997 and one in 1998. The major soil and water management treatment was permanent raised beds (PRB). Beds were constructed from soil tilled to a depth of 20 cm to remove most, if not all, of the ploughpan and/or to incorporate the top of the B-horizon into the seedbed. Gypsum was added where necessary to stabilise dispersible (sodic) soil. The control treatment was a normal uncultivated seedbed. No-tillage crop establishment practices were used on both treatments to increase soil organic matter, hydraulic conductivity and macroporosity in the essentially structureless topsoils (eg Adem & Tisdall 1984; Grabski et al 1995; Hamilton et al 1984; White 1984).

A bed width of 1.83 m was chosen on the basis that for soil in reasonably good condition a width of this magnitude would drain and aerate within 2 days. This width also minimised the cost of adapting machinery to track in the furrows between beds. In consequence, this system of raised bed farming ensured that no machinery traffic would pass over the soil in the beds.

Data collected included:

- bulk density (0–30 cm, undisturbed cores)
- hydraulic conductivity (surface and 10–15 cm depth, disc permeameters)
- soil-water content (0–30 cm, time domain reflectometer (TDR))
- soil-water potential gradient (45–75 cm, recording tensiometers)
- perched watertable (0–50 cm, observation wells)
- run-off amount (weirs and loggers) and nutrient content (nitrogen (N) and phosphorus (P) by standard laboratory methods)
- rainfall (recording gauge)
- dry matter at 8 and 12 weeks
- whole-plot grain yield (weighbridge and yield maps)
- grain (quality (protein and oil)).

Yield maps of each plot were also obtained from commercial harvesters.

Waterlogged and saline land

Capillary rise control

Modelling was undertaken to assess whether the soil and water management practices developed for raised beds on waterlogged land could be refined to reduce capillary rise from a shallow watertable on waterlogged and saline land. In particular, the effectiveness of loosening the soil in the upper root zone to simulate a mulch soil (ie a water-stable, loose seedbed) was studied. Such soil conditions have been shown by a number of workers to achieve a reduction in the salinity of surface soil (Benz et al 1967; Carter & Fanning 1964, 1965; Talsma 1963). The theory for the steady-state capillary rise of water from a shallow watertable (Philip 1957) was used, based on hydraulic conductivity characteristics computed using the method of Jackson (1972) and soil-water retention curves and hydraulic conductivity values determined on undisturbed core samples from a loam-over-clay field soil (Hamilton 1974).

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A range of contrasting surface and subsurface soil conditions was examined. These conditions included seedbeds of varying surface soil depths (10 cm and 30 cm) and densities (freshly cultivated, partially consolidated and fully consolidated) (Hamilton et al 2001). The loose and partially consolidated conditions were simulated by scaling the hydraulic characteristics according to bulk density and saturated hydraulic conductivity data obtained from soils in these conditions (Hamilton, unpublished data). The first application of this theoretically based soil management objective was in an ACIAR project in Pakistan (Project LWR 2/1998/131).

Leaching and sodicity control

To create and maintain near-permanent stable-structured PRBs an annual blade ploughing was instituted as an experimental treatment. The objective of this treatment was to capture (besides capillary rise control) the attributes of unsaturated soil-water flow, which (i) leaches salt from soil more efficiently than saturated flow (Nielsen et al 1965); (ii) reduces sodium exchange capacity (Mokady & Bresler 1968); and (iii) prevents dispersion in sodic soils (D.E. Smiles, pers comm).

Experimental design and treatments

Three large experimental areas were installed, each with four replicates of three treatments:

- a control – a normal seedbed, with no-tillage crop establishment
- no-till beds in which furrows are excavated and the soil in the 'beds' is left undisturbed, apart from the minimal amount caused by no-tillage crop establishment
- raised beds, with an annual blade ploughing and no-tillage crop establishment.

The data and methods used to monitor soil conditions and crop production are the same as those used for the waterlogging research, with the addition of regular monitoring of the salt content in the upper root zone by EC 1:5 soil:water samplings and electromagnetic induction (EM-38) surveys.

Results

Waterlogged land R&D

Seasonal conditions

Over the growing season (April to November) for the duration of this research project, rainfall was mostly well below long-term median values. The average annual median deficits for the five sites for 1997 to 2001 were: –52 mm (13%), –31 mm (8%), –9 mm (2%), –137 mm (34%), –80 mm (20%). There were some waterlogging events but there was no prolonged or frequent waterlogging at any site.

Waterlogging modelling

The waterlogging modelling revealed that:

- seasonal rainfall is the major determinant of waterlogging
- the depth of surface soil is the next most influential factor
- the texture of the surface soil exerts a third-order influence.

A criterion of daily frequency of waterlogging in July being > 50% was chosen to identify regions that were predisposed to waterlogging wherever shallow texture contrast soils were common. In combination with field surveys conducted to locate areas with this soil type, sites were selected for experimentation where both conditions were satisfied.

The modelling also allowed some assessment of the likely effectiveness of alternative soil management practices. For instance, soils with deeper topsoils (300 mm), which have a greater infiltration capacity, effectively mimicked soils that had been ripped. The frequency of waterlogging on these soils was shown to be only about 10% less than that on shallow soils. Therefore ripping, which increases infiltration capacity and delays the onset of waterlogging, was shown to provide only a minor and transient control, rather than prevention, of waterlogging.

Modelling the waterlogging process to estimate the frequency of its occurrence also showed, by implication, that the prevention of waterlogging could only be achieved by using shallow drains spaced closely enough to ensure that perched watertables would fall (Hamilton & Bakker 1998).

Drainage modelling

Using an arbitrary criterion of a maximum of 2 days for a perched watertable to drain from the upper root zone of soils and thus prevent waterlogging damage to plants, the drainage modelling (Figure 1) revealed that, for a soil with a saturated hydraulic conductivity of 30–50 mm/hour and a drainable porosity (aeration) of ≥ 5% by volume:

- the drain spacing could range between 1.5 m and 3.5 m
- the bed height could be up to 25 cm.

Bed dimensions

A number of factors were considered in choosing appropriate dimensions (spacing of 1.83 m centres, height of 25–30 cm) for the PRBs used in this research:

1. The drainage modelling showed that wherever the aeration and hydraulic properties of soils are good enough for the rapid drainage of perched watertables and the rapid aeration of soils, the spacing of drains is not critical. In other words, given appro-

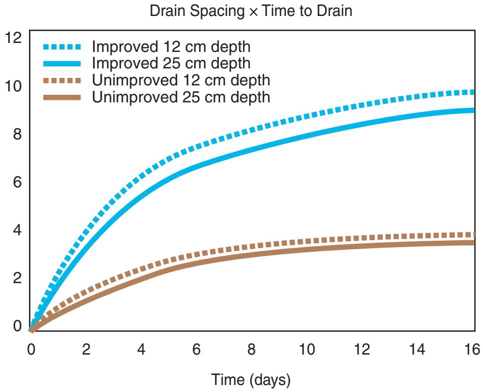

Figure 1. Time for perched water tables to drain 12 cm or 25 cm depths in improved and unimproved soil conditions. Improved soil had a hydraulic conductivity of 50 mm/hour, unimproved a value of 5 mm/hour. Note at 2 days' drainage time drain spacing for the improved soil is 3.5 m to 4.0 m.

priate soil conditions, bed width (or drain spacing) can be determined by other factors important to the practice of cropping, such as the trackwidth of machinery and the cost of adapting it to match the spacing between drains/furrows. After careful evaluation of the characteristics of commonly available cropping machinery and the cost of adapting it to match furrow spacings, a width of 1.83 m (6 feet) was chosen (Hamilton et al 2005, p 35).

2. Earlier research into the soil structure benefits of no-tillage crop establishment practice provided confidence that the hydraulic and aeration properties of soils required to prevent waterlogging could be created and maintained through the adoption of such practices. This research had shown that no-tillage practices increase soil organic matter (through the retention of roots and the biopores they create) and can, in consequence, improve the permeability and macroporosity properties of poorly structured soils by up to an order of magnitude (Hamilton et al 1984). Thus, no-tillage crop establishment was adopted as the standard soil management practice to create and maintain the soil conditions necessary to prevent waterlogging in beds with drains spaced at 1.83 m.
3. Consideration of a number of additional factors led to the choice of a bed height of between 25 cm and 30 cm. These factors included (a) the shallowness and contrasting texture and density of B-horizon soils in WA; (b) the productivity increases that result when crops are grown on deeper, loose seedbeds (or ripped soils); and (c) knowledge from the drainage modelling work that the greater amount of water that must drain from higher beds to prevent waterlogging would not substantially increase the time taken for a perched watertable to fall the extra distance.

Soil structure

Bulk density data revealed that an initial cultivation combined with drains at 1.83 m spacing and no-till crop establishment practices successfully created and maintained low density (high porosity) soil in the beds. The 0–10 cm and 10–20 cm bulk density data at the beginning and end of the project were, respectively: raised beds 1.38 g/cm^3 and 1.58 g/cm^3, and control seedbed 1.43 g/cm^3 and 1.72 g/cm^3 (Figure 2).

The saturated hydraulic conductivity data reflected the lower bulk density of the soil in raised beds. Geometric mean saturated hydraulic conductivity data was obtained from all sites (Figure 3). These data show about an order of magnitude, or more, increase in the saturated hydraulic conductivity of soil in the raised beds over that in the normal (control) seedbed.

Perched watertables

Trace data of continuously recorded perched watertable depths (Figure 4) show that in wet seasonal conditions when waterlogging was common, the perched watertable in the raised bed treatment did not rise much above the base of the beds, level with the floor of the furrows (ie a depth of 25 cm). In contrast, the perched watertable levels in the normal (control) seedbed frequently rose close to the surface and remained at this level for several days. Although the data in Figure 4 are from one site, this type of contrasting perched watertable behaviour between the treatments was reproduced at all experimental sites.

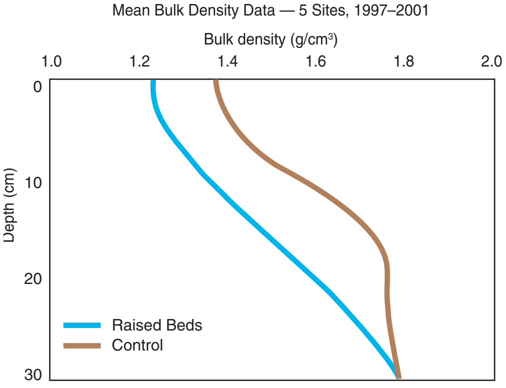

Figure 2. Mean bulk density profiles for the upper root zone in permanent raised beds and a normal seedbed. Mean data taken from PRB field experiments at five sites in Western Australia between 1997 and 2001.

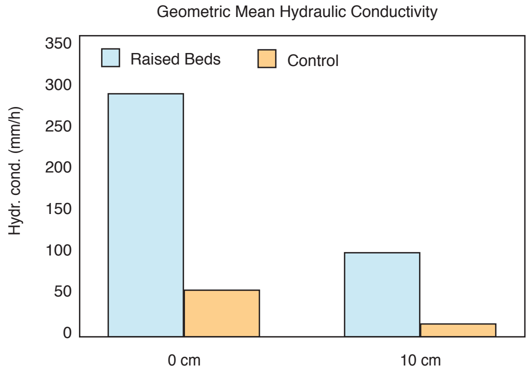

Figure 3. Geometric mean saturated hydraulic conductivity data for PRBs and a normal seedbed. Data collected from five field sites between 1997 and 2001. Note the approximate order of magnitude increase for both depths of sampling.

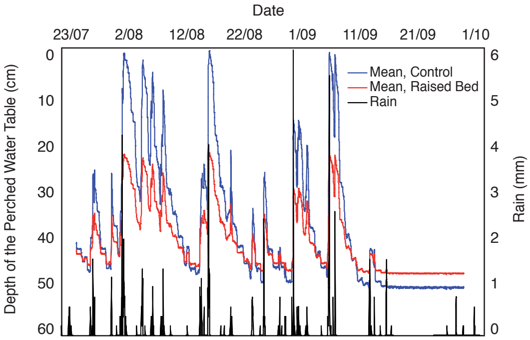

Figure 4. Traces of the depth to perched watertables in the root zones of crops grown on PRBs (blue line) and normal seedbeds (red line) at Cranbrook, Western Australia, in August 1999. Daily rainfall is shown as black columns.

Run-off

Run-off data showed that the raised beds shed 5–30 mm more water per growing season than normal seedbeds. In wet periods some of the extra water is drainage from the beds, and in dry periods run-off is generated by the compacted and impermeable floor of the furrows. Generally, because of their greater infiltration capacity, PRBs shed less water than normal seedbeds in large rainfall events.

Grain yield

The yield data summarised in Figure 5 are presented as averages for each of the crop types used over the spread of experimental sites. The data illustrates that improved soil conditions in raised beds generate productivity increases in all the common broadacre crop types in most if not all seasonal conditions. This result also illustrates the economic viability of applying a sound crop rotation. The average extra income (Table 1) generated by these crop-specific yield increases illustrates the level of additional income that can be produced by PRBs.

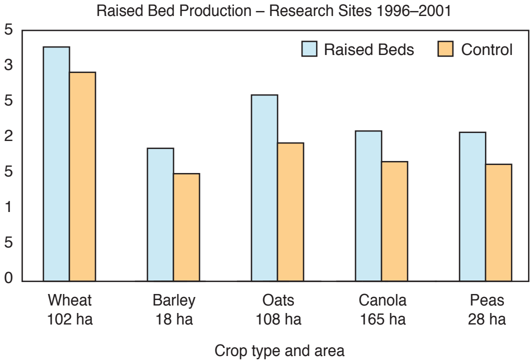

Figure 5. Mean grain yields for specific crops grown on PRBs and normal seedbeds on research sites between 1996 and 2001. The overall average yield increase was ~0.5 t/ha for all crop types. Data from the normal seedbeds would have been less had average seasonal rains fallen during the experimental period.

Significantly, these results were achieved in drier than normal seasons in WA (1997–2001), indicating that improved soil conditions increased plant water use, even in conditions where waterlogging was infrequent and not severe (Figure 6). In wetter seasons waterlogging would cause a greater reduction in yield from crop grown on a normal seedbed.

Waterlogged and saline land R&D

Capillary rise control

The capillary rise modelling results (Figures 7 and 8) illustrate that soils with a discontinuity in their hydraulic properties (as is produced by cultivation) have a vastly reduced ability to transmit capillary rise from watertables. In fact, in soils with a deep, loose and water-stable topsoil, watertables have to be very shallow (~20 cm) before this effect becomes insignificant.

Specifically, the data show that:

- Disturbed and consolidating topsoils reduce capillary rise.
- The deeper a loose topsoil, the greater the reduction in capillary rise.
- The different capillary rise properties of deep vs shallow topsoils persist until the watertable is less than about 20 cm deep.

In reality, the contrast between a loosened topsoil with many macropores and an undisturbed subsoil with few if any macropores will not be permanent,

Figure 6. Poorly productive wheat crop on a normal seedbed at Woodanilling, Western Australia, in 2000 (left). This plot is adjacent to a highly productive wheat crop grown on permanent raised beds (right).

or as significant as that illustrated by the modelled results. Wetting and drying and the weight of soil above the interface between topsoil and subsoil will cause subsidence and compaction of the base of the loosened soil. Furthermore, the degree of contrast will depend on the texture of the topsoil and its clay content and chemistry. Coarse, single-grained textures will relatively quickly establish a more compact transition zone, and clayey textured soils will also establish a transition zone depending on the stability of their structure to wetting. In consequence, there will be a need to regularly re-establish the contrasting pore size distributions by undertaking an operation to loosen the topsoil. This operation is probably best done annually (Figures 9 and 10).

Field evaluation

The crop yield data from the first three growing seasons of applying PRBs to waterlogged and saline sites (Table 2) have been collected under very variable rainfall conditions. In 2002 monthly rainfall was rarely greater than decile 2 amounts. In 2003 normal rains were received at Woodanilling and North Stirlings, but it remained dry at Cunderdin. In 2004 Woodanilling received normal rains, but Cunderdin and North Stirlings were drier than normal. The generally inadequate rainfalls have precluded substantial and measurable leaching in either bed treatment. Two factors which have an impact on the magnitude and interpretation of grain yield from the experimental treatments are the wide range and inconsistent distribution of salinity between the treatments and the general lack of major leaching rains.

Little conclusive information can be drawn from the yield data at this stage, except from sites where rains have been adequate for periods during the growing seasons (at Woodanilling and North Stirlings). At these sites the bedded treatments have yielded significantly better than the control treatment. However, these data require further analysis to adjust the harvested areas of individual plots for patches that recorded zero production because of high levels of salinity. The size of these highly saline patches varies seasonally in the bed treatments, depending on the wetness and drainage efficiency of the furrows. Also, across the three sites, which are spread over a north–south distance of ~ 350 km, differences in seasonal growing conditions make comparisons between

Table 1. Gross extra income generated by increased yields on permanent raised beds at research sites, 1996–2001.

Crop type	Yield increase (t/ha) & grain price ($/t)	Extra income ($/ha)
Wheat	0.38 t @ $180	68.40
Barley	0.50 t @ $160	80.00
Oats	0.52 t @ $110	57.20
Canola	0.21 t @ $350	73.50
Peas	0.26 t @ $155	40.30
Lupin	0.45 t @ $120	54.00
Average extra income ($/ha/yr)		**62.23**

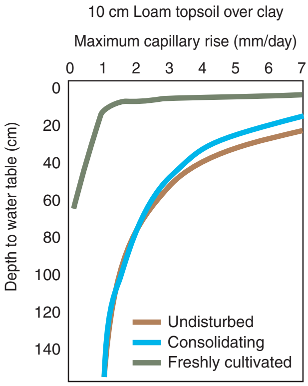

Figure 7. Maximum capillary rise from a shallow watertable through a compact subsoil and a shallow topsoil in undisturbed (red line), consolidating (brown line) and freshly cultivated (green line) condition.

sites impossible. The Cunderdin site has been substantially drier than the other two sites.

Salinity

Spatially referenced EM-38 surveys undertaken each year show small reductions in the salt content of the surface 0.8 m depth of soil in both bedded treatments. Figures 11 and 12 are graphs of the proportional plot areas of land in normal (control) seedbed and PRB treatments at the North Stirlings site in WA. The solid (2002) and dashed (2003) lines illustrate changes in salinity in each of the four replicates of these treatments in these years. The movement of these curves to the left in 2003 indicates a reduction in salinity, which appears to be greater in the raised bed treatment than in the control treatment. Note that such movement seems, at this stage, to have been influenced more by the seasonal rainfall than the soil management treatments.

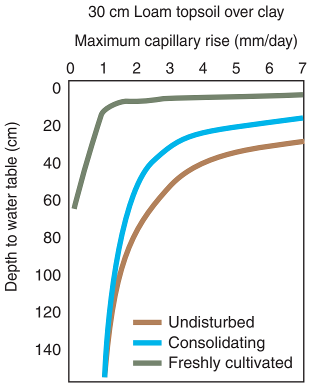

Figure 8. Maximum capillary rise from a shallow watertable through a compact subsoil and a deep (30 cm) topsoil in undisturbed (red line), consolidating (brown line) and freshly cultivated (green line) condition.

Farmer adoption of raised beds on waterlogged land

Adoption of raised bed technology has been rapid on farms that suffer frequent waterlogging over significant proportions of their cropping area. Raised bed farming was estimated at the end of 2001 to cover about 30,000 ha in WA. Since then, while no additional surveys have been done, the area has increased gradually to be currently about 35,000 ha. Most of this adoption is along the south coast of WA. Surveys between 1999 and 2001 revealed that increases in yields from farmers' raised beds relative to untreated areas were larger than yield increases obtained on the

Figure 9. Machine used to renovate PRBs. Blades pass through the base of the PRBs level with the base of the furrows, causing zero soil inversion.

Figure 10. View of renovated beds at Woodanilling, Western Australia. Note the lack of visible disturbance and retention of the previous crop's stubble.

Table 2. Preliminary yield data over the experimental period 2002–04.

Details	Cunderdin			Woodanilling			North Stirlings		
	Control	No-till beds	Raised beds	Control	No-till beds	Raised beds	Control	No-till beds	Raised beds
2002–04 crops	Barley	Wheat	Wheat	Barley	Canola	Wheat	Barley	Canola	Wheat
2002–04 average yield (t/ha)	1.17	1.10	1.15	0.85	1.51	1.51	1.86	2.12	2.18
Percentage of control		–6%	–2%		+78%	+78%		+14%	+17%

research sites (Figure 13). The farmer data show an average yield increase of 0.85 t/ha, which, in terms of 2001 grain prices, equates to extra income of $184/ha/yr. Most of this extra income is additional profit because yields from normal seedbeds produced a positive gross margin return.

Discussion

The challenge of assessing the theoretical and practical feasibility of raised bed farming technology to prevent waterlogging has been successfully met. This modelling of the waterlogging and drainage processes identified the environmental conditions that increase waterlogging risk, and also the soil properties and engineering works required to drain and aerate the upper root zone of soils. The application of sound soil management practices, which also resulted in the complete removal of traffic from seedbeds, created and maintained the improved infiltration, drainage and aeration properties needed to prevent waterlogging and increase productivity.

Two factors have facilitated the coincident development and adoption of this technology. The first was theoretical modelling, which identified the best of a range of potential treatments and simplified field experimentation. The second was the existence of commercial farm machinery in the irrigation industry that could be used immediately for extensive dryland farming operations. Both combined to allow field experimentation to be done on a scale useful for farmers.

Raised bed technology has the advantage of being robust enough to succeed for first-time adopters, to produce significant yield improvements in drier than normal seasonal conditions, and to appeal as a highly profitable investment where large areas require treatment. Investment analyses based on the following factors produced internal rates of return of 20–106% over 10 years:

- the average yield increases achieved by the research sites and farmers (see Figures 5 and 10)
- $50,000 loans at 10% interest to cover the cost of bed-forming machinery and wheel track adjustments to existing farm machinery
- a range of incremental expansion in the area installed with raised beds up to a maximum of 1,000 ha.

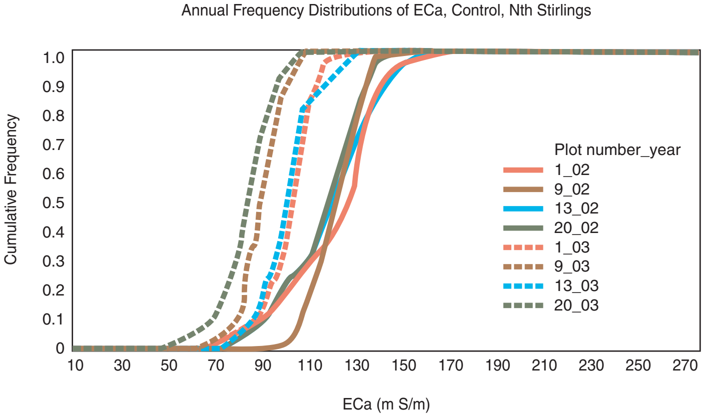

Figure 11. Spatially referenced EM-38 data of apparent electrical conductivity of the surface ~0.8 m depth of soil in the control (normal seedbed) treatment at a North Stirlings research site in Western Australia. Data are expressed as cumulative frequency of pixels (ie proportional plot area) with salinity less than the next lowest value. Note the reduction in salinity from 2002 (solid lines) to 2003 (dashed lines), and that this reduction is less than in the PRB treatment (Figure 12).

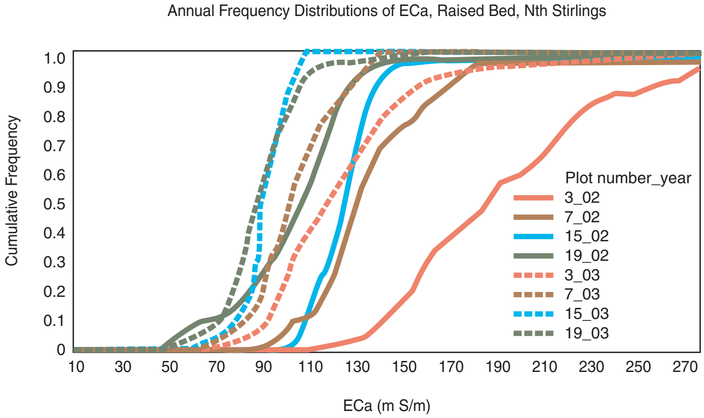

Figure 12. Spatially referenced EM-38 data of apparent electrical conductivity of the surface ~0.8 m depth of soil in a permanent raised bed (PRB) treatment at a North Stirlings research site in Western Australia. Data are expressed as cumulative frequency of pixels (ie proportional plot area) with salinity less than the next lowest value. Note the reduction in salinity from 2002 (solid lines) to 2003 (dashed lines), and that this reduction is larger than in the control treatment (Figure 11).

Working with commercial sized machinery and machinery manufacturers has been mutually beneficial. Soil-specific design requirements and insights in combination with manufacturing expertise and experience have produced small but important changes to implements that have improved machinery performance.

The application and adaptation of raised bed technology for waterlogged and saline land is clearly in its infancy. However, this experience with waterlogged sites, plus the 2002–04 results, provide confidence and optimism that large tracts of this type of degrading land may be able to be reclaimed to profitable agriculture by the application of this technology.

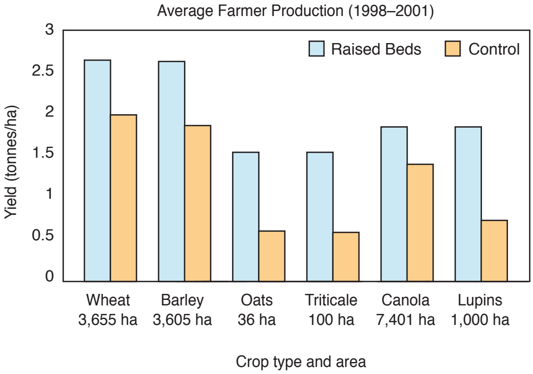

Figure 13. Mean grain yields for specific crops grown on PRBs and normal seedbeds by farmers between 1996 and 2001. The overall average yield increase was ~0.85 t/ha for all crop types. Data are mostly from the Esperance district between 1998 and 2001, during which time waterlogging of the normal seedbeds was reasonably common.

Conclusions

Permanent raised bed technology is an effective and profitable form of farming that prevents winter waterlogging in rainfed cropping areas. Its application to waterlogged and saline land seems to offer a reasonable prospect of success.

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The potential for permanent raised beds in sugarcane cropping systems in Australia

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Abstract

Sugarcane cropping systems in Australia have long been exploitative of resources, being largely based on a monoculture and with excessive tillage and heavy machinery causing severe soil compaction. Research carried out in Queensland by the Sugar Yield Decline Joint Venture over the past decade has clearly shown there is a need to develop a more profitable, sustainable and environmentally responsible cropping system. The impetus to adopt a raised bed system has come from the need to accommodate a move to controlled traffic farming to reduce the level of compaction by heavy harvester and haul-out equipment and the amount of tillage required to alleviate that compaction between crop cycles. However, there are numerous other potential benefits for the Australian sugar industry from adopting a permanent raised bed system. In this review the background to the development of permanent raised beds in sugarcane cropping systems is discussed and potential benefits and problems are identified. It is concluded that permanent raised beds are likely to become an integral part of sugarcane cropping systems.

Introduction

The development of permanent raised beds in sugarcane cropping systems is in its infancy. The traditional sugarcane farming system has been very exploitative of soil resources; heavily dependent on chemicals, tillage and horsepower; and a major user of fossil fuels, both directly and through large inputs of inorganic fertiliser. Over the years high world market prices for sugar have adequately accommodated high costs of production, and the industry has developed an intensive monoculture system. However, declining prices and yields in more recent times have caused the industry to seriously question its production methods. The Sugar Yield Decline Joint Venture (SYDJV) was established in 1993 to research the cause of a productivity plateau that has existed since 1970 (Garside 1997a; SRDC 1995, 2004). The outcomes of early research conducted by the SYDJV clearly showed that there were many deficiencies in the established sugarcane cropping system. A range of degraded soil properties were identified in areas where sugarcane had been grown as a monoculture for extended periods of time (Garside et al 1996, 1997b).

This review discusses the deficiencies in the traditional sugarcane cropping system and their causes, and suggests that the past approach of tackling those deficiencies in isolation is unlikely to result in improvements that will overcome yield decline. Means to overcome deficiencies are defined within the context of a farming systems approach. A new sugarcane cropping system that will deliver profitability, sustainability and environmental responsibility is proposed based on minimum tillage, controlled traffic and legume breaks to the monoculture. Permanent raised beds have an important role to play in facilitating the practical adaptation and utility of this new cropping system.

Problems with the traditional sugarcane cropping system

Initial studies within the SYDJV involved the evaluation of paired old (at least 20 years under sugarcane in a burnt cane system) and new (virgin land or first year under sugarcane) land sites to identify differences in soil properties. Essentially, the results showed that old sugarcane land was degraded in chemical (Bramley et al 1996; Skjemstad et al 1995), physical (Ford & Bristow 1995a,b) and biological (Holt & Mayer 1998; Pankhurst et al 1996; Magarey et al 1997) properties, although soil property differences varied between sites in accordance with soil type, climate and management. Further, cane yields were lower on old land (Garside & Nable 1996; Garside et al 1997b).

Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico
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The main soil property factors varying between old and new land were summarised by Garside et al (1997b). These factors included old land being more acid, having lower levels of organic carbon, lower cation exchange capacity, more exchangeable aluminium, lower levels of copper and zinc, more plant parasitic nematodes, more root pathogens, less microbial biomass, greater soil strength (ie more compacted) and lower water infiltration rate and storage capacity. The number and diversity of factors that indicated degraded soil properties in long-term sugarcane land clearly suggested that, overall, soil degradation was the cause of yield decline, and the problem was complex and would not be overcome unless all the factors were addressed to some extent. The likelihood of making major gains by tackling these properties individually, as had traditionally been done in the sugar industry, was daunting and unlikely to provide practical solutions.

The approach taken by the SYDJV was to investigate how the system might be improved in a practical way, and in so doing have a positive effect on degraded soil properties. It was decided that if:

- the monoculture could be broken (by using rotations or break species)
- excessive tillage was reduced for plant cane establishment (with minimum/zero tillage) and
- heavy traffic (ie harvesters, haul-out) was isolated from cropping rows, thus reducing compaction (ie controlled traffic),

there would be a good chance of improving the cropping system. Initially, experiments in these three areas were carried out separately. When the SYDJV commenced in 1993, a harvesting system (GCTB) based on green cane and trash retention was being adopted, so much of the research carried out by the SYDJV was in a GCTB system. The virtues of GCTB have been thoroughly discussed by Wood (1985, 1986, 1991).

Breaking the monoculture

Rotation experiments aimed at breaking the monoculture and measuring the effect on sugarcane growth and yield were initiated by the SYDJV in 1993 and 1994. Large yield improvements (20–30%) in sugarcane were recorded from breaking the monoculture with legume crops such as soybeans, pasture and bare fallow (Garside et al 1999, 2000a, 2001, 2002a). These yield increases were associated with improvements in chemical (Moody et al 1999), physical (Braunack et al 2003) and biological (Pankhurst et al 1999, 2000, 2003; Stirling et al 1996, 1999, 2001) soil properties, particularly the latter. Based on the results of these rotation experiments, there has been a substantial increase in the area planted to well managed legume crops in the sugar industry. Traditional legume fallows were poorly managed cowpea crops that suffered from poor establishment, severe weed competition, waterlogging and root diseases (Croft 1988; Garside et al 1996). Legumes provide both a source of fixed nitrogen (a good soybean crop negating the need for any inorganic nitrogen fertiliser in the plant crop) and improvements in soil health (Garside et al 1996, 1997c, 1998; Garside & Bell 2001; Noble & Garside 2000). These nitrogen benefits can be maximised if the legume is surface mulched or left as standing residue (as opposed to traditional incorporation) as the nitrogen is mineralised more slowly and thus more is available when needed by the following sugarcane crop (Bell et al 2003; Garside & Berthelsen 2004; Garside et al 1997c; Noble & Garside 2000). Surface mulching or standing residue fits ideally into a permanent raised bed system.

Minimum/zero tillage and controlled traffic

The SYDJV also researched minimum tillage and controlled traffic because compaction resulting from heavy traffic associated with harvester and haul-out machinery was recognised as a substantial problem (Braunack 1998; Braunack & McGarry 1998; Braunack & Peatey 1999; Braunack et al 1999; Garside et al 2000c). Experiments compared zero tillage with numerous passes, as in the traditional system. No yield losses were recorded with zero tillage provided a fallow was included (Braunack et al 1999; Garside et al 2000c), and substantial cost savings in terms of labour, tractor hours and fuel were produced (Willcox et al 2000). In addition, improvements in physical and biological soil properties were measured (Braunack & Magarey 2002). In other studies the effect of controlled traffic in terms of isolating crop and traffic rows resulted in a number of advantages, including substantial reductions in soil compaction (Bell et al 2001; Braunack & Hurney 2000; Braunack & Peaty 1999).

A major problem with compaction in the sugarcane cropping system has resulted from mismatched row and wheel spacings. Traditionally the sugarcane crop has been grown on 1.5 m rows whereas harvesting and haul-out equipment has wheel spacings of 1.8–1.9 m. With this combination and less than fastidious operators, wheel encroachment on cropped areas causes soil compaction and yield losses from later ratoons, and is largely unavoidable (Bull et al 2001; Norris et al 2000; Robotham 2003). The adverse effects are more pronounced under wet harvesting conditions (Garside 2004). The perseverance with 1.5 m spacing has been based on a perception that yields will be reduced if row spacing is widened. However, recent row spacing and plant density studies have shown that sugarcane possesses a degree of environmental plasticity, and that it is possible to adopt row spacing to match wheel spacing without loss of yield and thus allow controlled traffic to be implemented (Garside et al 2002b; Garside et al 2004; Robotham & Garside 2004). In recent studies dual rows on 1.85 m spacing have been shown to yield as well as 1.5 m single rows (A.L. Garside and B.G. Robotham, unpublished data).

Using permanent raised beds to incorporate components into the sugarcane cropping system

The traditional sugarcane system is based around tillage to both remove the old cane plants and reduce compaction from previous heavy traffic (harvesters and haul-outs). The land is then left bare, as a weedy fallow, or further tilled to provide a seedbed for legume establishment. Legumes are grown through to flowering and incorporated as green manures, followed by numerous passes to provide a fine seedbed for cane planting with a double mouldboard opener.

Each of the three components, namely legume breaks, minimum tillage and controlled traffic, has been demonstrated to improve sugarcane yields and/or reduce the cost of production. However, substantial benefits are likely to accrue if they can be collectively incorporated into a sugarcane cropping system. The SYDJV program is now dedicating much of its time to developing such a system, based around permanent raised beds on row spacings compatible with the wheel spacings of the heaviest equipment (harvesters and haul-outs) to avoid stool damage and minimise compaction near the cane row. The appropriate spacing at present is 1.8–1.9 m but it is entirely dependent on matching row and wheel spacings. Minimum tillage or direct planting is being combined with controlled traffic on permanent raised beds (Robotham 2003) to provide permanent traffic lanes, avoid waterlogging, reduce operational costs, minimise damage to soil physical properties, minimise adverse effects on soil biota, conserve organic matter and improve timeliness of operations. Legume rotations are included to break the monoculture and provide a different root system to sugarcane, manage root pathogens, and provide a source of biologically fixed nitrogen. Both cane and legumes are being direct planted into these permanent raised beds. Further, by using minimum/zero tillage, cane trash can be conserved between cane cycles, thus further improving soil organic matter, soil physical properties and water holding capacity.

The approach taken to developing permanent raised beds in the sugarcane cropping system has been based around substantial soil disturbance to form the beds at the end of a cane cycle. These formed beds are then sown to a legume which is grown through to mid-pod fill or crop maturity and then harvested for grain and/or mulched on the bed surface, with care taken to maintain the integrity of the beds. The bed surface is then tilled and/or not tilled before planting to sugarcane with a double-disc opener planter that has been specifically developed to provide minimal soil disturbance.

The changes proposed to the cropping system are being supported by the development of appropriate equipment, such as bed-formers and double-disc opener no-tillage planters, and appropriate harvester modifications to suit dual rows and match row spacing and wheel tracks (Norris et al 2000; Robotham 2000a,b). Machinery is available to direct plant legumes into sugarcane residue. A specific focus of the machinery development program has been to keep initial machinery changes to a minimum, thus minimising capital investment and facilitating adoption. Indications from cane growers who have made the change are that the costs are insignificant, and that adopting the proposed system opens the possibility of substantial machinery savings through downsizing tractors and disposing of redundant tillage equipment.

Cane and sugar yield in raised bed experiments

The first experiment comparing raised beds involving zero tillage with conventional tillage in a sugarcane cropping system was conducted at Bundaberg (Bell et al 2003). It was concluded that raised beds and no tillage enhanced earthworm activity, resulting in increased water infiltration and consequent raised sugarcane yields.

The results of large-scale experiments established to integrate the components (legume breaks, minimum/zero tillage, controlled traffic) into a cropping system are just starting to emerge. They are showing that the proposed system is feasible and has no major impediments, although yield increases have not been consistently recorded at this stage (Table 1) except for the response to legume breaks discussed above. Substantial cost savings associated with legume breaks removing the need for N fertiliser on plant crops, and lower costs in establishing sugarcane with minimum tillage/direct planting on permanent raised beds, are definite advantages (Table 2)

Table 1. Cane and sugar yields from experiments comparing permanent raised beds with a conventional sugarcane system.

Site	Crop Class	Conventional		Raised beds		Level of significance a = cane b = sugar
		Cane yield (t/ha)	Sugar yield (t/ha)	Cane yield (t/ha)	Sugar yield (t/ha)	
Gordonvale	Plant	102	12.17	95	11.47	*a=nsd* *b=nsd*
	First ratoon	119	15.48	116	14.95	*a=nsd* *b=nsd*
Ingham	Plant	84	–	80	–	*a=nsd*
	First ratoon	127	15.18	113	14.41	*a=nsd* *b=nsd*
Mackay	Plant	120	14.23	107	15.95	*a=nsd* *b=nsd*
Bundaberg	Plant	101	13.80	119	16.90	*(a) p<0.05, lsd =14* *(b) p<0.05, lsd=1.66*

PRB is dual rows on 1.8 m beds; conventional is single 1.5 m row

(Bell et al 2003; Garside 2002; Garside et al 2004, 2005). More benefits are expected to emerge in later ratoons as the effects of controlled traffic isolating crop and traffic areas are realised. Unfortunately, during the period when these experiments were conducted, rainfall conditions well below average were recorded throughout the sugarcane growing regions. Harvesting has therefore been carried out under conditions least conducive to stool damage and compaction, and expected damage with resultant poor ratoon yields under the conventional 1.5 m spacing system has not occurred (Garside 2004).

Potential benefits of using permanent raised beds

The enhanced cropping system being promoted is still in its development phase. However, enough confidence is being shown for many sugarcane growers in Australia to adopt at least parts of the system, while a small number are embracing the whole system. The system is based upon the basic agronomic principles that organic matter is the key to healthy soil; monocultures are undesirable; compaction should be avoided as much as possible; and excessive tillage destroys organic matter, soil structure and soil biota, and is very costly.

The benefits that can be envisaged by adopting such a system include the following.

Legume breaks

Rotation provides a better-balanced biology, controls root pathogens, biologically fixes nitrogen and greatly reduces the need for nitrogen fertiliser, and improves cane growth and yield.

Isolation of traffic and crop areas

Matching wheel and row spacing and using permanent raised beds can guide harvester and haul-out tracking and thus reduce the impact of compaction.

Table 2. Cost of growing and gross margin for a plant crop of sugarcane under a conventional production system and a raised beds system.

System	Cane yield (t/ha)	Cost ($/ha)	Cost relative to conventional	Gross margin ($/ha)
Conventional	102	1116	–	–5
PRB	95	864	–252	105

Data from Gordonvale experiment

Minimum/zero tillage

This method conserves organic matter, improves soil structure, doesn't disrupt beneficial soil biota, and reduces run-off and erosion.

Permanent raised beds

- eliminate the need to till to remove compaction from the cropping zone
- reduce the impact of waterlogging through improved surface drainage
- with compacted inter-rows, improve the timeliness of operations by allowing earlier access onto wet soils.

Fuel and labour costs

The combination of compacted inter-rows and minimum tillage provides savings in fuel and labour.

Weed management

There are indications that weeds will become less of a problem and herbicide use will be reduced with continual trash cover and non-disturbance of the soil surface.

Potential problems of using permanent raised beds

Very few problems have been encountered to this stage and few are expected to develop in the short term. However, in the long term the maintenance of effective permanent raised beds will be dependent on a number of issues.

Slower crop emergence

Direct planting of sugarcane with a double-disc opener planter has resulted in slower sugarcane establishment due to lower soil temperatures in the immediate vicinity of the sugarcane sett. This appears to be because the narrow slot in the double-disc opener does not expose as much of the soil around the sett to radiation as the double mouldboard. This is not regarded as a serious problem as final stalk numbers and ultimate yield are not affected.

Stool tipping

Stool tipping has been raised as a major concern and some evidence is emerging that it can be a problem in some situations, depending on growing conditions, soil type and variety. In a traditional sugarcane farming system the cane sett is eventually located some 20–30 cm below the soil surface following several soil moundings around the developing plant. With direct planting into permanent beds, as the cane grows the sett remains where it was placed, normally around 10 cm below the soil surface. Under some circumstances the closeness of the developing root system to the soil surface can result in the stool tipping out of the ground. However, there is considerable conjecture as to whether this is due to shallow planting depth or degraded soil structure and soil compaction, attacks on root systems by pests and diseases, and varieties that have been bred for tops biomass at the expense of root development. Work is underway to better understand this issue.

Bed maintenance

It is unsure at this early stage how much maintenance beds will require to maintain their integrity and whether they will need to be heavily renovated on a regular basis. If the latter, the benefits will surely be reduced. However, it is not expected that bed maintenance will be a major issue; if at all, it is more likely to be so on sandier soils with weaker soil structure.

Nutrient stratification

Concerns have been raised about the availability of non-mobile elements such as potassium and, particularly, phosphorus in permanent raised beds and whether they may remain near the surface and not be mixed with the bulk soil. However, there is a high likelihood that the observed increase in earthworm populations under zero tillage will partly compensate for nutrient layering because of increased bioturbation.

Acidity management

Many sugarcane growing regions on the Queensland coast are on acid soils deficient in calcium and magnesium. In addition, acidity is promoted by the application of high rates of nitrogen fertiliser. The regular addition of lime and calcium/magnesium mixes is practised between cane cycles, their effectiveness being dependent on thorough mixing through cultivation. Permanent beds could present a problem for lime incorporation as the extent of cultivation is greatly reduced. Whether periodic destruction of the permanent beds for lime maintenance purposes will be required is as yet unknown but should be expected. However, work on zero tillage in Brazil has indicated that in humid climates, surface applied lime may eventually leach into the root zone. Also, the expected increase in earthworm activity with permanent raised beds may lead to the incorporation of lime.

Soil erosion

The use of permanent beds in conjunction with controlled traffic and minimum tillage is often promoted as a means of erosion control. However, on sloping lands and light textured soils under heavy monsoonal rainfall, the compacted inter-rows could well act as preferred pathways for excess run-off and be heavily eroded. There is no evidence of this occurring at this stage but it requires careful monitoring.

Compacted inter-rows creating barriers between beds

Whether this will be an issue in long-term permanent beds is again unknown, but certainly with a sugarcane cropping system compacted inter-rows will occur every 1.8–2.0 m and this compaction could eventually impinge on the crop growing area. It requires careful monitoring.

Furrow irrigation in poorly structured soils

To comply with controlled traffic requirements, minimum row spacings will need to be 1.8 m, and there will be situations, particularly in long-term sugarcane land where soil is degraded, where lateral water movement will not be sufficient to fully irrigate the beds. Some growers in these situations are moving to 2 m beds, establishing dual rows 800 mm apart and including a non-trafficked furrow between the dual rows to facilitate irrigation. Although this practice appears to be working, it raises other considerations such as mismatched wheel and row spacing because no standard equipment (harvesters, haul-outs) has 2 m spacings. Alternatively, the issue of insufficient lateral water movement with beds of 1.8 m or greater may be overcome by establishing trickle irrigation lines in the permanent beds. This has not been evaluated at this stage.

Conclusions

Early development work in Australia on permanent raised beds is discussed by Borrell and Garside in these proceedings. Recent work in sugarcane cropping systems has followed a similar path in that permanent raised beds have not been a primary focus but, rather, have provided a means by which a more sustainable sugarcane farming system can be developed. The research to date has resulted in a very positive outlook for the future of permanent raised beds in the sugarcane cropping system. Early results from comparing sugarcane grown on permanent raised beds with that grown in the traditional way with full cultivation are indicating similar cane yields but substantially reduced costs of production. It seems very likely that permanent raised beds will become an integral part of the sugarcane cropping system as the benefits appear to clearly outweigh the problems.

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Permanent beds in Australian cotton production systems

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Abstract

'Permanent' raised beds, which preserve the same wheel tracks and remain in place for several seasons before renovation or realignment requires them to be ploughed down and reconstructed, are widely used in Australian cotton production systems. Benefits include better soil physical and chemical quality and lower costs than full tillage each year. Yields are not necessarily higher but reduced costs give greater returns. Higher yields and further improvements in overall soil quality can be achieved by using suitable rotation crops such as wheat (*Triticum aestivum* L.) and by planting cotton into retained crop stubble. Problems associated with managing permanent beds in cotton production systems include:

- beds shifting over compacted furrows with time
- managing both wheat and cotton stubble to optimise water flow during irrigation
- applying anhydrous ammonia through crop stubble
- excessive tillage during compulsory post-harvest bed cultivation for heliothis (*Helicoverpa* spp.) pupae control.

These problems can, however, be overcome by using appropriate machinery and agronomic management practices.

Australian cotton production systems — geography, climate, soils, farming systems

Major Australian commercial cotton (*Gossypium hirsutum* L.) production areas in New South Wales and Queensland are located between Emerald (23.53S, 148.18E), which is west of Rockhampton in central Queensland, to Hay (34.31S, 144.31E) in central New South Wales (NSW) and in the Murrumbidgee valley in southern NSW (Figure 1). Climatically, they range from the summer-dominant rainfall regions of the subtropics in Queensland to the winter-dominant rainfall regions in southern NSW.

Under normal rainfall, approximately 80% of Australian cotton is irrigated. The major areas under irrigation include the Gwydir, Namoi, Macquarie and Lachlan Valleys of NSW; and the St George, Darling Downs, Theodore–Biloela and Emerald districts of Queensland (McKenzie et al 2003). The most widely used method of irrigation is furrow irrigation (>94%) with smaller areas being grown with drip (4%) and sprinkler (<2%) irrigation systems (Raine & Foley 2002). The major soil types on which cotton is grown are grey, brown and black Vertisols (~75%) and Alfisols (15%) (McKenzie et al 2003; Table 1).

Cropping systems under which irrigated cotton is grown can be broadly classified into three groups: cotton monoculture, where cotton is sown in the same field every year indefinitely; long-fallow cotton, where cotton alternates with a bare fallow; and cotton-rotation crop sequences, where cotton alternates with either summer or winter rotation crops (Cooper 1999). Wheat (*Triticum aestivum* L.) is the most frequently sown rotation crop, with about 75–80% of cotton growers sowing wheat either in a 1:1 or 2:1 cotton–wheat rotation (Cooper, 1999; Hickman et al 1998). Other crops sown in rotation with cotton include corn (*Zea mays* L.), sorghum (*Sorghum bicolor* Moench.), faba bean (*Vicia faba* L.), chickpea (*Cicer arietinum* L.), soybean (*Glycine max* L.) and, more recently, woolly pod vetch (*Vicia villosa* Roth.) (Cooper 1999; Hickman et al 1998; Rochester & Peoples 2004). Rainfed cotton is grown as part of an opportunity cropping farming system where the specific crop sown is dependent on the amount of rainfall received and soil moisture stored (Marshall 1998).

Land preparation methods used in cotton production range from intensive tillage (deep ripping, discing, chiselling and bed reconstruction every year)

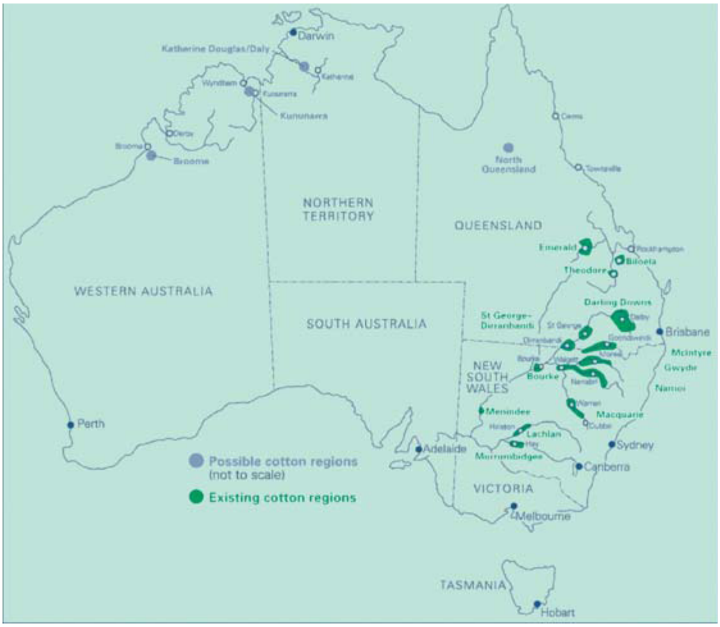

Figure 1. Cotton regions in Australia and areas where cotton could potentially be grown.

Table 1. Areas of cotton and major soil types in the cotton growing locations of New South Wales during the 1998–99 season (McKenzie et al 2003).

Locality	Area (ha)	Major soil types	Approx % cotton on soil type	Soil parent material
Gwydir Valley	112 000	Grey and brown Vertosols (Vertisols)	80	Alluvial plains of mixed origin
		Chromosols, Sodosols (Alfisols, Aridisols)	10	Slightly elevated ridges in clay plains
		Dermosols (Mollisols)	10	Recent alluvium
Namoi Valley	63 350	Grey and brown Vertosols (Vertisols)	90	Alluvial plains of mixed origin
		Chromosols, Sodosols (Alfisols, Aridisols)	10	Slightly elevated ridges in clay plains
Macquarie Valley	50 000	Grey and brown Vertosols (Vertisols)	60	Alluvial plains of mixed origin; less basaltic influence than Namoi
		Chromosols, Sodosols (Alfisols, Aridisols)	30	Slightly elevated ridges in clay plains
		Dermosols	10	Recent alluvium
Macintyre Valley	42 000	Vertosols (Vertisols)	100	Alluvial plains of mixed origin
Bourke	14 750	Grey and brown Vertosols (Vertisols)	100	Flood plain of the Darling River
Walgett	15 000	Grey Vertosols (Vertisols)	100	Flood plain of the Barwon/Darling Rivers
Liverpool Plains	40 750	Black and grey Vertosols (Vertisols)	100	Alluvial plains of basaltic origin
Lake Tandou	5 750	Grey Vertosols (Vertisols)	100	Alluvial plains of mixed origin
Lachlan Valley	5 250	Grey Vertosols (Vertisols)	100	Alluvial plains of mixed origin
MIA	200	Grey Vertosols (Vertisols)	100	Alluvial plains of mixed origin

Notes:
USDA's Soil Taxonomy (Soil Survey Staff 2003) approximate equivalent is given in parentheses.
MIA = Murrumbidgee irrigation area.

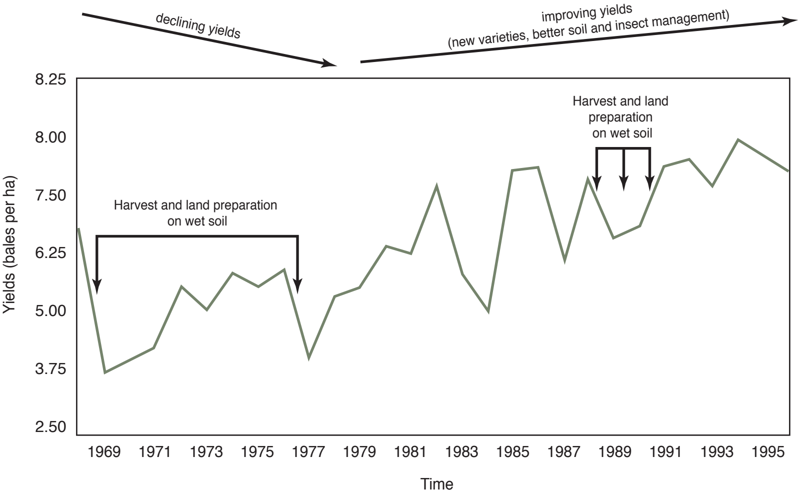

Figure 2. History of cotton lint yields and their association with soil conditions in the Macquarie Valley between 1968 and 1999. The poor yields in 1984 and 1999 were caused by cool, wet conditions (McKenzie et al 2003).

through minimum tillage or permanent beds in irrigated systems (McKenzie 1998; Schoenfisch 1999) to zero and minimum tillage systems in rainfed systems (Marshall 1998; Schoenfisch 1999). Tillage implements and machinery used for land preparation in cotton production systems have been reviewed by Schoenfisch (1999). Spacings of 'permanent beds' are commonly either 1 m (also referred to as retained hills) or 2 m ('broad beds') (Cooper 1999).

Properties of permanent beds

By definition, a permanent bed implies that the bed stays in place for several seasons, in comparison with being ploughed down and reconstructed every year as with more intensive tillage systems (Cooper 1999; McGarry 1995; McKenzie 1998). The term permanent bed does not, however, imply that all bed disturbance is totally excluded. Some pre-sowing light cultivation may be necessary to renovate or reshape beds. Bed disturbance is also necessary to destroy heliothis (*Helicoverpa* spp.) pupae (McKenzie 1998; Rourke 2002). Mechanical disturbance of beds facilitates entry of parasitic wasps and other predators of heliothis pupae into the moths' pupating chambers, thereby greatly reducing the numbers of adult moths which emerge in early spring.

Permanent beds were first introduced in the mid 1980s after yield declines occurred in the Australian cotton industry due to causes related to soil structure (McGarry 1995; McKenzie 1998; McKenzie et al 2003; Figure 2). Surveys conducted during the early 1990s indicated that approximately 80–90% of Australian cotton growers used some form of permanent beds (Cooper 1999; McGarry 1995), although with the current industry-wide recommendation of compulsory post-harvest tillage for heliothis moth pupae control (Rourke 2002), numbers may have fallen since then.

The definition of 'permanent' depends on the individual cotton grower (Cooper 1999; McGarry 1995). Usually it involves ploughing in the beds once every 2–7 years (Cooper 1999; McGarry 1989–90, 1995), although experiments where beds have been retained for 18 years have been reported (Hulugalle et al 2004a, 2005). Cooper (1999) notes, however, that more cotton growers use permanent beds because of reduced production costs (72% of growers) than for improved soil physical condition (49% of growers). Improved soil working conditions were cited by 22% of cotton growers surveyed as a reason for adoption of permanent beds, and 8% stated that it was due to yield increases. Among the growers who used permanent beds, 44% stated that they had few or no management problems. The survey also indicated that some cotton growers had problems such as difficulties with trash management (24% of growers), inability to keep rows straight (16% of growers) and insect, weed and disease-related issues (14% of growers) when using permanent beds (Cooper 1999). Since this survey was conducted (1991–92), solutions have been provided to problems with respect to trash and weed management, and vehicle guidance (eg the Beeline^{TM} tractor guidance system[1]) (Hulugalle et al 2004b, 2005; McKenzie 1998; Schoenfisch 1999; Tullberg et al 2003; Weaver et al 2000).

The process of ploughing down the beds, in combination with effects from the associated vehicular traffic, leads to increased rates of soil structural degradation, particularly in wet or moist soil. It can result in high compaction rates, reduction in drainage pores and pore continuity, and poor aggregate stability (Constable et al 1992; Daniells 1989; Hulme 1987; Hulugalle & Entwistle 1997; Hulugalle et al 1997a, 2005; McGarry 1995; McGarry & Daniells 1987; McKenzie 1998; Figure 3). Structural degradation related to 'wet' tillage in any given depth appears to be associated with an increase in the zones of striated clay. McGarry (1989) has suggested causes such as shearing of soil in a plastic state by tillage implements and tractor wheels. Associated yield losses can be high. McGarry (1995) reports yield and growth losses between 20% and 50%. Better soil structure and existence of higher numbers of drainage pores result in better drainage and salt leaching, and more plant-available water under permanent beds (Hulugalle et al 2004a; Tennakoon et al 1998, 2005; Weaver et al 2004). At the same time the improved drainage also results in some disadvantages, such as higher nutrient leaching losses (Weaver et al 2004).

Primarily, use of permanent beds has two main benefits. First, soil structure is improved because there is less tillage. This is of particular benefit when the soil is wet (Daniells 1989; Hulme 1987; McGarry 1995; McGarry & Daniells 1987; McKenzie 1998). Second, compaction from wheel traffic is confined to permanent tracks during both bed preparation and crop maintenance such as mechanical weeding and ground pesticide spraying (McGarry 1995; McKenzie 1998). In recent years the system has become known as controlled traffic-reduced tillage farming (Tullberg et al 2003). Confining compaction to permanent tracks has the added benefit of better traction and accessibility during wet weather. In the early days of permanent beds, there was little benefit from controlled traffic because cultivation equipment was narrow. Tractor wheels are spaced on 2-m-wide axles to fit across two rows of cotton. Therefore, with four-row equipment, every row of cotton is adjacent to a wheel track and its accompanying compaction (McKenzie 1998). As cultivation equipment became wider (6, 8, 12 or 16 rows), more rows were distant from the wheel tracks, and the crop responded by showing improved growth.

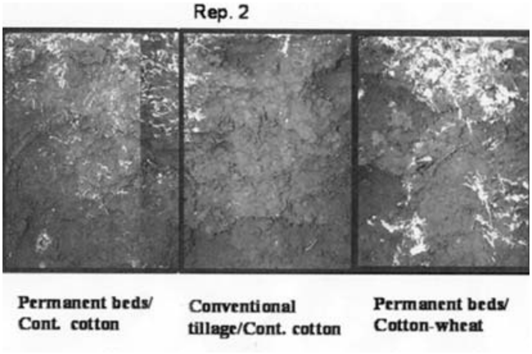

Figure 3. Effect on macroporosity of wheat rotation crop in cotton on permanent beds at field capacity in a grey clay near Narrabri, NSW.

Permanent bed systems can greatly minimise degradation of soil chemical properties. Beneficial effects can occur with respect to N; soil organic carbon and particulate organic matter; exchangeable Na, K and, to a lesser extent, Mg; and sodicity, salinity and pH (Constable et al 1992; Hulugalle 2000; Hulugalle & Entwistle 1997; Hulugalle et al 1997a, 2000, 2004a, 2005; Figure 4). For example, sodicity in a long-term experiment near Narrabri, NSW, was higher with conventional tillage than with permanent beds (Hulugalle et al 2000, 2004a; Figure 4). This is due to deeper tillage bringing sodium-rich subsoil to the surface; and better pore distribution and drainage under permanent beds (Weaver et al 2004) enabling sodium in the surface soil and irrigation water to be leached out faster.

A similar trend occurs with respect to chemical properties such as soil organic C, N, $EC_{1:5}$ (electrolytic conductivity of 1:5 soil:water suspension), pH and exchangeable K (Constable et al 1992; Hulugalle 2000; Hulugalle et al 1997a, 2000, 2004a, 2005). The primary reason for these differences appears to be related to better drainage and leaching. The differences in organic carbon and nitrogen are probably due to faster decomposition of crop stubble and organic matter with conventional tillage, which disrupts soil aggregates and exposes organic matter to microbial populations (Baldock & Skjemstad 2000; Skjemstad et al 1998).

There have been few investigations on soil biology under permanent bed systems in Vertisols sown to cotton. Hulugalle et al (1997a, b) observed that

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[1] The BEELINE^{TM} system uses a process called a differential global positioning system (DGPS) coupled with an inertial navigation gyroscope to automatically control the vehicle's position. The onboard computer in the tractor uses the position provided by the DGPS and the gyroscope to control the hydraulic steering system and keep the vehicle in its pre-determined path. Precision navigation is unaffected by poor light, glare or dust, so farmers are able to operate machinery 24 hours a day.

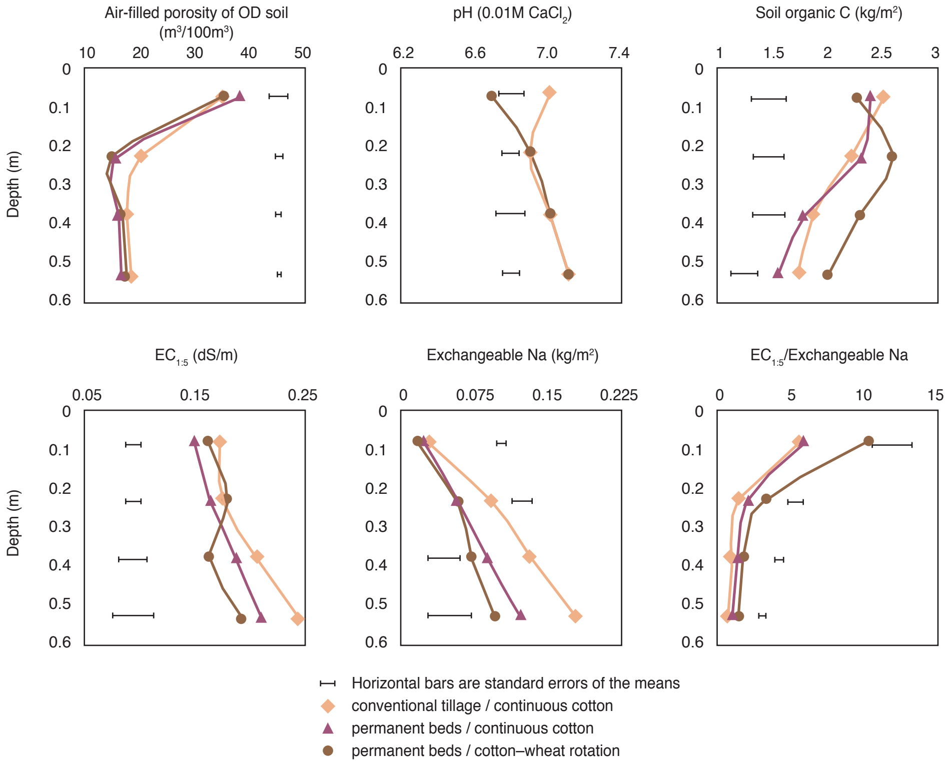

Figure 4. Effects of tillage system and rotation crop on soil quality indices (Hulugalle et al 2000).

populations of springtails and ants were higher under permanent beds than under conventional tillage. Population dynamics of soil macrofauna were, however, determined primarily by frequency of pesticide application and irrigations. Beneficial microorganisms of cotton such as vesicular-arbuscular mycorrhiza (VAM) populations are not affected by permanent bed systems (Hulugalle et al 2000, 2004a), although incidence of soil-borne diseases such as black rootrot (caused by *Thielaviopsis basicola*) are reduced, particularly when a wheat crop is sown in rotation with cotton (O. Jorar, pers comm; Figure 5).

Cotton sown into permanent beds has better crop growth, higher lint yield and superior fibre quality than cotton sown after conventional tillage (Constable et al 1992; Hulugalle & Entwistle 1997; Hulugalle et al 1997a, 2004a, 2005; Figure 6). Crop water-use efficiency under permanent beds is, however, only marginally better or does not differ from cotton sown after conventional tillage (Tennakoon et al 1998, 2005). The reported yield improvements with permanent beds appear to be due primarily to better water conservation and plant-available water rather than improved efficiency of water use. Profitability, evaluated as gross margins, is higher when a cotton monoculture is sown into permanent beds (Table 2). This

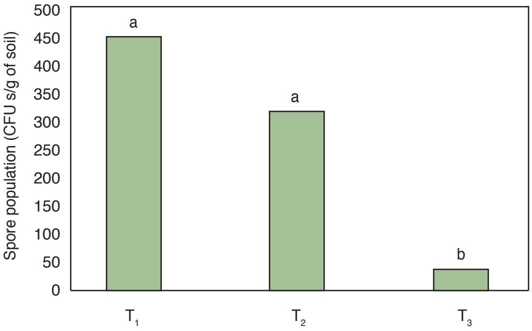

Figure 5. Spore density of *Thielaviopsis basicola*, the causal agent of black rootrot of cotton (averaged over 2 years) in treatments T_1 (conventional tillage/continuous cotton), T_2 (permanent beds/continuous cotton) and T_3 (permanent beds/cotton–wheat rotation) (Jorar, unpublished data 2004).

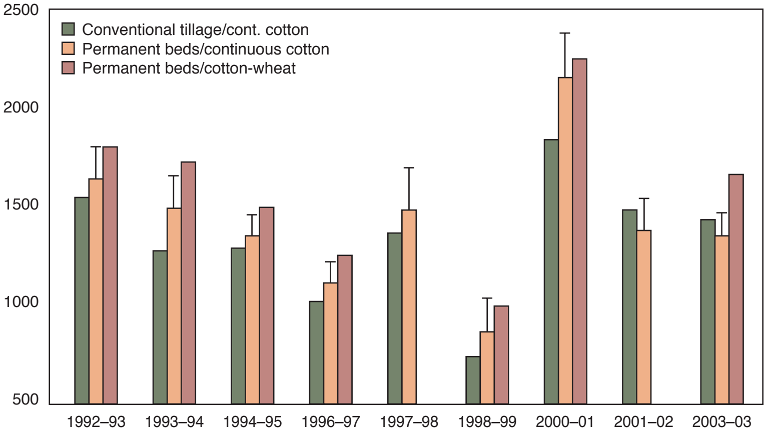

Figure 6. Effect of permanent beds and cotton–wheat rotation on cotton lint yields, near Narrabri, NSW. Vertical bars are LSDs (P = 0.05). Wheat rotation crops were not sown between 1992 and 1996 and cotton was sown in all treatments. The cotton–wheat yield between 1993 and 1997 is, therefore, the residual effect of past wheat rotation crops. Adapted from Hulugalle & Entwistle (1997) and Hulugalle et al (1997a, 2004, 2005).

is in spite of the fact that between 2001 and 2003, yields under permanent beds decreased (Figure 6).

Cotton yield decline can occur over the long term despite improvements in soil structure and other physical properties associated with permanent beds (see earlier discussion). This is because maintenance of the beds in the absence of good in-field vehicular traffic management and effective guidance systems causes the furrows and beds to shift such that beds can become located over compacted furrows (McGarry 1989–90). This physically degraded soil is characterised by poor structure, high soil strength (Figure 7) and low plastic limit (McGarry 1989–90; Hulugalle et al 2004a; Tullberg et al 2003). Consequently, cotton yield decline occurs with time. In an ongoing long-term experiment at the Australian Cotton Research Institute near Narrabri, NSW, cotton monoculture yield in permanent beds was 8% lower after 16 years than that under conventional tillage (discing to 0.2 m, chiselling to 0.3 m and bed reconstruction every year) (Figure 6). Soil structure related yield decline can be avoided by: timely tillage at soil water contents drier than the plastic limit (Daniells 1989; McGarry 1995; McGarry & Daniells 1987); sowing suitable rotation crops to facilitate wetting/drying cycles (Pillai & McGarry 1999; Figure 3); or careful in-field traffic management with effective guidance systems (Schoenfisch 1999; Tullberg et al 2003).

Other frequently cited problems related to using permanent beds include management of in-situ crop residues and the higher incidence of disease, weeds and insect pests such as heliothis moth pupae (Cooper 1999; Rourke 2002). Research conducted at the Australian Cotton Research Institute near Narrabri in NSW suggests, however, that the compulsory ploughing-in of beds to control heliothis moth pupae ('pupae-busting'), as recommended by the cotton industry (Rourke 2002), may not be necessary in all instances. Hulugalle and Tann (Hulugalle et al 2000; N.R. Hulugalle & C. Tann, unpublished data,

Table 2. Effect of tillage system and wheat rotation crop on profitability shown as gross margins in Australian $/ha (Hulugalle et al 2004b)

Tillage system	Cropping system	2000 winter	2000–01 cotton season	2001 winter	2001–02 cotton season	2002 winter	2002–03 cotton season	2003 winter	2003–04 cotton season	Cumulative
Conventional	Continuous cotton	–28	2003	–28	1816	–45	1582	–54	1799	7045
Permanent beds	Continuous cotton	–28	2643	–39	1802	–45	1317	–54	2442	8083
Permanent beds	Cotton–wheat[a]	–81	2859	119	-194	–19	2051	212	–69	4946

[a] Wheat yielded 2.0 t/ha during winter 2001 and 2.8 t/ha during winter 2003.

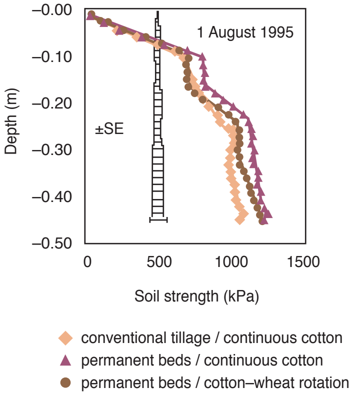

Figure 7. Effect of tillage and cropping systems on variation of soil strength with depth (Hulugalle et al 1997b).

1997–2003) observed that practices commonly used in managing permanent beds, such as root cutting and shallow bed cultivation with disc-hillers, when the soil water content is less than the plastic limit resulted in negligible numbers of pupae emerging. In a separate experiment they also observed that tillage implements such as the aer-way cultivator, when used at soil moisture contents at or below the soil's plastic limit, resulted in minimum soil disturbance (macroporosity was similar to zero tilled soil) and maximum pupae destruction. This may be because cultivation with an aer-way cultivator results in increased micro- and mesopores at field capacity, but not macropores. The increase in micro- and mesopores may be sufficient to enable parasitic wasps and parasitoids such as *Heteropelma scaposum* to gain access to the pupating heliothis larvae.

Experimental evidence does not support the opinion that permanent beds facilitate any increase of soil-borne diseases over conventional tillage, although research is ongoing (D.B. Nehl, pers comm). Continuing research also suggests that weed management in permanent bed systems can be optimised by sowing Roundup-Ready® cotton varieties (Hulugalle et al 2004b, 2005; I. Taylor, pers comm).

Permanent beds and crop rotations

The efficacy of permanent beds in both irrigated and rainfed farming systems can be further improved by sowing a cotton-rotation crop sequence instead of a cotton monoculture. By sowing cereal crops such as wheat in rotation with cotton, improvements in soil physical and chemical quality, yield, fibre quality and profitability; better nutrient recycling; and lower frequency of incidence of black rootrot have been observed in most cotton growing regions of Australia and under a range of soil conditions (Constable et al 1992; Hulugalle 2000, 2004, 2005; Hulugalle & Entwistle 1997; Hulugalle et al 1997a, 1997b, 2000, 2002a, 2002b; 2004a, 2005; Jorar et al 2002; Marshall 1998; Figures 3, 4).

However, the relative improvements in soil properties, yield and profitability are dependent on the specific rotational crop. In general, improvements in soil structural and other physical properties, greater profitability, recycling of leached N, and a lower incidence of black rootrot are more likely with wheat than with grain legumes (Hulugalle 2005; Hulugalle et al 1999, 2001, 2002a, 2002b, 2004b; Jorar et al 2002; Nehl & Allen 2002). On the other hand, soil N is higher with a cotton grain legume rotation. Legumes in the rotation may also reduce cotton yield and/or profitability because: (a) they have higher production costs than wheat; (b) herbicides commonly used with legumes are incompatible with cotton; (c) they are alternative hosts of black rootrot of cotton; and (d) their seed material can be allelopathic to cotton (Hulugalle et al 1998, 2001, 2002a; Jorar et al 2002; Nehl & Allen 2002). Namoi woolly pod vetch is an exception in that it is not an alternative host of black rootrot of cotton, although it can be a host to other disease-causing organisms of cotton such as *Fusarium, Rhizoctonia* and *Pythium* (Nehl & Allen 2002). In low potassium soils, soil fertility can be improved most by sowing sorghum (Hulugalle 2004; Hulugalle et al 2002b).

Managing crop stubble in permanent beds

Managing rotation and cotton crop stubble in permanent bed systems usually involves either slashing and incorporating the stubble into the beds with shallow cultivation equipment such as Lilliston cultivators and 'go-devils', or burning the crop stubble (CRC for Sustainable Cotton Production, unpublished survey, 1995; McKenzie 1998; Schoenfisch 1999). A majority of cotton growers in NSW tend to slash and incorporate crop stubble with a range of machinery (Schoenfisch 1999). The proportion of growers burning stubble is higher in Queensland, where an unpublished survey conducted by the CRC for Sustainable Cotton Production in 1995 indicated that more than 95% of cotton growers in the southern Queensland regions of Dirranbandi and St. George (Figure 1) were burning their crop stubble.

More recently, cotton growers and researchers have experimented with a permanent bed system where cotton is sown into in-situ standing rotation crop stubble which is retained on beds and in furrows (Henggeler et al 2000) (Figures 8, 9). This can:

Figure 8. Cotton sown into standing wheat stubble at the Australian Cotton Research Institute, near Narrabri, NSW, Australia (Hulugalle et al 2005).

Figure 9. Run-off water from plots near Boggabri, NSW, Australia, where cotton was sown either into standing wheat stubble or after wheat stubble had been incorporated. (Hulugalle et al 2004b). Photograph provided by M. Hickman.

- reduce erosion, run-off, and off-field movement of pesticide residues and nutrients (Waters & Sequira 2000; Waters et al 2000; Figure 10)
- reduce early season soil temperatures during periods of high temperatures (Hulugalle, unpublished data, 2004)
- increase water infiltration, winter rainfall harvesting (by 50–70 mm), soil organic C and exchangeable K (Hulugalle et al 2003, 2005; Hulugalle, unpublished data, 2004)
- reduce heliothis moth infestation in young cotton (Waters & Sequira 2000).

Disadvantages include blocking of 'gas knives' by wheat stubble during application of anhydrous ammonia as fertiliser, increased waterlogging during irrigation, and inability to incorporate residual herbicides (Henggeler et al 2000; G. Roberts, pers comm 2000). Anecdotal evidence also suggests that where cotton is sown into stubble from wheat sprayed out with herbicides ('green wheat'), N immobilisation may occur. Experimental evidence for such an N immobilisation is, however, lacking. Blocking of 'gas knives' by wheat stubble during anhydrous ammonia application into the beds can be avoided by attaching coulter discs to the front bar of the gas rig, in front of the gas tines, to cut through wheat stubble (Weaver et al 2000; Figure 10). A press wheel, which follows the tine, seals the soil and leaves a rolled surface ready for planting. The gas tines and press wheels are fastened onto the back bar of the gas rig. During the pass of the rig, the only residue disturbed is that on the top of the bed. After anhydrous ammonia has been injected, a residue-free strip approximately 10 cm wide remains on the top of the beds.

Waterlogging during irrigation events is avoided by retaining the stubble in the furrows only until the start of the irrigation season (Hulugalle et al 2004b). At this point, except for a 2-m-long buffer strip in the furrows at the tail drain end of the field, the point of a sweep (V-shaped tillage implement which performs shallow tillage over broad widths) is run through the furrow to a depth of 10 cm to clean out the stubble from the base of the furrow. This facilitates water flow through the field. The retained 2 m strip slows water flow just enough to settle out dispersed clay as sediment (Figure 11). Excess salts and nutrients adsorbed onto clay particles are deposited in the furrow and do not move off field with run-off.

Figure 10. Modified anhydrous ammonia rig with coulter discs in front of gas knives (Hulugalle et al 2004b).

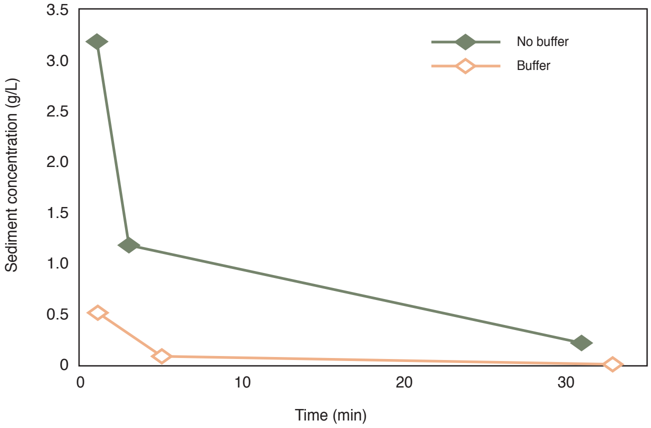

Figure 11. Effect of 2 m vetch buffer on sediment concentration in run-off from 1st irrigation in October 2003 at the Australian Cotton Research Institute, near Narrabri, NSW, Australia (Hulugalle et al 2004b).

Conclusions

Permanent beds have been used successfully in the Australian cotton industry since the 1980s. The resultant benefits, particularly when integrated with suitable rotation crops (such as wheat in northern NSW), include better soil physical and chemical quality and lower costs than with conventional tillage systems. The efficacy of permanent beds can be improved by retaining rotation crop stubble undisturbed in situ. Long-term use, however, requires effective and careful in-field vehicular traffic management. Permanent beds are of most benefit after a wet harvest, when conventional tillage causes much damage to soil structure. Realignment (ploughing out and reforming) of beds that have shifted over compacted furrows should be done after a dry harvest. Other problems such as heliothis pupae control, and fertiliser, weed and water management, can be overcome by using appropriate machinery and agronomic management practices.

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Permanent raised bed cropping in southern Australia: practical guidelines for implementation

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Abstract

When Southern Farming Systems (SFS) (a partnership between farmers, agribusiness and the research and development workers of the Victorian Government) began in southern Victoria in 1995, its primary aims were to develop a system of farming that would both reduce the prevalence of waterlogged crops and improve soil structure in crop paddocks. After many years of trying to grow crops in southwestern Victoria, it became evident that consistently good crops could only be achieved on paddocks with well-drained and well-structured soil. By addressing these issues SFS were confident they could improve yields and substantially reduce the risks associated with crop production in this region.

After some preliminary demonstrations and commercial work using various drainage techniques, including wide (20 m) raised beds and underground systems, the SFS decided to concentrate their efforts on a narrow raised bed cropping system incorporating controlled traffic to help drain the soil and improve its structure.

Permanent raised beds, by their very nature, encourage the concept of controlled traffic, where all vehicle wheels travel along the furrows between beds, thus limiting compaction on the majority of the paddock. Extensive research throughout Australia has shown significant soil structure improvements by removing vehicle compaction from the soil where the crop is grown.

Since 1995 SFS has developed various techniques to successfully install raised-bed controlled traffic programs. These techniques include contour surveying, waterway construction, soil cultivation, bed forming, crop sowing, crop spraying, windrowing and harvesting. Techniques to accurately apply fertiliser only to the top of beds have also been developed. Two concept farms (400 ha) trialling a combination of raised beds, alley trees, water harvesting and irrigation have been established.

SFS farmers, research workers and commercial sponsors have all worked tirelessly to help develop the system to where it is today. The SFS continues to study all aspects of this new technology so that cropping becomes more profitable and sustainable into the future.

Introduction — the rationale for using permanent raised beds in southern Australia

Permanent raised beds (PRB) and controlled traffic broadacre farming are recent phenomena in southern Australia, developed to overcome waterlogging and improve soil structure on cropping soils in the high rainfall zone [>550 mm] of this area. The high clay content of the B horizon and its low permeability in some of these soils result in a perched watertable during the long, cool growing season, which can cause complete crop failure when grown on flat or gently sloping ground without drainage.

Raised bed farming (RBF) is not a new idea. In Asia and other parts of the world soil beds have been raised and furrows used for irrigation for centuries. In many countries, including Australia, the technique has been used for many years by home gardeners and commercial vegetable and flower growers to assist with drainage. In the early 1980s scientists from Tatura in Victoria developed a system of growing broadacre grain crops on raised beds and using the furrows for irrigation (Tisdall & Adem 1986a, 1986b, 1988). The system has been widely adopted for grain and horticultural crop production in the New South Wales Riverina districts, particularly around Griffith (Beecher et al 2005). The use of raised beds can have several benefits depending on the circumstances. In the context of farming in southern Australia, the main reasons for their use are:

- *Better drainage:* Raised beds are primarily a field drainage tool aimed at decreasing waterlogging

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and increasing crop yields. When soil becomes saturated with water, as is the case for many 'duplex' soils in Australia[1], anaerobic conditions result in poor plant root growth, which causes plants to become stressed and in some cases (eg under prolonged waterlogging) to die. Where soils become saturated in winter due to high rainfall and/or poor drainage, soil drainage needs to be considered.

- *Better soil structure:* By their very nature, raised beds encourage implements to travel down the furrows, which reduces the amount of soil compaction occurring where the plants are growing. Soils that aren't compacted have a greater ability to hold plant-available water, are less cloddy, allow for greater plant root growth and give higher plant yields. Raised beds offer a form of controlled traffic, the benefits of which have been proven in many areas and over many years (Blackwell et al 2003; Ellis et al 1992; Tullberg 2001; Tullberg et al 2001).
- *Risk management:* The incorporation of raised beds means that the complete failure of crops due to waterlogging is eliminated. Hence, more accurate budgeting of crop yields can occur and there is greater confidence in achieving good results. Many paddocks that were once too risky to crop due to waterlogging problems can now be brought into production with confidence.
- *Higher profits:* Due to more uniform and higher yielding crops under situations where waterlogging would normally be a problem, higher profits can be realised. In many parts of southwestern Victoria crop yields have doubled in recent years where raised bed technology has been used, considerably increasing profit for farmers. It is important to note that many of the costs associated with the installation of raised beds, such as surveying, grader work etc, are one-off costs and should not need to be repeated.

The rapid research and development of raised beds and controlled traffic has been a combined team effort involving farmers, machinery manufacturers, agronomists and researchers, with the Grains Research and Development Corporation (GRDC) and SFS helping to sponsor the project along the way. A range of practices and recommendations have been developed by the SFS group over the years for the establishment of PRB systems in southern Australia. As a consequence of the SFS being a farmer partnership, much of the research underpinning these practices was carried out in an on-farm participatory mode. The aim of this paper is to describe the PRB systems developed for conditions prevailing in southern Australia.

Main features of raised beds

An overview of the steps and recommendations being made to farmers when establishing PRB systems is provided in this section.

Design of raised bed paddocks

Inspecting soil and sampling the paddock

The first step is to visually inspect the paddock and decide where the water runs across it. It is recommended to take soil samples at both 0–10 cm and 10–60 cm and send them for analysis to assist in decisions on the need for any soil remediation measures.

Initial survey

A simple survey with a dumpy or laser level will inform the farmer about the general slopes across the paddock. This requires taking a series of readings at 100 m intervals. Slopes are given as a percentage; therefore, a fall of 0.5 m over 100 m is a slope of 0.5%. A double slope is best, so water can run down the furrows and then down the collector drains. It is also important to determine where the water discharges from the paddock and where it goes to.

Making the decision

If the paddock slopes generally fall between 0.2% and 1.5% and a discharge point is available, then raised beds may be a viable option. Once the decision to use beds in the paddock has been made, a full detailed plan must be prepared for the paddock.

Development of a detailed plan

Normally this step requires the assistance of a professional surveyor to carry out a full contour survey at 10 cm intervals using laser and GPS technology. It is practical to have the plans laminated for outdoor use and to enable drawing on the layout with a felt pen (Figure 1).

The contour survey will accurately show all paddock slopes and also define low spots where water may lie in the furrows and waterlog the beds. If low spots are likely to be a problem, the farmer should consider land levelling, for example with a land plane.

The plan should show features in and around the paddock such as roads, creeks, dams, buildings and fences. If there are any moveable features that will prevent an optimum paddock layout, the farmer

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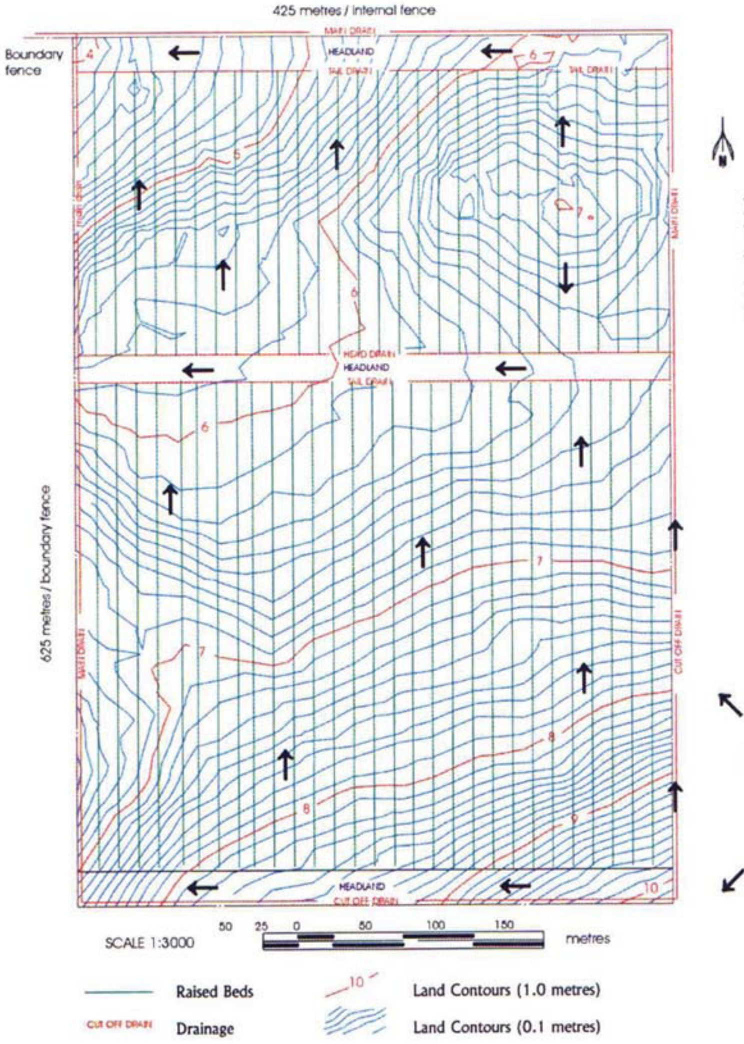
[1] 'duplex' soils are texture contrast soils, where a sandy to loamy A horizon overlies a clayey subsoil with low permeability and, often, sodic properties



Note: This main headland drain can be a grassed waterway or an underground pipe. If at all possible this waterway should be at right angles to the bed direction.

Note: Cut off drain at top of paddock - this drain stops water running onto the paddock from adjacent areas.

(Contour map provided courtesy of McFarlane Irrigation Design.)

Figure 1. The contour survey will accurately show paddock slopes and facilitate the best plan for beds and drain direction.

should consider moving them or doing without them (Figure 2).

Deciding on the direction of the beds

Success or failure may depend on this critical decision. A professional raised bed survey will usually show recommended bed directions and the placement and layout of all drains. Farmers who have plain contour plans must apply their own layout ideas. The beds must go down the steeper slope; and the collector drains, which carry all the water from the furrows, must go down the lesser slope. This is because the maximum slope and bed run length depend upon the soil's susceptibility to erosion, and serious problems can occur if the guidelines are exceeded. For all slopes and soils, the maximum bed run length between collector drains should be 400 metres.

While it is preferable to run the beds north–south to evenly capture winter sun, that decision must be dictated by the contour plan and the guidelines.

Designing the headlands

After selecting the direction of the beds, the farmer needs to mark the headlands on the plan. Headlands are required for machinery accessibility and turning and should be 20–25 m wide.

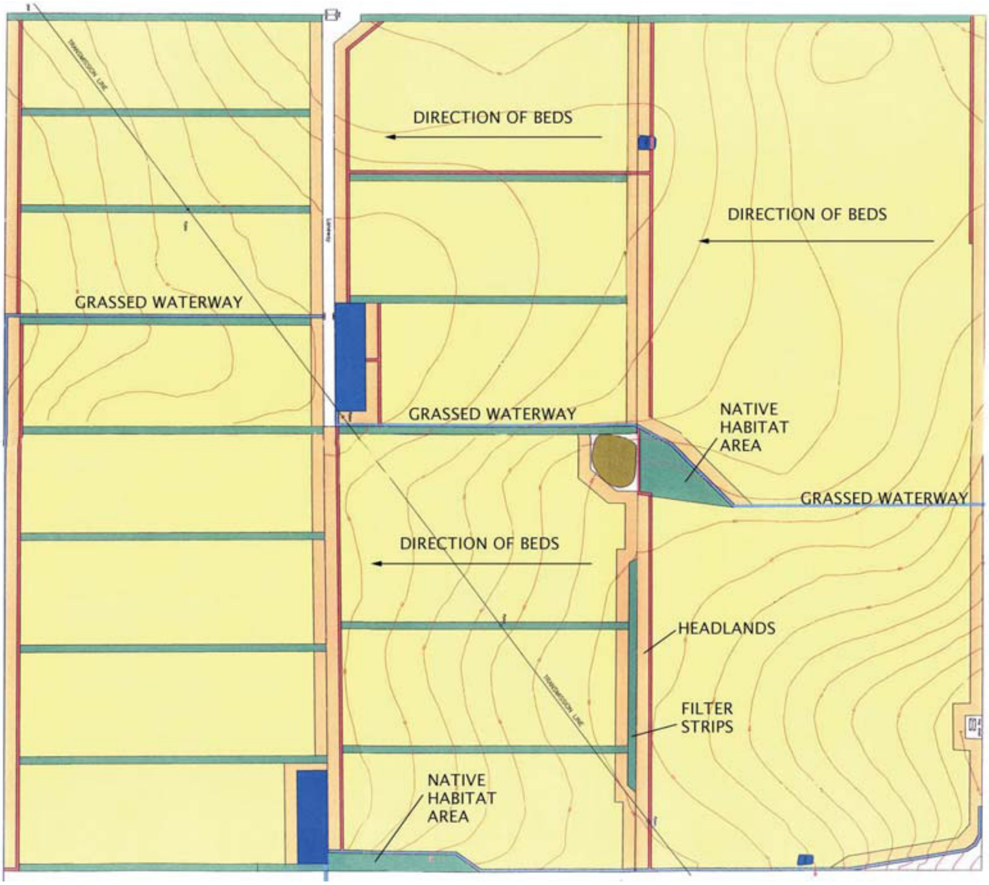


Figure 2. It is recommended that a full farm plan be designed so overall water movement, tree lines and buffer dams can be incorporated with other enterprises.

Planning the collector drains, other surface drains and grassed waterways

The collector drains, which pick up water from the furrows, need to be added to the plan. Because they collect water from many furrows, they often carry large volumes of water and their slope must be well below 1% to minimise scouring and the formation of gullies (Figure 3).

Grassed waterways can also help in managing excess flow and need to be included in the plan. Usually they will run along fencelines, to relieve pressure on the collector drains. This step also requires the farmer to decide on the location of wide, flat herringbone drains that cross the headland at intervals, into which water will be diverted from the collector drains.

Raised bed paddocks should only have to deal with water that falls directly onto them. Hence, it is necessary to add to the plan any other surface drains that

Figure 3. To stop bogging and improve trafficability, collector drains at the ends of the beds can be installed with underground plastic slotted pipes and backfilled with heavy, coarse gravel.

may be required to ensure that no water runs onto the paddock from roads, next-door paddocks or any other areas of land. These drains must be designed so they do not erode, and must be big enough to cope with all likely water flows (see 'Choice of design' below for details on handling excess water).

Planning soil treatments

Finally, on the basis of local experience and the soil test results, any applications of lime, gypsum, poultry manure or other soil treatments that may be needed should be planned before proceeding with the next steps.

Preparation of the paddock

Primary cultivation

Before primary cultivation can be started, consideration should be given to removing any obstacles such as rock piles, surface rock or trees from the paddock. Any rocks brought to the surface during cultivation, bed forming or sowing should also be removed. Any trees that are removed should be replaced elsewhere on the farm, according to the local environmental rules and guidelines.

Soil preparation should ideally begin prior to sowing in the spring, which is the ideal time to spray out potentially troublesome weeds and perennial plants such as phalaris. Adding an insecticide to the tank mixture at this stage will break the life cycle of pests such as red-legged earth mites. If the soil is susceptible to wind erosion, cultivation should not start before autumn.

Cultivation is best done when soil moisture is high enough to allow the cultivation gear to achieve the desired depth. Raised beds can be successfully installed in dry conditions but achieving the initial deep cultivation in dry soil can be difficult. Machines such as rippers, chisel ploughs and scarifiers are all suitable for primary cultivation.

The depth of cultivation required depends on the planned bed height. Deeper cultivation will produce a greater volume of loosened soil for mounding; the higher the beds, the deeper the tilth required. Loose cultivated soil must extend below the anticipated furrow depth to enable accurate, straight furrows and uniform bed height. The minimum cultivation depth of 17.5 cm will achieve about 20 cm of loose soil, which is possible in most paddocks in southwestern Victoria.

It is not recommended to try to obtain full depth in one pass but, rather, to gain depth slowly and stop if too much clay in very large clods is being brought to the surface. A fine tilth is not required at any stage, and cloddy soils with enough fines to achieve good soil seed contact at sowing are ideal. In fact, scattered clods the size of a fist can offer protection from run-off on newly bedded paddocks, and from wind damage to newly emerging crop plants.

The final cultivation should be run at right angles to the proposed direction of the beds to help the bed-former travel in straight lines and not hook into grooves formed by cultivator points or ripping tines.

Paddock levelling

The contour survey and general paddock knowledge gained from primary cultivation will help determine if land levelling is required. Laser levelling, as practised in irrigation areas, does not usually offer many benefits to the generally undulating paddocks typical of southern Australia. However, land planes can be extremely useful in helping to even up the surface, removing small depressions and bumps and greatly aiding water movement down the furrows.

Application of soil treatments

After land planing any soil treatments in the plan, such as lime and gypsum, can be applied.

Final cultivation

A final cultivation may be required to achieve an even 20 cm depth over the whole paddock.

Construction of the beds

Choice of bed design

The first step is to make sure that the bed width and bed height decided on at the planning stage are appropriate. The chosen width and height of raised beds quite often depends on paddock/farm conditions, availability of machinery/contractors and farm finances, and a case-by-case approach is necessary. Ground that has little slope and waterlogs easily may need high beds, while paddocks with good slope and better internal drainage may be best served by little or no bed height and concentration on controlled traffic alone. Raised beds alone and controlled traffic alone are quite compatible in the one paddock (Figure 4).

In most situations a new bed height of approximately 20–25 cm is very effective, and gives room to practise water harvesting on top of the bed and still have enough relative height between the water harvesting groove left by the sowing press wheel and the drainage furrows between the beds.

Bed width quite often depends on the machinery availability. For example, our first attempt at commercial bed farming in 1997 contained beds ranging from 1.5 m to 2.16 m (centre of furrow to centre of furrow) due to the availability of existing farm

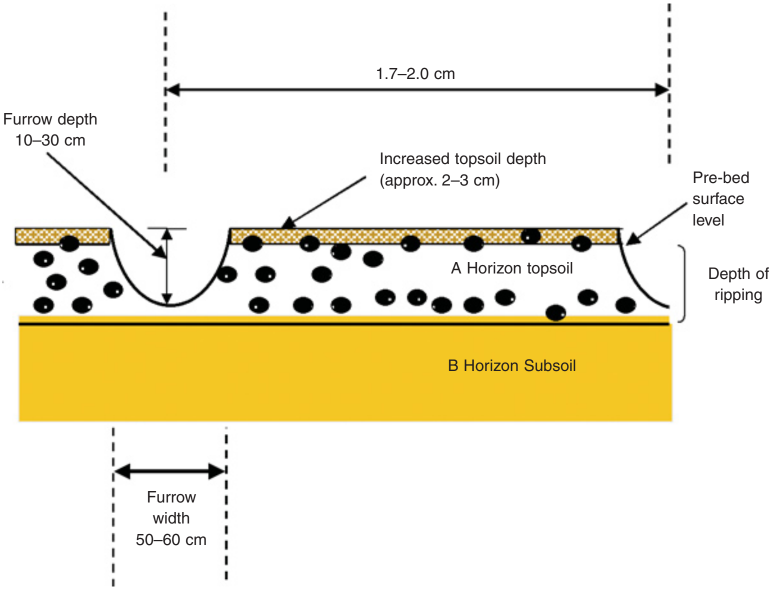


Figure 4. Schematic diagram of raised bed.

machinery. All these sizes worked well but farmer experience in Victoria and Western Australia (Greg Hamilton, pers comm) indicates that beds in most of these soils should not exceed 2 m in width. Bed widths of 2 m are becoming more and more popular and air seeders are easily manufactured to suit these widths. Also, with 2 m beds standard 450-mm-wide tractor tyres are quite suitable. The only problem with 2 m beds is that full controlled traffic is very hard to achieve because the header needs to be 4 m wide. Because soils in southwestern Victoria are naturally dry and strong at harvest, running the header on top of the beds has so far not created serious soil compaction problems.

Selection of a bed-forming machine

Bedding machines suitable for southwestern Victoria have been evolving since 1997. Most types have been successful but the more up-to-date models may be faster, stronger and lighter.

Options for farmers include purchasing their own machine, sharing one with neighbours or using a contractor to construct the beds. Contractors may have the largest and most modern machines, and may also have plenty of experience. Some are now using GPS guidance systems to install beds, ensuring that the beds formed in two halves at the ends of the machine are the same width as those formed in the middle of the machine.

The very first machine used in southwestern Victoria was based on a rotary hoe with shaping baffles fitted, but these have not been used recently. They evolved into types based on rotary harrows, which are still favoured by some farmers. However, they are slow and have great difficulty coping with rocks, and the bigger ones, especially, have a high power requirement. They may come back into favour as a means of incorporating heavy cereal stubbles into beds to avoid the need to burn.

Most bed-formers are based on tool frames carrying furrow formers, with a range of levelling devices (including grader boards, heavy chains and crumble rollers) fitted behind, either singly or in combination. As the furrowers dig out the furrows, they throw a mound of soil onto the edges of the beds. The levelling devices then move this soil across towards the centre, flattening out the bed top. Grader boards and furrower ‘wings’ are often made of plastic to reduce weight. Using chains to level the soil on the beds between the furrows does have a weight advantage, but they are less effective than grader boards and crumble rollers.

Many of these machines make two (one complete and two halves) or four (three complete and two halves) beds at a pass. The former is a good option for farmers who wish to install one or two paddocks per year using their own relatively small tractor.

Machines that make half beds each side have a grader board at each end of the tool frame. There are also some machines that make three whole beds and have a furrower at each end of the tool frame. Machines that make a half bed at each end are preferred because when whole beds are formed the furrower at the extreme end of the tool frame passes for a second time down what was the outside furrow formed on the previous run, digging out a furrow deeper than the others. This uneven furrow depth can hamper subsequent passes over the paddock with other equipment (Figure 5).

Bed-forming machines are made in both trailed and three-point linkage configuration. Large linkage machines may require very large tractors to lift and operate them.

Spring release gear on furrower tines was used for some time but has been superseded by hydraulic breakaway tines. The added tension available means the furrow depth can be made more even and smooth because the machine has added ploughing ability. However, if the paddocks are fully and evenly cultivated to the correct depth there is less advantage in using hydraulic breakaway gear.

Another development is machines fitted with double listers. The second lister simply sits in the furrow and cleans out clods, and is usually fitted with small grader boards on its wings to spread its spoil over the bed.

Trailing multipurpose machines have been developed that make raised beds, renovate beds and sow seeds into both bedded soil and flat soil. The bedding component comprises excellent high-winged listers and is sometimes fitted with heavy duty chains to help spread the soil. In well-cultivated and prepared soil the machine makes excellent beds. Rolling the bed tops may be beneficial if the soil is light and/or fluffy after bed forming.

Machines should be set up and operated in a way and at a speed that ensures they make the smoothest, most even beds possible, with furrow depths as even as can be achieved. This care will pay large dividends when it comes to sowing and establishing the crop on the beds, and spraying and fertilising the crop.

Alternatively, raised beds can be formed in uncultivated soil. This is easiest to achieve into a burnt stubble situation but has also been done successfully on old pasture ground. In both cases multiple passes of the bedding machine are usually required, gradually increasing the furrow depth with each pass.

Figure 5. A bed-former used in Southern Australia.

Establishment of turning headlands, surface drains, collector drains and buffer dams

Choice of design

Correct construction of the headlands, collector drains, grassed waterways and other components of the water management system is very important if environmental problems such as serious erosion are to be prevented.

When a paddock of raised beds is being sown, sprayed or harvested, or some other operation is being conducted, the tractor or vehicle travels along the furrows. It must then cross the collector drain before climbing up onto the headland, turning, crossing the drain again and proceeding up the next run of furrows.

Collector drains must be carefully engineered to avoid erosion, and this requirement usually means they must be wide and flat, which conflicts with the need to travel across them at right angles.

Turning headlands must not only be wide enough (see ‘Designing the headlands’ above), but must be constructed well enough and high enough to drain effectively and remain trafficable. They are built up like highly cambered roadways (see Figure 4).

Choice of machinery and construction method

A variety of suitable vehicles is available for constructing headlands and collector drains, including scrapers, road graders and linkage graders behind farm tractors. The use of dumpy or laser levels will ensure that drain falls and headland heights are optimised during construction.

Vegetation on collector drains and headlands

Collector drains and headlands should be kept vegetated or covered with crop residue at all possible times. Fully grassing collector drains with a perennial species such as tall fescue, perennial ryegrass and clovers is preferable, but it will always be hard to maintain these species because the sprayer has to cross them when applying crop herbicides. An alternative is to ensure that collector drains and headlands are completely sown down to the crop being grown on the beds.

Grassed waterways and herringbones

It is often a good idea to construct a grassed waterway in behind the headland, and to make herringbone drains across the headland from the collector drain at appropriate intervals. These drains and permanently vegetated waterways become an important part of overall water management. Appropriate machines such as scrapers, graders or drainers should be used to construct them, and dumpy or laser levels used to ensure the falls are correct. These waterways need to be kept well grassed and, if desired, trees can be planted alongside them.

Buffer dams

The final part of water management engineering at the raised bed paddock scale is to use a buffer dam, which receives all the water from the fenceline grassed waterway as well as the collector and surface drains, and is used to regulate the flow of that water out of the paddock. Buffer dams ensure that the rate of water run-off from raised bed paddocks is as close as possible to the rate before the beds were installed (Figure 6).

Figure 6. To reduce peak water flow run-off events, off-site buffer dams can be installed. Dam levels are kept low between rainfall events.

They require careful location, design, engineering and construction if they are to fulfil that role. They must be built with sufficient capacity to fill up and hold flows from most water run-off events, and must be equipped with pumps or siphons so that between each run-off event they can be slowly emptied into the natural water drainage lines outside the paddock.

Environmental risks

Water and nutrient losses from conventional flat and raised bed cropping systems

Since 1999 an experimental site near Geelong has been used to investigate changes in the hydrology of raised beds compared to conventional non-bedded flat-crop and pasture systems. Annual rainfall in this region is 520 mm and the Sodosol soils (Isbell 1996) are typical of the majority of soils on the basalt plains. Current results indicate that the intensity, duration and timing of rainfall during the season are significant contributors to measured differences in run-off volumes between raised bed and flat-cropped treatments (Table 1) (Johnston et al 2003).

When rainfall intensity exceeds soil infiltration capacity, raised beds tend to release greater volumes of run-off than conventional flat-cropping and pasture treatments. These ‘infiltration excess’ run-off events have been dominant over the period of the experiment, typically occurring prior to or following a dry start to a season and during seasons of below average rainfall. To reduce run-off from the top of the beds in these situations, it is recommended that press wheels are used on sowing equipment to install drill row grooves on the tops of the beds (T. Johnston, pers comm).

Table 1. Mean annual surface run-off volumes (mm) for 1999–2004.

Year	Annual rainfall (mm)	No. of overland flow events in year	Dominant run-off process	Surface run-off volume (mm)		
				Conventional non-bedded flat crop[a] (n=3)	Permanent raised bed crop[a] (n=3)	Conventional non-bedded flat pasture[b] (n=1)
1999	451.6	0	-	0	0	0
2000	430.9	2	IE	1.9	2.5	9.8
2001	599.4	7	IE	104	140	96
2002	376.2	4	IE	9.3	16.8	0
2003	440.0	4	IE	0.2	1.4	0.2
2004	479.2	2	SE	13.7	9.1	5.8

IE = infiltration excess, SE = saturation excess

[a] Mean annual surface run-off from 3 × 0.2 ha plots

[b] Annual run-off from 1 × 1.5 ha plot

However, when waterlogging is prevalent mid to late in a cropping season on flat-cropped land, 'saturation excess' run-off events can occur. During these events, trends indicate that the volumes of run-off from conventional flat-cropping treatments are greater than from raised beds (T. Johnston, pers comm). The benefits of using raised beds can be attributed to alleviation of waterlogging during the period, leading to increased dry matter production and greater canopy cover during the season, and higher grain yields. The resulting enhanced soil environment within the beds and higher water-use efficiency of the crop leads to the increase in grain yields (T. Johnston, pers comm) (Table 1).

There has been very little research on nutrient losses in run-off from cropping systems in southern Australia. However, data from this project indicates that growers are losing a significant amount of phosphorus and nitrogen from both crop and pasture systems. Total phosphorus and nitrogen concentrations from all treatments measured were well in excess of the 'safe' levels considered for Victoria's inland rivers and streams.

Phosphorus is generally only applied at sowing, typically as mono-ammonium phosphate (MAP), at rates of 20–30 kg P/ha/year. Phosphorus loads in run-off from all cropping treatments have ranged from 0.01 to 1.4 kg P/ha/year, with trends indicating higher loads from the conventional flat-cropped compared to raised bed treatments (Table 2) (T. Johnston, pers comm). Phosphorus in run-off water is predominantly in a dissolved form, suggesting that previous nutrient management strategies based on physically trapping phosphorus attached to sediment (ie grassed waterways and buffer strips) are unlikely to be successful.

Nitrogen fertiliser is commonly applied at sowing (typically as MAP) and as a further in-crop application of urea, commonly known as topdressing. Annual fertiliser application rates are generally around 60 kg N/ha/year, while N loads in run-off from cropping systems range from 0.50 to 30 kg N/ha/year. Trends are indicating higher N loads from the raised bed compared to conventional flat treatments (Table 3).

Topdressing with urea is commonly undertaken with a spinner, resulting in considerable amounts (30–40%) of fertiliser accumulating in the raised bed furrows. Current best management practices recommend that growers use equipment that directs the urea only onto the tops of the beds, thus reducing potential nitrogen loss in subsequent run-off events,

Table 2. Annual P loads (kg P/ha/year) in surface run-off from Mt Pollock (2000–04).

Year	Annual P loads (kg P/ha/year)		
	Conventional non-bedded flat crop[a] (n=3)	Permanent raised bed crop[a] (n=3)	Conventional non-bedded flat pasture[b] (n=1)
1999	0	0	0
2000	<0.01	<0.01	0.1
2001	1.4	1.0	1.2
2002	0.09	0.09	No flow
2003	No significant flow	<0.01	<0.01
2004	0.2	0.1	0.1

[a] Average annual P loads from 3 × 0.2 ha plots
[b] Annual P loads from 1 × 1.5 ha plot

Table 3. Annual N loads (kg N/ha/year) in surface runoff from Mt Pollock (2000–04).

Year	Annual N loads (kg N/ha/year)		
	Conventional non-bedded flat crop[a] (n=3)	Permanent raised bed crop[a] (n=3)	Conventional non-bedded flat pasture[b] (n=1)
1999	0	0	0
2000	0.44	0.58	1.3
2001	26	43	14
2002	3.8	5.4	No flow
2003	No significant flow	0.10	<0.01
2004	1.2	0.60	0.50

[a] Average annual N loads from 3 × 0.2 ha plots
[b] Annual N loads from 1 × 1.5 ha plot

fertiliser usage and ultimately off-farm nutrient loss. Incorporation of slow release fertiliser prior to sowing could also be considered to minimise volatilisation and run-off losses.

Pest problems

A range of potential problems can occur when crops are grown on raised beds, and the potential damage caused by some pests and diseases may be different or more of a risk compared with crops grown 'on the flat'. Such problems need to be monitored and carefully managed. A few examples include:

Rodents

It has become clear that mice seem to thrive in the dry friable soil of raised beds. In the cold wet winters of southwestern Victoria mouse problems in broadacre paddocks have been rare, but this is a problem to watch out for on raised beds.

Disease

The friable, well-aerated soils in raised beds have many advantages but they may stimulate some soil fungi, such as Rhizoctonia, to be more of a problem (see 'Sowing points' below).

Insects

Many insects such as false wireworms thrive in well-drained and well-structured soils, as in raised beds.

Slugs

Due to the use of mulch and consequent moister conditions in the furrows, slugs may become an increased problem in raised bed crops.

Managing soils, crops and pastures on raised beds

Farming systems and crop rotations

Grazing by livestock

An important decision included in the choice of which farming system to adopt on a raised bed paddock is whether livestock should be grazed on the paddock; and if so, how and when it should be done.

Grazing the stubbles on raised beds is usually safe for soils because the dry conditions minimise compaction damage from the animals' hoofs, but it may be advisable to remove the sheep after summer rain until the soil dries out. There are simple but very important guidelines to follow for the safety and management of animals grazing on raised bed paddocks (GRDC 2004).

Some farmers may wish to establish pastures and graze their stock on raised beds, and this can be quite successful if care is taken. Tactical grazing is recommended and sheep should be moved out of raised bed paddocks during the rainy season. Again, livestock safety considerations are vital.

Livestock safety

The problem of sheep getting cast in the furrows when grazing raised beds has never been as bad as was feared and many farmers now successfully graze raised beds, but it is a potential problem that must be properly managed. Sheep can get stuck upside down or on their sides in the furrows, as happened in the early years of raised bed trials, and can die in that position. Factors influencing the problem include the bed height and furrow depth, and the nature, condition and state of the fleece of the sheep.

When farmers are attempting to graze beds for the first time with a new mob of sheep, it is very important that frequent inspections are carried out during the initial period to assist any sheep that may be cast in the furrows. Experience on farms and from the trial program suggests that, with time, the sheep adjust to the furrows, the furrows themselves may become shallower and the problem almost disappears. For stock welfare reasons, regular inspections must still take place.

Crop rotation

The standard rotations that have been used for years in the high rainfall zone (>550 mm) are generally applicable on both flat-cropped paddocks and raised beds. The principles underlying those rotations, such as soil fertility, crop disease control and economics, are also the same. However, soil improvements and waterlogging prevention resulting from raised beds may increase the choice of crops available. Presently, the most economic and practical rotation used by farmers is canola–wheat–barley–canola, which may be continuous or broken up with a phase of mixed pasture or lucerne. With the alleviation of waterlogging, pulse crops such as field pea and faba beans have shown to be suitable rotation crops producing economic returns.

Growing and using pastures on raised beds

Pasture productivity and benefits

Experimental evidence indicates pasture productivity and survival on raised beds during a series of dry seasons can be relatively poor (Peries et al 2004a) but this does not mean that pasture rotations on raised beds are unproductive or uneconomical. A pasture phase can help to improve soil structure and enhance soil water storage, especially in soils that have been cropped for long periods or become degraded.

Trial results have shown that a pasture phase on raised beds contributed to improved aggregate stability of the soil, which in turn improves soil aeration, water retention and soil structure (Jaikirat Singh, pers comm) (Figure 7). However, the below average seasonal rainfall experienced on the trial site in three out of five growing seasons between 1999 and 2003 resulted in poor performance from the recommended pasture varieties. Persistence was also poor, with few of the recommended annual pasture varieties surviving beyond 1 year.

It must also be noted that soils on raised beds are generally more friable and porous than on the flat. In the absence of significant autumn rain (delayed autumn break), pastures struggled to regenerate until late in the season in the absence of a good seed soil contact. The result was a lower than expected carrying capacity from pastures on raised beds between 1999 and 2003. Peries et al (2004a) shows the rainfall distribution over the 6 years from 1998 to 2003. Compared to the previous 6 years there was a reduction of over 30% in the January to March rainfall, which apparently had a huge impact on pasture regeneration and growth.

Re-establishing crops after the pasture phase

Trials over a 5-year period showed that it is possible to direct seed a crop on beds following grazed pasture without the need for any re-forming of beds (GRDC 2004). This may not be the case on sandy and sandy loam soils, or when there has been excessive movement of soil from bed shoulders into the furrow. Reshaping the beds before crop sowing is advisable if this has occurred.

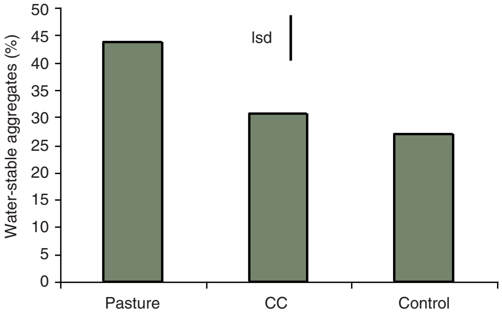


Figure 7. Water-stable aggregates >0.5 mm diameter (% of total soil) (0–0.2 mm depth) from permanent raised beds at Gnarwarre after more than four years of pasture (Pasture), continued crops (CC), or fallow (Control).

Grazing guidelines for raised beds

Grazing of raised beds mainly occurs on stubbles over summer and autumn when soils are dry and structurally strong. If raised beds are grazed when the soil is wet, compaction damage can occur. Whenever sheep are on beds, it is advisable to remove them when the soil is wet and likely to be damaged by compaction.

Principles of sowing on beds

Compared with cropping on the flat, successfully sowing and establishing crops on raised beds introduces a new set of variables, requiring alignment of thought processes and machinery for successful management. The basic aims when sowing crops on raised beds are to:

- establish crop over the entire surface of the paddock including bed tops, shoulders and furrows (but not the permanent grassed waterways) (Figure 8).
- retain as much rainfall within the paddock as possible, while at the same time improving trafficability and preventing waterlogging.

Cultivation

To conserve bed shape and benefit from improvements to soil structure, it is desirable to use direct drilling whenever possible on raised beds (ie adhere to a permanent raised bed system). Direct drilling is a proven method of achieving good seed germination, plant establishment and growth in most stubble situations. Cultivation should only be considered when renovating the beds, or adding and incorporating products such as gypsum, poultry manure or lime.

Figure 8. To slow water movement, reduce nutrient runoff and compete with weeds, crop is sown (without fertilizer) into the furrows between the beds.

Bed shape

Difficulties such as uneven cultivation depth, inaccurate bed forming and presence of underground rocks can make the beds and furrows uneven in height. Sowing, operating machines such as harvesters with tyres wider than the furrow, and grazing all cause the beds to become very rounded as soil falls off the shoulders and into the furrows. Under such conditions using seeders with normal rigid undercarriages and tine assemblies results in uneven sowing depth, especially on the bed shoulders.

Soil structure

Raised bed controlled traffic systems greatly improve soil structure. Soil properties such as slaking, dispersion and bulk density are all decreased while water infiltration is increased (SFS 2000). The loose and friable nature of the soils can make good soil–seed contact hard to achieve. Firming the seed bed after sowing will enhance the soil–seed contact and improve seed germination and plant establishment.

Run-off from bed tops

The rounding of beds also accelerates water run-off, particularly from the bed shoulders. Grooving the beds in the direction of the bed using water harvesting furrows, usually formed with press wheels, can greatly help retain this valuable moisture (Figure 9).

Nutrient loss from paddocks

One option to minimise nutrient loss with run-off leaving the field is to sow the furrows between the beds with crop. Especially in drier seasons these furrow-planted crops will contribute to overall yield, and crop plants growing in sown furrows will also compete with weeds.

Figure 9. To improve water harvesting on bed tops and reduce surface run-off, beds are left with grooves after sowing, made by the press wheels.

Sowing machinery

Combine and drill modifications

A normal sowing combine or drill is quite adequate to sow good quality, even and level beds; however, some modifications will be needed. Generally, a 24-row machine can be adjusted to sow three beds of 1.7 m width, while a 28-row machine can sow three beds of 2 m width. A machine with easily adjustable tine positions is the best choice.

Stubble clearance and tine positions

For best stubble handling characteristics ‘combine seeders’ need to be modified to a ‘drill’ configuration by removing all tines without sowing boots. The undercarriages on most combines and drills are not wide enough to sow the shoulders of the outside beds, and outriggers must be added, either to the front or back of the undercarriage or to both for increased versatility, so that tines can be fitted closer to the wheels.

Elevated seed and fertiliser boxes

On gravity-fed combines and drills the delivery tubes to the outrigger tines may be too horizontal for good seed and fertiliser flow, but elevating the boxes will solve this problem.

Sowing height

At sowing the wheels of the machine travel in the furrows so the sowing points need to be 15–20 cm above this height. Most machines will be at or near their normal ‘travelling position’ when operating at this height, but If adjustment or modification of the travelling position cannot be achieved, larger wheels may need to be fitted to lift the overall height. Alternatively, some tines can be adjusted for height or shorter tines can be fitted.

Wheel and tyre width

To minimise furrow width and compaction of the bed shoulders, the maximum tyre width on tractors and seeders should be 350 mm for 1.7 m beds and 450 mm for 2.0 m beds.

Sowing points

Long narrow knife points, angled as vertically as practical, work well on raised beds. Their narrowness and vertical aspect help to minimise soil throw and disturbance, resulting in more even seed cover and reduced soil shedding into the furrows (Figure 10).

Importantly, these long points also cultivate the soil below sowing depth, helping to break up and destroy Rhizoctonia fungi and allow the primary roots of cereals and tap roots of canola to quickly and easily access the deeper topsoil in the bed and the subsoil below it.

Long narrow points can help to compensate for uneven bed heights and bumps and hollows, as they may still cut a sowing groove when the bed height falls away below the drill undercarriage.

Tine length

Adjustable tine lengths can be very useful for sowing the bed shoulders, which are almost always lower than the bed tops. A longer, or a lowered, tine will ensure seed is drilled into those lower shoulders. However, the relative heights should not be too great, or adjustment will be needed every time the machine needs to sow flat ground such as the headlands.

Sowing the furrows

A delivery tube positioned in front of the machine at 150–400 mm height will evenly distribute seed into the furrow. The seed will be covered by soil thrown by the other tines or will be pressed in by the machine's wheels. Seeds sown into furrows may germinate first because the furrows stay moist.

Rollers and press wheels

The soil in raised beds is often quite fluffy, and therefore improvements in crop establishment can be obtained by rolling after sowing (see Figure 8). On flat-topped beds a ridged steel or rubber tyred roller can be used, while for rounded beds a flexible roller that fits the bed shape is best. However, raised beds can be very uneven and the best results are usually obtained by using press wheels, which can be readily fitted to most combine seeders, drills or air seeders. These wheels have independent travel and adjustable springs so the pressure they place on the soil can be adjusted to suit the conditions.

The use of press wheels in flat-cropped paddocks in the high rainfall zone is considered to be very risky as rainfall after sowing can fill the grooves with water, waterlogging the drill row and reducing germination. On raised beds, however, the improved soil structure prevents waterlogging in press wheel grooves, and the improved seed–soil contact results in less free water close to the seed. Another very important benefit from using press wheels (Figure 11) on raised beds is that the furrows they leave harvest rainfall and reduce run-off from the bed tops.

Press wheel depth control

Press wheels are often used as the ideal means of controlling sowing depth. Sowing assemblies have been designed that incorporate good trash clearance, breakaway tines fitted with long knife points, and a press wheel that controls the depth of the sowing boot. These are working very well in beds of all shapes. With each assembly being independent, the whole surface profile of a raised bed paddock, including the bed tops, shoulders and furrows, can be sown with seed at the correct depth.

The multi-purpose sowing machine

Multi-purpose machine development

Machines are now available, including a model from a consortium of Geelong machinery manufacturers, that meet the full requirements of raised bed farming in southern Victoria.

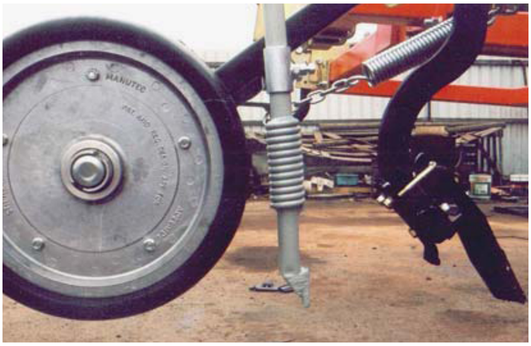


Figure 10. Knife points and press wheels are standard, good agronomy on raised beds.

Figure 11. Press wheels ensure improved seed-soil contact and also help in the formation of grooves for water harvesting.

Such machines are designed to have the following necessary capabilities:

- bed making ability
- bed renovating ability
- excellent clearance and sowing height to accommodate the tallest of beds
- ability to sow raised beds as well as controlled-traffic flat country and beds with few adjustments
- ability to cultivate soil below the sowing seed
- press wheel sowing depth control
- excellent trash clearance
- foldability for easy transport
- light enough to sow through wet conditions
- ability to sow more hectares than a normal combine/drill between fills
- ability to handle soil conditions ranging from sand through to rocky heavy clays
- press wheels that can handle sticky and cloddy soils.

These Geelong built machines have so far lived up to all expectations, offering farmers in southwestern Victoria a locally adapted piece of equipment.

Crop management on raised beds

Spraying

Successful spraying has been one of the easy operations to achieve on raised beds. Of course, once the tractor wheels are set up to the correct centre-to-centre measurement for the beds, a three-point linkage sprayer becomes the cheapest option. Otherwise, trailing rigs can easily be set up to the right wheel track width, and some commercial machines even come with adjustable width axles.

Gantry-type self-propelled sprayers have recently been released which have variable axle widths, narrow wheels and excellent ground clearance. These machines are generally owned and operated by contractors.

Because all guidance comes from the tractor travelling in the furrows, the need for foam markers is eliminated. Spraying at night, when wind speed is often much lower than during the day, becomes perfectly possible and very easy. If the boom width is a good fit to a number of bed widths, overlapping and missed strips are also eliminated, provided the operator accurately counts or marks the correct number of beds to straddle on each pass. This improves safety, saves money on chemicals and reduces adverse impacts of pesticide drift.

Fertiliser application

For economic plant growth and environmental reasons it is most important that fertilisers are only applied to the tops of beds (Figure 12).

When a twin spinner is used to apply urea, up to 40% of the product ends up in the furrow. Although the furrows only occupy 25–30% of the total surface area the urea granules that fall into the furrow don't bounce out and those that fall on the top of the bed quite often bounce into the furrows.

A pneumatic fertiliser spreader has been developed which blows granular fertiliser along a boom with outlets positioned only above the bed tops. The current model covers five beds but such a machine could cover seven or even nine beds.

Such a machine would be fast and accurate and would considerably cut the fertiliser budget for a cropping enterprise because the 40% of the fertiliser that falls in the furrows is essentially wasted. It would improve crop yield by allowing the application of multiple low doses of essential nutrients to be applied, as required by the crop, at all critical stages of the growing season. This would benefit both the crop and the environment by reducing nutrient losses from the bed furrows.

Although such spreaders have been available since 1999, they had not been widely adopted by 2004, perhaps surprisingly given the benefits and savings possible.

Windrowing

Both power-take-off (PTO) and self-propelled windrowers can be adapted to fit raised beds, with the wheels running in the furrows. Narrow wheels can also be fitted to avoid bed shoulder damage. It is also considered acceptable to leave windrowers unchanged and allow them to travel on the tops of the beds. Provided the soil is dry and in a strong condition, compaction damage can be minimised.

Machinery modifications

Achieving controlled traffic with harvesting equipment is the most difficult and expensive of all

Figure 12. Recent developed machinery ensures the application of fertiliser confined to only the top of beds.

machinery modifications for raised beds. Harvesters can be built or modified so that their wheels straddle two beds, which means a 4 m track for most raised bed systems, but the modifications are not easy and must be safely and correctly engineered. Suitable strength wheels and tyres must be used especially if narrow tyres are chosen. When harvesters have to run on the bed tops, soil damage is generally minimised because the soil is usually dry. However, if the soil is wet and compacted by headers, a full bed and furrow maintenance operation should be carried out the following autumn to restore structure and smooth/deepen furrows.

The length of the bed runs needs to be considered. If the header has a 9 m front and the bed length is 400 m, the harvest area is 0.36 ha. For a 10 t/ha crop, the header box needs to have a 3.6 t capacity if storage is available at each end of the paddock, and a 7.2 t capacity if storage is only at one end. Chaser bins that fit the bed furrows can solve this storage problem.

Stubble management

Dealing with crop residues is important in high rainfall zone crop production. While raised beds do not greatly alter the issues, they may alter the options available.

Harrowing, slashing, mulching and burning are the main stubble management methods used. The best method depends on the crop type, the amount of stubble, how well it has been chopped and spread behind the harvester, and other factors including farmer choice.

Burning

This is still a legitimate method of stubble disposal but it causes nutrient losses and environmental problems from smoke, and is becoming a method of last resort rather than a preferred option.

Canola and pulse stubbles

These are the easiest crop residues to manage, and burning is rarely required if the straw has been chopped and spread.

Cereal stubbles

Crop residues from cereals, especially from higher yielding raised bed crops, can be a difficult problem. Large amounts of cereal straw left on the surface can have major impacts on sowing and on the establishment of the following crop. For cereal crops with a low grain yield, less than 2.5 t/ha, most direct drilling machines can handle the remaining standing stubble. Once again, a chopper and spreader fitted to the header is beneficial. However, if the yield is over 2.5 t/ha, there can be a range of potential problems when sowing the following crop.

Achieving good trash clearance through heavy stubbles can be very difficult. Cereal stubble provides a suitable habitat for slugs, which can severely damage canola and pulse seedlings in the following crop.

Because heavy cereal stubble acts as mulch, the soil can remain very wet and cold following heavy autumn and winter rains, and this can adversely affect crop sowing operations and crop growth. Also, toxins released from cereal stubble can poison new seedlings and reduce establishment.

For these reasons many farmers choose to burn heavy cereal stubble. However, a range of alternative methods involving using the straw on or off the site is being developed.

Harvesting low with the header and baling the straw is one emerging possibility. Potential markets include pig producers, dairy farmers and mushroom growers. Sowing into the remaining short stubble can be very successful.

Some farmers have successfully baled and carted straw from raised bed paddocks using full controlled traffic, with all machinery wheels in the furrows. It is challenging but possible.

Incorporating the stubble to retain nutrients and improve the soil is an increasingly attractive option. Farmers and researchers are working to develop satisfactory methods, including cultivation with disc ploughs or disc harrows. However, with raised beds it may take two or three passes, and the final pass will have to involve bed renovation and reshaping.

Yield monitoring and mapping

Yield mapping is very effective on raised beds. Because the crop is grown in rows, it is easy to apply various treatments, study the results, observe the effects on yield maps in future years, and plan ongoing management.

Ongoing bed management

Trials and on-farm experience show that renovation of raised beds used for cropping is beneficial from time to time. Many farmers are now carrying out renovation every 2 or 3 years to:

- return some of the collapsed soil from the furrows (or gutters) back to the top of the bed and regain the original bed shape, height and crop rooting depth
- reduce some of the compaction that may have occurred on the beds
- address, on a regular basis, any hostile subsoil issues

- facilitate improved water infiltration into beds, especially in soils known for low macro-porosity and therefore poor water movement
- smooth and even out the furrows to allow free water movement.

Timing of renovation of raised beds

A decision about when to renovate beds is very site specific. The farmer needs to decide on when and how to renovate based on knowledge of the local soils and the shape and physical condition of the beds. If any one or a combination of the factors listed above may be beginning to have an impact on machinery operations or crop performance, it could be time to consider renovating the beds.

Renovations are best carried out during relatively dry periods, and experience suggests that late summer to early autumn is about the best time. Avoid periods when the soil is too moist because use of bed renovation equipment under such conditions may do more harm than good.

Measured benefits of farming systems on raised beds in southern Australia

Yield performance

Since the mid 1990s there have been many trials, demonstrations and surveys comparing grain yields from raised beds and flat land over a very diverse range of environments and soil types.

Commercial results reflect this research work, which has shown that grain yield responses depend on the degree of waterlogging experienced during various stages of crop growth.

A recent analysis of 56 comparisons of raised beds and flat land throughout southern Australia, including trials, demonstrations and surveys, showed that 40 indicated a positive yield response for beds, 13 a negative response, and 3 were similar for beds and flat land. Overall, the yield response was +35% in favour of raised beds.

Soil structure improvement

Research conducted by SFS to date suggests that improved yield on raised beds may be the result of better drainage during wetter years (SFS 1997), as well as increased root proliferation (SFS 2000) under conditions of minimum tillage (MT) and controlled traffic (CT) associated with raised beds (Peries et al 2004a, 2004b).

In a farming systems trial conducted near Geelong, southwest of Melbourne in Victoria, from 1998 to 2004, the hypothesis was tested that crops on raised beds will experience a different root environment over time. A black Vertosol (Isbell 1996) and a brown sodic Vertosol behaved differently in response to minimum tillage and controlled traffic and the alleviation of waterlogging. Three years after the installation of raised beds, crops experienced a lower soil bulk density and a consequent higher total porosity in the root zone compared to crops on the flat.

These differences in soil structure were also detected below the initial depth of tillage (20 cm), suggesting that processes other than the simple mixing of soil during the installation of beds and/or the wetting and drying cycles on beds were having an impact on soil structure under the beds in the long term. These differences may be explained in part through processes that are triggered by the removal of compaction compared to conventional farming practice. The improvements in soil structure resulted in enhanced plant available water (PAW) capacity in the subsoil, which could aid crops under suboptimal rainfall conditions (Peries et al 2004b) and lead to yield stability in the long term (Figure 13).

Economic benefits

The use of raised beds is expanding rapidly into the higher rainfall zones and commercial yield responses are quite often between 50% and 100% where waterlogging is severe. It is estimated that there are between 70,000 and 80,000 ha of raised beds in the high rainfall zones of southern Australia.

The grains industry in Victoria now produces over $200 m in grain exports annually. Raised bed development has led to the direct creation of more than 150 skilled jobs in the last 4 years, and it is expected

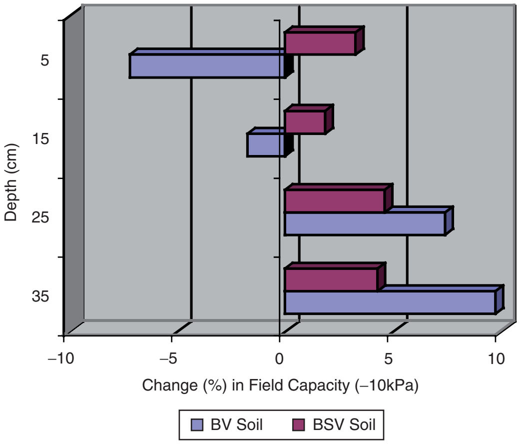


Figure 13. Measured differences in the upper level of plant available water (field capacity) in a black Vertosol (BV) and a brown sodic Vertosol (BSV) to a profile depth of 40 cm in 3-year-old permanent raised beds.

that there will be continued exponential growth in grain production and raised bed farming for the foreseeable future.

Farmer experience and adoption

This research and development of raised beds and controlled traffic began with the SFS partnership, including government agronomists, farmers and agribusiness. This partnership was formed with the primary aim of solving waterlogging and improving soil structure. After just 2 years of research and development and commercial trialling, the concept received very positive responses from farmers, media and machinery manufacturers. Positive peer group influences were and still are present throughout most of the high rainfall cropping areas.

The keys to development of this positive attitude were the initial success in reducing waterlogging and the low-cost methods demonstrated to farmers to enable them to begin bed farming very cheaply. Many contractors saw the potential of raised beds and entered the business. Their presence, together with the cheap modifications developed from existing farm machinery, has resulted in easy access to the technology. However, there are still a few issues that act as constraints to adoption which need to be addressed in the future, including:

- dry seasons — which reduce the impact of waterlogging damage
- machinery cost — initial costs could be a significant deterrent to some farmers
- paddock suitability — not all paddocks may be suitable for PRBs, eg red gum country with scattered trees
- non-arable country — eg rocks (due to the cost of clearing) or flat country
- disposal of excess water
- conservative farmers.

A number of research gaps have also been identified that need to be addressed if PRBs are to be significantly adopted as recommended best practice in the high rainfall zone. These include:

a. More plant available water (PAW) in spring — the low harvest index (HI) of cereals grown on raised beds has been attributed to the non-availability of adequate PAW in the subsoil during grain filling. Future research needs to address ways of overcoming this situation.
b. Managing stubble on raised beds — low HI of crops further exacerbates the problem of stubble loads on beds, leading to issues such as physical handling, slugs and toxicity. Inter-row sowing, inter-row weed control and herbicide resistance would also need to be addressed.
c. Trafficability of furrows in wet conditions — there is a need for guidelines for minimum damage to soil.
d. Compaction by windrowers and headers — at this stage it is assumed that the damage is minimal because these operations occur during early summer when soil is generally dry.
e. Fertiliser type, placement and timing are important to minimise nutrient run-off and improve the development of drainage plans for whole catchments.
f. Good comparisons of PRBs vs controlled traffic (CT) – many of the benefits of PRBs may be realised simply through CT, an area not yet investigated sufficiently.
g. Bed sizes, eg the use of 3-m-wide and deeper (400 mm) beds – the aim is to concentrate on improving a larger volume of soil above the hostile (sodic, dense and waterlogging) zone in the subsoil.

Acknowledgments

The rapid research in, and development of, raised beds and controlled traffic has been a combined team effort involving farmers, machinery manufacturers, agronomists and researchers. Authors acknowledge the financial support of the Grains Research and Development Corporation (GRDC) Australia; Department of Primary Industries, Victoria; and Southern Farming Systems in conducting the research and development work reported in this paper.

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Economic assessment of permanent raised beds for rice-based farming systems in Australia: An analytical framework

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Abstract

Natural contour field design, which is still a common design for rice–pasture–wheat based farming systems in Australia, offers a limited scope for growing other high-value summer and winter crops. Alternative designs incorporating permanent raised beds may offer more flexibility to grow different crops or more readily adapt cropping sequences to market conditions and water availability. This paper presents a progress report on the proposed framework for economic analysis of measuring benefits of permanent beds over other existing irrigation designs. Also presented are findings of a preliminary analysis of measuring the benefits of switching over to permanent beds from different existing field designs. The results of the analysis are very encouraging. The next step, determining the costs involved in establishing different irrigation designs, will help measure the net benefit of conversion to permanent beds over an existing design. For the final analysis it will be necessary to identify and compare more crop rotations with varying lengths from each field design to fully quantify the benefits to be gained from permanent beds.

Introduction

In recent years low water allocations, increased water costs, restrictions on further expansion of the area under rice cultivation and cost–price squeezing of agricultural commodities have had a serious impact on the economic viability of rice farms in Australia. Further, the natural contour field design that is still common in rice production, and in the rice–pasture–wheat based farming system, offers limited scope for growing other high-value summer and winter crops such as maize, sunflower, soybeans and canola that perform better on a raised bed design.

Permanent raised beds are an alternative strategy for growing rice and other crops in rice-based farming systems. Raised beds are a system where the crop and traffic zones (furrows) are distinctly separated. From a whole-of-system perspective, there may be significant advantages in growing rice on raised beds. Beds greatly improve surface drainage for both rice and other crops in rotation, improving establishment and yield of crops grown after rice, and increasing crop flexibility due to the ability to grow more waterlogging sensitive species. The use of raised beds also helps to improve field conditions, which allows farmers to undertake field operations (eg sowing, herbicide/insecticide applications, harvesting) in a more timely manner, thus contributing to improved yield outcomes and minimising losses. Furthermore, when uncertainty exists with the timing of water availability and the level of available water allocation, farmers have more cropping options in which to use the available water rather than carrying it over to the next season or selling unused water. It is also hypothesised that water productivity on a permanent bed cropping system, and the resulting potential for double cropping, would increase while the net groundwater recharge would decrease.

The ACIAR–GRDC–RIRDC–Rice CRC funded project ‘Permanent beds for rice wheat farming systems in Australia and India’ was initiated in response to increasing concerns about declining profitability of rice-based farming systems, and the need to reduce net groundwater recharge. The project aims to assess the effects of growing rice, other summer crops and winter crops on raised beds on various factors, including crop water use and its resources, net recharge of the watertable, productivity, profitability and water-use efficiency. This paper presents a progress report on the proposed framework for economic analysis of the permanent beds for

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rice–wheat farming systems in Australia. It details the methodological approach being taken and its underlying assumptions, as well as presenting some preliminary results.

Aims of economic analysis

The economic analysis aims to assess the likely benefits and costs of adoption of permanent beds in rice-based farming systems. More specifically, it aims to:

- evaluate the impact of conversion to permanent beds from different existing irrigation designs
- measure the potential benefits to rice farmers
- estimate capital and operating/management costs
- identify constraints of adoption
- evaluate and compare these benefits with the costs to the funding bodies.

Options considered for evaluations

Soils of the broadacre irrigated farms in southern New South Wales (NSW) have relatively poor physical characteristics with low infiltration, due to which rice–pasture has been a most successful farming system. Until the 1970s, the non-lasered natural contour design was the most common design for rice–pasture rotation. However, this design is inefficient in terms of water use, drainage, use of machinery and productivity.

To improve water-use efficiency and productivity, farmers began laser levelling their rice–pasture paddocks. It has been found that in a laser-levelled paddock, an even application of irrigation at a depth to match plant water requirements helps to improve profitability and water productivity. Now almost 70–80% of the farms in the Murrumbidgee Irrigation Area and the Coleambally Irrigation Area have laser-levelled regular design, whereas in the Murray Valley there are a significant number of farmers still using the conventional natural contour design.

Furthermore, with the current low level of water allocations, increasing restrictions on rice growing and a decline in livestock profitability in the late 1990s, many farmers have moved away from pasture-based rotations to follow more intensive cropping rotations, which require different field designs depending on the crops grown.

This study considers the following four field designs for evaluation of benefits and costs of conversion to lateral permanent raised beds over an existing design. Lateral raised beds are beds placed laterally across the main slope of the field within bankless channel or drain-back level basin designs, rather than conventional raised beds running down the field slope (see Beecher et al, these proceedings)

I. Non-landformed natural contour
II. Laser landformed natural contour
III. Laser landformed square contour
IV. Laser landformed square contour alternating with raised beds.

Methodology

The proposed analysis uses partial as well as whole-farm budgeting to capture changes in the annual costs and benefits of conversion to permanent beds from different selected field designs on large area rice farms. Two components of the methodology have been developed and are used in the analysis.

Farm-level analysis

The first step is to measure the on-farm impact of converting from a number of different irrigation designs to lateral permanent raised beds, which are more irrigation efficient. The study measures the financial, social and environmental benefits of research on permanent beds. However, the main focus of the evaluation is on the economic effects of the research, which are driven by productivity gains, shifts in cropping rotations, reduction in production costs, and water and labour savings at the farm level. The analysis of the social and environmental benefits necessarily involves qualitative rather than quantitative measurements.

Financial benefits to growers

The financial benefits received by farmers from permanent raised beds vary across the different designs, but include:

- an increase in returns from an individual crop/enterprise due to:
  - an increase in yield
  - a reduction in variable input costs
  - a reduction in production losses from improved timeliness of operations
  - water savings, which lead to a reduction in variable cost of the water used
- labour savings
- machinery cost savings
- changes in cropping rotations with more profitable cropping options
- improved chances of growing opportunistic crops straight after rice
- income from potential sale of saved water
- savings in overhead and operating costs
- a potential increase in area under cropping due to better design.

Measurement of financial benefits and costs

A range of techniques is used to measure the on-farm financial benefits and costs of adoption of permanent bed designs on rice farms.

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Gross margin analysis

The gross margin (GM) is the gross return from a crop (yield times price) less the variable costs of production such as soil preparation, seed, fertiliser, irrigation water, plant protection, fuel, harvesting, insurance and levies. Overhead and operating costs that do not vary with the level of production are not considered in the GM analysis. Crops and rotations can be compared using GMs as long as there is no significant change in overhead costs between the alternative options being compared.

Costs of some inputs or operations such as irrigation water, fertiliser, machinery operations etc are different under different field designs. Increase in yield or price also leads to increase in cost of some variable inputs and operations such as harvesting costs, insurance and research levies. Therefore, the variable costs and returns of an individual crop/enterprise are measured for different irrigation designs and cropping rotations separately, following GM analysis.

Crop sequence gross margin analysis

Gross margin analysis deals with only one crop. Farmers grow a number of crops from the same paddock in a particular rotation. Furthermore, selection of an enterprise is done not only on the basis of its profitability as an independent enterprise but also by its contribution to other enterprises or to a cropping system. To maintain the productive capacity and economic sustainability of a farm, farmers grow certain crops that may not be profitable on their own, but by improving soil fertility they help to increase yield of other crops grown in the rotation. They may act as a break crop to help reduce yield losses from weeds and disease. Therefore, the study analyses the impact on crop sequence GM from conversion to permanent beds over other designs.

Improved field design offers opportunities to change to a more profitable crop from an existing less profitable crop. Therefore, the study first identifies one typical rice-based cropping rotation from each selected field design. Different crops perform differently depending on their placement in a particular cropping rotation. This placement may lead to an increase in yield, or an increase or reduction in use of some of the variable inputs such as fertilisers, chemicals or irrigation water used. These interrelationships and interdependencies require analysis of crop sequence budgets to enable comparison of the performance of different rotations on different field designs. The study considers such variations while calculating GMs for each crop in a rotation.

Permanent beds help to improve drainage after rice harvest, which improves the chances of growing crops immediately after rice (an opportunity crop). The opportunity cropping not only helps to intercept water present in the upper soil profile but is also an extra source of income. Therefore, the GM from an opportunity crop is modified to reflect such changes.

The present value (PV) of the crop GM is calculated to assess the financial value of each selected rotation. The duration of most of the rice-based rotations is up to 9 years; therefore, the GMs in years 2 to 9 are discounted back to year 1 values using a discount rate to reflect the time preference of farmers. The PV of a rotation GM is the sum of the discounted annual GMs from the crops in the rotation.

The PV is calculated using equation 1:

$$\mathrm{PV} = \sum_{\mathrm{i}=1}^{\mathrm{n}} GM_{\mathrm{i}} / (1 + rate)^{\mathrm{i}} \qquad \text{equation 1}$$

where rate is the discount rate (7% is the NSW Treasury recommended discount rate for economic evaluations (NSW Agriculture 1998)) and GM_1, GM_2, …, GM_i are the GMs for years 1 to n, n being the rotation length.

The PVs of different rotation GMs cannot be directly compared if they differ in duration (years). To make them comparable, the PV of an infinite series (PVI) of each rotation is computed using the *Faustman formula*, equation 2:

$$PVI = \mathrm{PV} \,/\, \{1 - [1/(1+i)^{\mathrm{N}}]\} \qquad \text{equation 2}$$

where the denominator is the Faustman factor and is one less than the discount factor from a standard discount table (Pearse 1990 in Elton et al 1997).

The study then measures the GMs from an expanded range of rotations for each selected field design, becoming more familiar with the process. A weighted average benefit from the selected rotations within a design is then calculated to measure the benefits from lateral permanent raised beds over different existing designs.

Development/cash flow budgets

Development refers to investing capital in a farm to increase its profitability and value. Development budgeting is a technique used to show future costs and returns associated with a development program.

Cash flows used in development budgeting demonstrate the difference between total income and total costs. The surplus or debt represents a cumulative total of the difference between income and costs in one year and the surplus or debt of the previous year. Development budgets use GMs to develop budget projections, but do not include fixed or overhead costs such as depreciation, interest payments, rates, insurance and permanent labour costs. Primarily used as one of the tools to evaluate an investment, development/cash flow budgets are a basis for deciding whether or not to undertake a project, for obtaining finance for it and for monitoring its performance once it commences.

The study develops cash flow budgets of a range of irrigation designs to demonstrate the difference between total income and costs involved and the breakeven years to recover costs.

Whole-farm operations

When switching to a different design or crop sequence, some factors that vary with the level of production can be captured easily by directly measuring changes in the benefits and costs. However, some other factors relate to whole-farm operations, eg permanent labour, land rates, electricity, diesel, and expenditure on machinery depreciation, repairs and maintenance, and operating costs. A whole-farm analysis is needed to measure the impact of changes in these parameters on the total income and costs.

Within an economics project funded by the Cooperative Research Centre for Sustainable Rice Production (Rice CRC), a whole-farm model has been developed that represents the broadacre irrigated rice farms of the MIA in terms of farm size, cropping rotations, water allocations, resource structure etc (Singh et al 2005). This model is used to analyse the whole-farm consequences resulting from shifts in cropping rotation or irrigation design, taking into account any changes in the variable, overhead and operating costs.

Value of water saved

At the farm level there are a number of options concerning any water saved as a result of changes to irrigation design and management that use less water. Farmers may choose to use the saved water to increase the area under different crops, carry over this water to the next irrigation season or sell any water saved. In the evaluations, it is assumed that the value of saved water is the price it could be sold for.

Value of labour saved

A typical rice farmer employs some casual labour to meet peak period whole-farm labour requirements. The benefits of labour saved will be measured through reduction in number of weeks of casual employment. In the whole-farm model the study considers the three most common rice-based farming systems. In each rotation it is assumed that a farmer employs casual labour for 6–12 weeks to meet peak period requirements. Any savings of such casual labour are a net benefit of labour savings from the adoption of the beds design.

Value of environmental benefits

The permanent beds design will improve the prospects of growing an opportunity crop immediately after rice. There are some expected environmental benefits to the broader Australian community from growing crops after rice. Wheat grown immediately after rice leads to higher water productivity, minimising run-off and accessions to groundwater and increasing water use through up-flow from shallow watertables. It is hard to measure the benefits of a reduction in groundwater accessions. While it is unlikely that spear-points could remove all this water, a cost of \$30/ML for pumping out groundwater is used as a surrogate measure of the benefits of reducing groundwater prior to the next crop. This includes the cost of pumping the water, the capital cost of a spear-point system, and the capital cost of a storage and drainage system for disposal of the water pumped out (Singh 2000).

Income from a fallow paddock

It is assumed that a farmer earns a GM of \$34 per hectare (@1 DSE/ha) from sheep grazing natural grasses and weeds in a fallow paddock after the rice phase of the rotation (Geoff Duddy, pers comm). This amount is included as income in evaluation of the ‘without opportunistic wheat’ rotations.

Regional analysis

The majority of the rice industry is located in four irrigation districts: the Murrumbidgee, Coleambally, West Murray Valley and East Murray Valley. There are some significant differences among these districts/regions (in terms of level of development, area under different irrigation designs, severity of major issues, cropping rotations, farm size, water allocations, percentage of area irrigated, rice input use and yield) that will lead to different levels of benefits and rate of adoption of lateral permanent raised beds. To capture these regional differences, a multiregional model is used to evaluate the benefits and costs associated with shifts in irrigation designs.

Benefit–cost analysis is an evaluation technique that determines the economic feasibility of a project by comparing the value of benefits arising from the new technology with the costs of developing and implementing the technology. The present value of benefits (PVB) and the present value of costs (PVC) are then compared to determine the net present value (NPV) of the project. If the NPV is positive (ie the benefits exceed the costs), the project is deemed to be economically feasible and will produce a positive return to investment.

Other measures of economic feasibility include the benefit–cost ratio (BCR) and the internal rate of return (IRR). For a project to be economically feasible the ratio of the PVR to the PVC, the BCR, should be greater than one. Instead of applying a specific discount rate such as 7% (NSW Treasury recommended discount rate for economic evaluations (NSW Agriculture 1998)), the IRR is used as the discount rate, which will give the project an NPV of zero. The IRR can be compared with returns from other investments. The specified discount rate, 7% in this case, can be considered as a 'break-even point'. If a project generates an IRR greater than 7%, it provides a better rate of return than investment in many of the safe government and banking sector financial instruments.

Costs involved in development of different irrigation designs

Costs involved in the development of different field designs differ depending on the life of the design, which can vary from 1 year to more than 10 years. The costs considered in the analysis include the initial cost of the survey design; capital costs; annual maintenance (reshaping) costs over the life span of the system; as well as the cost of a storage structure if required (eg for subsurface drip irrigation on beds), its annual maintenance cost, and loss of production from the area under the storage structure. The residual value of a design, machinery or irrigation technology (eg drip irrigation) is considered in measuring actual costs involved in developing and using a design over the accounting period.

Drawing these impacts into a benefit–cost framework

These costs, together with the benefits involved, are considered to measure the on-farm impact of the improved designs within a benefit–cost framework. Finally, an economic analysis is undertaken to measure the return on investments in research on permanent raised beds that would help to provide a basis for establishing priorities for research in rice. The study measures the returns to research development and extension investment (taking into account both in-kind and cash expenditure) associated with the project for the development of such designs. The farm-level benefits will be scaled, taking into account lags involved in the development and adoption of lateral permanent raised beds, and the rate and extent of adoption of permanent beds over the accounting period for both 'with' and 'without' project scenarios (see below).

Expenditure on research and extension associated with the project

To measure the returns to R&D investments in the project, direct expenditure by ACIAR–GRDC–RIRDC–Rice CRC and in-kind contributions from the researchers' organisations (CSIRO Land and Water and NSW DPI) to the project over the 5-year period from 2002–03 to 2006–07 will be considered. All costs will be expressed in 2006 dollars after inflating expenditure in previous years by the consumer price index. Direct costs, if any, for extension activities to promote this technology during or after the project will also be included in the analysis.

Defining the 'with' and 'without' project scenarios

In this evaluation the impacts of the project outcomes have been characterised as bringing forward the adoption of either new technology or best management practices by a certain number of years. That is, it is assumed that the maximum level of adoption 'with project' will be the same as 'without project', but adoption will occur earlier in the 'with' scenario.

It is assumed that attending field days and meetings and reading media releases issued by the project will also help to accelerate the rate of adoption under the 'with' project scenario. It is also believed that with a good network of extension professionals and a well-organised rice industry for the dissemination of information, rapid adoption would lead to significant financial and environmental benefits from the permanent beds technology, provided growers are trading profitably. This approach is illustrated in Figure 1.

Under the 'without' project scenario, farmers will still be able to adopt lateral permanent raised beds design because beds have been used for several years in other dryland and irrigated farming systems, not only in Australia but also in many other developed

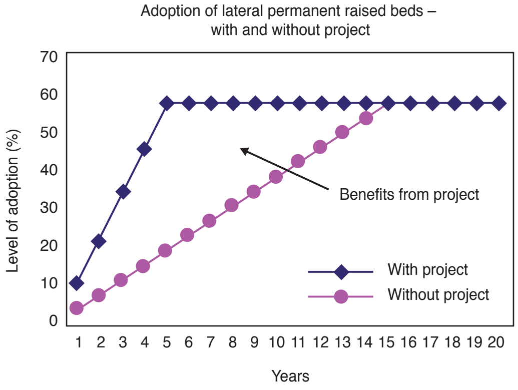

Figure 1. Approach to estimation of benefits of the research project.

and developing countries. CIMMYT researchers and partners in Mexico, South Asia, China, Central Asia, Turkey and other parts of the world have been experimenting intensively with bed planting for about a decade (CIMMYT 2004)

The benefits of the project are largely in the form of a faster rate of adoption of permanent beds technology. In the absence of any hard evidence of adoption trends, the study will be relying on the best estimates provided by research, extension staff and other industry people. The assumption is that, in 5 years time, the maximum adoption level will be, say, 60% of the area under rice-based farming systems. Without this project, it would take an estimated 15 years rather than 5 years for the maximum level of adoption to be attained. Apart from other constraints on the adoption of permanent beds, areas that are too steep or too flat may not be able to adopt a lateral permanent raised beds design.

Key assumptions and data used

To undertake a benefit–cost analysis of the project, the benefits estimated above have to be scaled up to reflect the rate and extent of adoption of the technology, lags in development and adoption of the technology, and an estimate of when the technology will become obsolete.

The impact of new technologies can be spread over many years. In this analysis the period over which benefits and costs of the proposal are accounted is 20 years, ie from 2006 to 2025. After 2025 it is anticipated that this technology would be replaced by new technology from future research and development.

All costs and streams of benefits will be discounted to the present value, ie expressed in 2006 dollars, which requires past expenditures to be converted to real 2006 dollars by the CPI, then compounded forward at the discount rate of 7%. All future returns and costs will be discounted to 2006 values to reflect the net present value of benefits and costs.

It is assumed that Australia is a price taker in the world rice and other commodity markets, and hence any changes in production in Australia as a result of this new technology will have no effect on world prices.

There have been large variations in the area under rice, and in prices of rice, wheat and other commodities, during the last few years. To minimise the effect of such fluctuations, averages over the last 5 years for each of the parameters are used in the analysis.

Sensitivity analysis

To demonstrate the effect of change of yield, prices, discount rate used on returns, and rate and extent of adoption, sensitivity analysis will be undertaken to give an idea about the sensitivity of these variables on returns.

Preliminary results of the crop sequence gross margin analysis

Analysis has been carried out to measure the benefits of using lateral permanent raised beds over other existing irrigation designs for growing rice and rice-based cropping rotations. This analysis has included gross margins (GMs), shifts in crop rotations and crop options in more general terms, considering one rotation selected from each irrigation design.

Typical rotations considered for raised beds vs other irrigation designs

Different rice farms follow different field designs depending on the level of on-farm development and the crops grown in combination with rice. There is no one rotation suited to every rice-based farm and every field design included in the analysis. Therefore, to begin with, the study has identified one typical rotation from each irrigation design that allows a comparison of the financial performance of different rotations under different designs. Details of the crops, cropping rotations and length of each rotation under different irrigation designs are provided in Table 1. The study has considered two options in the laser-landformed lateral permanent raised beds design which use different cropping intensities.

Information given in Table 1 shows that after the rice phase, on square contour with conventional beds (4) and lateral permanent beds (5a & b) designs, farmers can grow soybean and barley, compared to growing wheat and pastures on non-laser (1) and laser-level contour (2 & 3) designs. The lengths of rotations on the conventional and permanent bed designs are also much shorter compared to rotations on the other contour-based designs. Furthermore, rice, with the highest GMs per hectare, is grown in 3 out of 5 years on beds compared to 3 out of 8 years on the other contour-based designs. It has been observed that the non-rice phase of a rotation on beds includes double cropping of soybean and barley, whereas for the other rice–pasture based rotations on contour design, in most years farmers grow one crop each year. In a rice–pasture based rotation, winter pasture in the last year of the rotation is cultivated in September to allow time to prepare the field for sowing rice, resulting in a reduced GM in the third year.

To measure crop sequence GMs from the selected rotations, the GMs from each crop grown in different rotations under different selected designs are calculated separately, using the NSW DPI Farm Budget Handbooks for southern NSW irrigated summer and winter crops and for sheep and wool (Singh & Whitworth 2003; Singh & Whitworth 2004; Webster 1998). Some of the farming practices in these budgets are modified as per information provided by local

Table 1. Details of crops, crop sequences and lengths of rotation for selected irrigation field designs.

Irrigation design	Rotation analysed	Rotation length (years)
1 Non-landformed natural contour	RRRF(OW)WWPPP	8
2 Laser-landformed natural contour	RRRF(OW)WWPPP	8
3 Laser-landformed square contour	RRRF(OW)WWPPP	8
4 Laser-landformed square contour alternating with permanent raised beds	RRRFS/BSF	5
5a Laser-landformed lateral permanent raised beds	RRB/SB/S	4
5b Laser-landformed lateral permanent raised beds	RRRB/SB/S	5

Note: R = Rice, B = barley, S = soybean, W = wheat, OW = opportunity wheat, F = fallow

agronomists, researchers and rice growers to more closely reflect practices in different designs.

Information on GMs used in the analysis is provided in Table 2. In calculating the GMs the study used the following assumptions:

- All rice is medium grain in size.
- Australian Standard Wheat (ASW) was used both as the opportunistic wheat and standard wheat.
- Sub-clover was used as annual pasture, as in the budget handbook.
- Second-cross lambs were considered in this analysis.
- The study measured the crop sequence GMs from selected rotations (land use sequences). While measuring GMs from a rotation without an opportunity crop, the study assumes an income of $33/ha from a fallow paddock in the rotation.

Since the rotations selected for analysis vary in duration (years), the PVI of each rotation has been computed using equation 2 (see above). Information on the net present value of GMs from adoption of lateral permanent raised beds is presented in Table 3.

Critical appraisal of the results presented in Table 3 shows that conversion of a non-landformed natural contour design to a lateral permanent raised beds design could lead to a $12,968 (48%) increase in GMs per hectare over the extended period. Conversion to a lateral permanent raised beds design from any of laser-landformed natural contour, laser-landformed

Table 2. Gross margins of different enterprises used in the analysis of shifts in cropping rotations possible from changes in irrigation designs in 2004–05

Crop/ enterprise	Gross margins of different crops on different irrigation designs ($/ha)				
	Design I	Design II	Design III	Design IV	Design V
1st year rice	1682	1682	1813	1677	1949
2nd year rice	1463	1488	1688	1674	1944
3rd year rice	1494	1458	1658	1629	1944
Opportunity wheat	251	416	533	–	–
1st wheat	186	327	431	–	–
2nd wheat	65	235	326	–	–
1st barley	–	–	–	385	380
2nd barley	–	–	–	385	380
1st soybean	–	–	–	788	704
2nd soybean	–	–	–	576	704
1st pasture	181	248	248	–	–
2nd pasture	156	223	223	–	–
3rd pasture	81	125	125	–	–
Probability of opportunity wheat	0.50	0.66	0.80	–	–

Source: Singh & Whitworth 2003; Singh & Whitworth 2004; Webster 2004; and personal communication from rice growers, 2004.
Note: These budgets are subject to review with the local rice growers.

I	Non-landformed natural contour design
II	Landformed natural contour design
III	Landformed square contour design
IV	Laser-landformed square contour alternating with permanent raised beds
V	Lateral permanent raise beds

Table 3. Present value of infinite series of gross margins from different rice-based crop rotations under different irrigation designs.

	Irrigation design	PVI of gross margins ($/ha)
1	Non-landformed natural contour	14 041
2	Laser-landformed natural contour	15 595
3	Laser-landformed square contour	17 815
4	Laser-landformed square contour alternating with permanent raised beds	24 438
5a	Laser-landformed lateral permanent raised beds	24 953
5b	Laser-landformed lateral permanent raised beds	27 009

square contour, laser-landformed square contour with rice–soy rotation, and landformed permanent raised beds (5a) designs could result in increased GMs per hectare of $11,414 (42%), $9,194 (34%), $2,571 (9%) and $2,056 (8%) respectively.

As mentioned above, in this analysis only one rotation from each design was considered for evaluation of benefits of lateral permanent raised beds over the other selected designs. The next research step will be to determine the costs involved in implementing different irrigation designs, which will help to measure the net benefits of conversion to permanent beds over an existing design. For the final analysis, more rotations with varying lengths from each field design will be identified and analysed to measure the weighted average benefits from lateral permanent raised beds over different designs.

Social and environmental benefits

This study qualitatively identifies some of the on- and off-farm social and environmental benefits of using permanent raised beds although it does not quantify these benefits.

Social benefits

Social benefits resulting from the adoption of permanent raised beds could include the following:

- More confidence in achieving targeted results will help to increase on-farm capital investment, and the increased productive capacity will increase the value of the farm, leading to enhanced social status and better standing of the farmer in the local community.
- An increase in income and capital investment will have flow-on effects on the regional economy and development in terms of creation of better health, educational, recreational and sporting facilities for the local community as a whole.
- Labour savings will result in the farmer having more time available for participation in community activities.
- Increases in income and labour savings will help the farmer enjoy a better family lifestyle.

Environmental benefits

The adoption of permanent raised beds will lead to improved water productivity and better prospects of growing opportunity crops following rice. It would also lead to other environmental benefits including:

- a lowering of water accessions and the potential for reduced salinisation
- a reduction in losses though surface run-off
- a reduction in loss of chemicals through drainage/surface run-off
- a potential reduction of greenhouse gas emissions.

Conclusions

Natural contour field design, a common design for irrigated rice–pasture–wheat based farming systems in Australia, offers a limited scope for growing other high-value summer and winter crops such as maize, sunflower, soybeans and canola that perform better on a permanent bed design. Lateral permanent raised beds are an alternative strategy for growing rice and using rice-based farming systems. From a system perspective, there may be significant advantages to be gained from growing rice on lateral permanent raised beds.

The results of the preliminary crop sequence GM analysis have revealed that the adoption of permanent beds can lead to a significant increase in GMs over the other selected designs for rice-based farming systems. Further work to quantify the costs involved in development of different irrigation designs will help to measure the net benefits of conversion to lateral permanent raised beds over existing designs, and to evaluate changes in irrigated farming systems for growers and the rice industry.

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Evaluation and performance of permanent raised bed systems in Asia, Mexico and Australia: a synopsis

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These workshop proceedings have brought together a great diversity of papers, covering a broad range of conditions under which permanent raised bed (PRB) systems have evolved. Indeed, the papers presented show that, strictly speaking, in most case these systems are still in transition from fresh bed systems towards more permanent systems. There are, however, a few examples of cases where the PRB packages have matured and some examples of widespread uptake by farmers. An overview of the different systems that have evolved to date and that have been described in more detail in these proceedings is provided in Table 1. In this paper, we attempt to draw out some more generalised learnings and provide some conclusions for future research to underpin increased uptake by farmers. To achieve this, we asked ourselves the following questions:

- What are PRB systems; how do we define them, and what is their rationale?
- Why do we promote and why would farmers want to adopt PRB systems; ie what are the benefits and risks associated with PRB? How would we measure the benefits and risks?
- How can these benefits be achieved consistently; what are the critical design factors?
- What are the constraints to further adoption; ie what are the technical knowledge gaps, and socio-economic determinants that need to be addressed to maximise uptake?

Permanent raised beds: definitions and rationale

Conceptually, PRB systems can be regarded as a special case of direct drilling within a zero-till or minimum tillage context, with the only difference to conventional zero-till systems being the use of beds rather than flat field surfaces. Permanency of beds in the most general form is taken to mean beds that remain in place at least for several consecutive crops, in some cases indefinitely. In comparison, 'fresh' raised beds are formed for one crop and then flattened for the next (eg rice after wheat as currently practised). Under this somewhat broader definition, many of the systems described in this volume could qualify as 'permanent'; however, the ultimate intent is that beds be in place over longer periods of time than just a double crop. In some case, while the location of the beds is permanent, there may be a need to carry out some form of renovation, ranging from reshaping the furrows and beds or superficial light harrowing on the bed surface (eg to manage Heliothis pupae in cotton PRB systems), to ripping or passing sweeps through the base of the beds (eg in the system described by Hamilton et al[1]). There is some evidence that as soil structure stability improves, the need for/or frequency of such operations tends to decrease. Strictly speaking, the above cases, though the bed location is permanent, do not constitute zero-till systems, but rather represent a direct-drilling/minimum till system. Irrespective of the intensity of superficial tillage, another key potential characteristic of PRB systems, shared with zero-till, is the retention of residues on the surface, although the degree to which this happens currently varies from no or little retention to full retention of residues.

The other aspect requiring definition is the term 'bed'. In the broadest sense, beds are structures formed by mounding up loose soil, usually from a tilled, flat surface, in a way that they regularly alternate with furrows. Beds can vary in width

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[1] All references in this paper are to papers presented in these proceedings.

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Table 1. Overview of raised bed systems in Mexico, Australia and Asia

Country	System	Bed type[1]	Level of adoption	Reference
Mexico	Irrigated wheat	TRB	Widespread (>100,000 ha)	Sayre, pers comm
	Irrigated maize	TRB	Research phase	Sayre et al
	Rainfed M/W	PRB	Research phase	Sayre et al
Australia	Irrigated mixed cropping	PRB	~35,000 ha in Murrumbidgee Irrigation area; ~5,000 ha in Murray valley	Beecher et al
	Irrigated cotton	PRB	Widespread in NSW, QLD; about 80% of cotton growers	Hulugalle & Daniells
	Rainfed and irrigated sugarcane	TRB	Widespread in irrigated and humid cane growing areas	Garside
		PRB	Research phase	
	Rainfed wheat in high rainfall zone of SA	PRB	About 15% of cropped area; ~60,000 ha	Peries, pers comm
	Rainfed wheat in high rainfall zone of WA	PRB	Increasing farmer uptake (~35,000 ha)	Hamilton et al
Bangladesh	Irrigated rice/wheat	TRB	Some on-farm demo sites	Meisner et al
		PRB	Research phase	
China	Irrigated maize/wheat, Shandong Province	TRB	~40,000 ha	Sayre, pers comm
		PRB	Research phase	Wang et al
	Irrigated maize/wheat, Hexi Corridor (Gansu)	TRB	Some on-farm demo sites	Ma et al
		PRB	Research phase	
India	Irrigated wheat	TRB	Incipient uptake; 1000 ha?	Kukal et al
	Irrigated rice/wheat	PRB	Research phase	Kukal et al
	Irrigated soybean, maize/wheat	PRB	Research phase	Ram et al
Indonesia	Rainfed rice/soybeans, vegetables	PRB	Incipient uptake; 50 ha? On-farm demo sites	Ma'shum et al
Pakistan	Irrigated cotton/wheat	TRB	~500,000 ha in Pakistan ~40% of Punjab cotton farmers	Sayre, pers comm Gill et al
	Irrigated maize/wheat	PRB	Incipient uptake; 50 ha? On-farm demo sites	Hassan et al
Philippines	Irrigated rice	PRB	Research phase	Cabangon et al

[1] TRB = tilled raised beds, beds flattened and reshaped after one crop or rotation; PRB = permanent raised beds; in place for more than a crop or rotation cycle

(0.25–2.00 m) and the number of crop rows on each bed (single rows for crops like cotton, maize, sugar cane; multiple rows per bed for cereals). Often the bed width is determined by the width of machinery used, either the tractor axle width corresponding to furrow to furrow width, or multiples thereof. This definition encompasses many furrow irrigation systems, in so far as furrows are permanent, and may explain the origin of PRBs, the differentiation probably being determined by the permanency of the beds.

As can readily be gathered from the papers contained in these proceedings, the rationale behind use of PRBs varies quite considerably, and actual bed configuration varies accordingly. An extensive body of literature exists that indicates that zero-till systems, on flat fields provide a range of compelling benefits, such as significantly reduced costs of production, greater timeliness of field operations, control of runoff and erosion and, over time, significant increases in physical, chemical and biological indicators of soil health, generally resulting in increased yields. The question thus arises, given all the above benefits, why farmers would opt for the more costly option of PRB — what additional benefits would PRB systems generate beyond zero or minimum tillage systems on the flat?

Figure 1 portrays a conceptual framework that identifies four primary management objectives constituting a possible rationale for selecting PRBs as the preferred soil management system. Under rainfed conditions, one widespread purpose of PRBs is to enable crop production on waterlogged soils that would otherwise preclude or make cropping very risky. Examples for this case are mainly found in Australia, in particular the wheat growing areas of southern and

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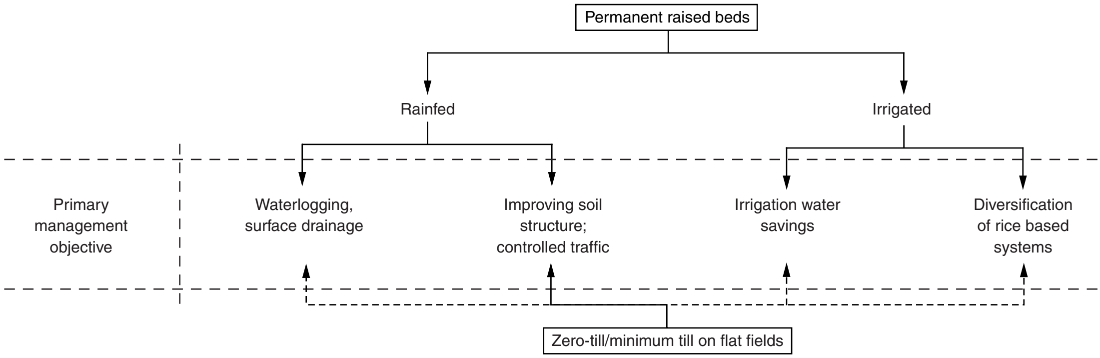

Figure 1. Interface between permanent raised bed sysems (with zero till) and zero-till on flat fields.

western Australia characterised by higher rainfall and low permeability duplex soils (Wightman et al; Hamilton et al). Whilst not a primary objective, management of waterlogging during the monsoon has also been stated as being an important objective of PRBs in rainfed systems (which have supplementary irrigation during the dry season) in Indonesia and Pakistan (Ma'shum et al; Hassan et al).

Also under rainfed conditions, PRBs have been established as a means of implementing controlled traffic, with a primary objective of addressing soil structural decline. Reducing the impact of soil compaction and soil structural decline is stated as a primary objective in some rainfed cropping systems of Australia, for instance cotton (Hulugalle and Daniells) and sugarcane (Garside), although in both cropping systems furrow irrigated systems are prevalent in some regions, and other objectives such as water savings then also play a role. Initially, the furrows between beds served as a wheel guide for controlled traffic; this may now be superseded with access to GPS guided systems enabling controlled traffic, but in less developed countries, using furrows to guide tractors will still be relevant for some time (China, India and Pakistan). It may also be a management issue in irrigated, non-monsoonal situations, where soils have poor internal drainage and are prone to waterlogging during irrigation.

In irrigated systems, one of the big drivers for using PRBs has been the concern over increasing levels of water scarcity, and hence the need to convert less efficient, traditional flood-irrigated systems to furrow irrigation based on PRBs; efficiency can be poor in the former systems, especially when there is no access to laser levelling. This is particularly true of rice–wheat systems of the NW Indo-Gangetic Plains (States of Punjab and Haryana in India; Indus Basin in Pakistan; parts of Bangladesh; see Kukal et al; Gill et al; Meisner et al), but is also true of maize–wheat systems in Mexico, Pakistan and China (Sayre et al; Hassan et al; Gill et al; Zhongming et al; Wang et al), as well as in Australian rice growing areas (Beecher et al).

In irrigated rice systems of Asia and Australia, a key driver for development of PRBs is the devising of systems that allow for both more efficient establishment of summer crops as alternatives to rice and easier establishment of crops following rice in order to provide more flexibility for crop diversification. The basic premise is that PRBs in rice systems may circumvent the need for both costly puddling operations before transplanting rice and excessive tillage post rice to generate adequate planting conditions for crops following rice.

In reality, in some cases PRBs may simultaneously meet several of the above four distinct objectives. For example, in rice–wheat systems in the IGP and Australia water savings may be the key objective in the rice phase, but management of waterlogging and soil structure the key objectives in the wheat phase. Despite this, we believe that the conceptualisation proposed in Figure 1 is a useful approach in drawing out some general statements.

Of the four primary management objectives shown in Figure 1, improving soil structure through controlled traffic would seem to be the best example of where PRBs as a prerequisite might seem uncertain and where zero-till or minimum-tillage systems on the flat would appear sufficient. The extent to which PRBs generate benefits that justify their development and adoption will be analysed in greater depth in the next section.

Benefits and risks associated with PRBs

A review of the papers collated in these proceedings quickly indicates that wide ranging benefits may be obtained, depending on the purpose and context of use of PRBs and also risks and disbenefits.

Crop yield is an important performance indicator. In cases where PRB systems are primarily used to manage waterlogging, results consistently indicate higher yields, particularly in wet years. Examples are up to 78% yield increase in cereals in Western Australia (Hamilton et al) and long-term average yield increases in southern Australia of 35% (Wightman et al). In very wet years, crops fail completely in conventional flat cultivation, whereas PRBs still enable good yields to be maintained. On the basis of soil water and soil physical data provided by Hamilton et al, it is possible to conclude that these benefits are directly related to the beds.

Yield increases are also reported for PRB systems targeting the issue of water savings in irrigated land. However, these are largely confined to maize–wheat or other row crop–cereal systems in Mexico, China, and, to a lesser extent, Pakistan, Bangladesh and India (Hassan et al; Ma et al; Meisner et al; Ram et al; Sayre et al; Wang et al). However, as a general principle, over time further yield increases in these PRB systems are dependent on retention of sufficient residues (Sayre et al; Meisner et al). Conversely, in rice–wheat systems both in the IGP and in Australia, there is a consistent trend for significant yield depressions in rice and, to some extent, also wheat (Beecher et al; Kukal et al). Yield depressions in irrigated wheat systems may be related to certain short varieties which are unable to fully compensate for the furrow gap in bed plantings (Fischer et al). Results from tropical rice growing areas in The Philippines and Indonesia show similar trends (Cabangon et al; Ma'shum et al).

Higher or lower yields do not necessarily translate into higher or lower profitability. Many of the papers presented here indicate that PRB systems deliver higher returns. There is some evidence that this is probably because PRB systems reduce input costs for labour, machinery, energy and seeds (eg Beecher et al; Hulugalle and Daniells; Kukal et al; and Sayre et al), rather than generating increased yields (eg Hassan et al; Meisner et al). However, in most cases reported these benefits arise out of the comparison with traditional systems, and it is conceivable that zero-till or minimum tillage on the flat would be more profitable than PRBs in many instances, as costs for bed establishment and renovation would not arise. Unfortunately, data on cost reductions are patchy and not always conclusive because of varying underlying assumptions, or because authors have only reported net marginal returns without specifying the breakdown of cost structures. In some cases, bed establishment costs (including capital outlays for bed forming and planting machinery) are not included in costs calculated, although from a farmer's perspective, these could be critical impediments to adoption. Moreover, as shown by Singh and Beecher, a true assessment of costs and benefits of PRBs can really only be undertaken if the whole farm budget is taken into account. This is because of the various flow-on effects of PRB systems within a farm context, including a range of opportunity costs often not considered. The approach outlined by Singh and Beecher was the most comprehensive one presented at the workshop, and it could serve as a useful model for others wishing to more rigorously assess the costs and benefits of PRBs.

In irrigation systems, water is a major production input, and water savings as a benefit constitute a key rationale for use of PRBs in this case. However, a scrutiny of reported water savings provides a mixed picture. First, there is some confusion between achieving absolute water savings, ie in hydrological water balance terms, the reduction of the evaporation term on the one hand, and on the other hand, the reduction of irrigation water usage (which is beneficial in terms of reducing energy and labour costs, but may or may not result in net water savings from a water balance perspective). In irrigated maize–wheat PRB systems, results suggest that significant reductions of irrigation water use can be achieved, essentially by converting flood irrigation systems into furrow irrigation systems (Ma et al; Sayre et al; Wang et al). In the system described by Ma'shum et al, a significant benefit of PRBs over conventional monsoon flooded rice was the ability to harvest water which could later be used for supplementary irrigation, providing greater yield certainty for the following dry season crops. However, few papers provide water savings data with a clear representation of how these savings were measured and what the benchmarks were. Nor are they accompanied by robust hydrological water balance data that would enable an evaluation of the extent to which the irrigation water savings also constitute *net* water savings (ie reductions in evaporation), or whether reduced water usage may in fact be generating future problems in relation to either insufficient salt leaching due to reduced leaching fractions or salt accumulation in the beds themselves due to greater lateral flow components from the furrows. Also, even if irrigation water savings were realised at the farm-scale through use of PRBs, it remains uncertain to what degree these savings may aggregate up to scheme or basin level water savings.

Another approach to assess water savings is to determine 'water productivity' (mass of biomass produced per unit volume of water used supplied to field). This term is preferred over 'water use efficiency', which, in engineering terms, is usually used to express efficiency of water conveyance. In some cases, PRB systems are reported to increase water productivity (eg Cabangon et al) and, in other examples, to decrease water productivity (eg Kukal et al). While this is a useful measure, one shortcoming is that it does not allow us to assess PRB performance in response to absolute reductions in water use, an issue of growing importance in water scarce parts of the IGP and Australia.

Several farm operational benefits have also been identified. A benefit observed in most systems is that of increased timeliness of planting and general improved accessibility for weeding and fertiliser top dressing, especially during wet periods using the furrows as traffic lanes. Timeliness is a major potential benefit in rice–wheat systems where rapid turnaround times after rice harvest would enable wheat planting to take place during optimum seeding periods. However, this can only be realised if heavy rice stubble loads can be managed in the future, should residue burning progressively phase out. The Happy Seeder concept (Kukal et al) provides such an option. However, increased timeliness and improved accessibility are benefits that PRB systems have in common with zero-till and minimum-tillage systems on the flat, and hence cannot be attributed to PRBs per se.

Results reported for cases where the main rationale for using PRBs is increasing the flexibility of diversification in irrigated rice systems have confirmed that growing rice on beds allows for a fairly rapid switch out of rice into alternative summer crops (eg maize, soybeans, cotton, other legumes) (Beecher et al; Ram et al). This ability to react at fairly short notice in response to market signals or amount of irrigation water allocated in a particular season, without having to expend resources on tillage or prepare for a particular crop, has been stated as a key benefit for Australian farmers adopting PRBs in the Murrumbidgee and Murray irrigation areas (Beecher et al). The economic value of this increased operational flexibility is hard to quantify, but possible, using the approach proposed by Singh and Beecher. Whether these benefits can offset the yield penalties recorded for rice on beds has not yet been fully assessed.

PRB systems generally also provide benefits in terms of soil health. Evidence provided by most papers in these proceedings shows that soil physical properties in the beds are significantly enhanced (in particular higher macroporosity, lower bulk density, increased infiltration, higher aggregate stability). However, the rate at which these benefits accrue depends heavily on the amounts of residues retained (Meisner et al; Sayre et al). Where there are competing demands for residues (fodder, fuel) or where residues are routinely burnt, many soil properties may only improve marginally, if at all. Less data is available for soil chemical and biological properties, but in the presence of sufficient residues, increases in soil organic matter and soil biological activity have been observed (Hulugalle and Daniells; Sayre et al).

Other benefits reported include the reduction of weed populations (Hassan et al; Kukal et al; Ram et al; Sayre et al) and decreased incidence of some diseases and pests (Sayre et al; Wang et al). However, in most of these cases it is not immediately clear whether these benefits can be attributed to the beds or to zero-till.

Environmental risks and benefits seem to have received less attention. Obviously, water savings generate environmental benefits (reduced energy usage for pumping; possible reduced depletion of ground water resources), but there may also be some risks ensuing from the changed soil hydrology under PRBs. Improved structure within beds could conceivably lead to higher proportions of continuous large biopores, leading to bypass flow containing contaminants (NO_3; pesticides). Such phenomena have been observed from long-term zero-till methods on the flat in the US and Europe, and there are some preliminary data to suggest this is occurring on PRBs on light soils of the northwest Indo Gangetic Basin (Humphreys and Kukal, pers. comm.)

Changes to the water balance in PRBs may also change solute balances. While aspects of the N cycle are being studied (eg Kukal et al, Wang et al), little or no work seems to have been done with respect to mineral N and other solute movement, in particular to assess the long-term changes to salt balances and the fate of N. There is some anecdotal evidence that N fertiliser rates can be reduced without yield penalties, backed by some data showing higher nitrogen use efficiency (eg Wang et al). Data presented by Hulugalle and Daniells indicate that there is increased leaching of subsoil exchangeable Na in cotton PRB systems on vertisols. Apart from changes to vertical flow of water and solutes, there is potential for increased runoff and sediment and nutrient loads in runoff coming from PRB on sloping land under high rainfall (Garside; Wightman et al). No conclusive evidence was presented at the workshop to indicate negative environmental effects, although these risks warrant further monitoring.

Another potential benefit that PRBs have in common with zero-till or minimum tillage systems on the flat is the sequestration of carbon in the soil, particularly if residues are retained and not burned. This potential benefit has yet to be fully quantified. Conversely, in irrigated PRB systems, alternate wetting and drying may lead to increased levels of denitrification and release of greenhouse gases (N_xO; CH_4), but to establish this would require study of more detailed C and N balances to be undertaken in PRB systems.

Critical design factors

Irrespective of the rationale behind the promotion of PRBs, it is possible to discern a number of common design factors that consistently appear to be critical to the development of practical PRB systems.

From an agronomical perspective, the choice of varieties suited to growing on raised beds is an important element, related mainly to the crop's ability to fill the gap in the furrow. As Fischer et al have clearly demonstrated, wheat varieties exist that have a broad plasticity and are able to readily compensate for the gap, although this ability diminishes somewhat in less favourable climatic and soil conditions, and there are bed: furrow ratios beyond which the ability to compensate decreases significantly. There are wheat varieties suitable for PRBs (Fischer et al; Ma et al), and row crops like cotton, maize, soybeans and sugarcane are by nature generally well adapted to PRBs. However, there is consensus that rice varieties suited to PRBs are lacking, and this may be one of the possible causes of poorer yield performance by rice on PRBs (eg Meisner et al).

Apart from the crop's ability to compensate for the gap opened by the furrow, the configuration of beds and furrows also depends on soil and machinery factors. The soil's ability to laterally transmit water from the furrow to the bed centre is another critical factor to consider in designing PRB systems. Based on experience in zero-till systems, it is conceivable that bed stability and porosity should increase with time, in turn increasing subbing to the bed centre. However, upon reviewing the papers presented in these proceedings, it would seem that bed geometry and configuration are more strongly driven by machinery considerations than soil hydraulic properties. There is evidence that in some cases, beds were initially constructed too wide, either to match existing machinery (Hamilton et al; Wightman et al) or to reduce labour requirements where beds are formed manually (Ma'shum et al).

From a practical point of view, it is legitimate for machinery to be an important determinant of bed configuration, as capital costs for new machinery represent a major constraint to uptake by farmers. Consequently, any option that builds upon existing tractor sizes and planters is likely to significantly increase the prospects of adoption. As well, in many developing countries appropriate small machinery simply may not exist. In those cases where beds are wide as a result of existing tractor width, a frequently proposed option is to design narrow beds, where tractor axle width becomes a multiple of bed and furrow widths (eg as described in Hassan et al; Sayre et al). Equally important, in more mechanised situations such as those in Australia and Mexico, axle widths of tractors and harvesters also need to match; otherwise harvesters will run on beds, resulting in their compaction (Beecher et al; Garside et al; Hulugalle and Daniells). Tractor tyre width is an important consideration affecting the width of the gap in the trafficked furrow and narrow tyres are desirable for small gaps.

There is consensus that most of the machinery requirements for the highly mechanical PRB systems in Australia have been identified and solutions developed. However, availability of adequate machinery in Asian PRB systems is still a constraint. 'Adequate' in this context means suited to the prevailing tractors (single-axle in Bangladesh; narrow, ~20HP double-axle in China; medium, 40–50HP in parts of Pakistan and India), which are built with locally available materials and matched to local soil and tillage conditions. In general terms, adequate bed-formers and shapers are already available, either commercially, or at least as tested prototypes. The main machinery constraint tends to be the lack of planters. While planters for individual crops exist, in many cases they are not attractive to Asian farmers, who seek multipurpose, precision planters, capable of planting both row crops (maize, cotton) and wheat (Gill et al). Simple, precision machinery, the ability to deal with varying stubble loads and residue types, and the possibility of simultaneous fertiliser banding are seen as some of the required prerequisites that planters should fulfil. The question of whether the planters should be based on tines or discs is still being debated. Tines are cheaper and easier to build but have the disadvantages of not being able to cope with high stubble loads and inducing too much soil disturbance. Discs can more readily cope with heavy trash and enable true zero-till planting, but they are more expensive and materials to construct them are not always available locally. One alternative option is the Happy Seeder concept, but that may only be viable for medium to large tractors due to weight, cost and the PTO requirements. Another alternative yet to be tried widely is the star wheel punch planter.

A final design consideration in irrigated PRB systems should be the nature of the irrigation layout. Farmer friendly layouts (eg the bankless system described by Beecher et al) should reduce labour in relation to irrigation time (and ease of water harvesting, if applicable). Providing sufficient flat headland for machinery to manoeuvre effectively without damaging the beds is seen as critical. This is easier to implement in the broadacre conditions of Australia and Mexico, but is a significant design issue in small field sizes prevailing in many Asian countries and is an aspect that has not yet received much attention.

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Addressing technical knowledge gaps and maximising adoption.

The workshop on PRBs in Griffith, March 2005, and the papers presented in these proceedings have made it possible for the first time to systematically assess the current situation with respect to developing PRB systems suited to a wide variety of climatic, crop, soil and socio-economic conditions. It is evident from the information assembled in this volume that much has already been achieved. However, invariably, research raises new questions, and the fact that PRB systems are being adopted in some and not in other situations is testimony to the fact that more needs to be done.

On the one hand, a review of the papers presented here and information generated during the workshop discussions has enabled us to identify critical technical knowledge gaps that are relevant across many geographical regions and PRB systems. On the other hand, while not raised in the papers, the discussion during the workshop also highlighted a prerequisite to successful adoption of PRB systems. Embedding the practical development of PRBs at the onset within the socio-economic context of farmers, contractors and extensionists and engaging with these groups is more likely to achieve success than technical solutions on their own.

Further research needs in technical areas can be grouped within the following sets of priority issues:

Agronomic issues

1. Selection of rice cultivars for bed planting.
   This was consistently raised by those working in rice-based PRB systems as being a major impediment; the current poorer performance of rice on beds is being attributed to the use of varieties selected for anaerobic/puddled conditions. Other crops that may have to be screened for their adaptation to PRBs are short-stemmed wheat cultivars and crops such as lentils (because of reduced ability to compensate for the furrow gap).
2. Stubble/residue management.
   Based on work in zero-till systems on the flat, there is unanimity about the beneficial effect of residue retention (on weed suppression, soil health improvement, reduced evaporation losses etc.). However, in many instances the reality is that farmers have preferred alternative uses for residue (eg fuel, fodder or sale). In order to be able to offer farmers compromises between alternative residue use and PRB benefits, the livestock component needs to be integrated to determine the trade-off between fodder needs and minimum residue threshold levels to achieve soil and water benefits. Also, once it becomes possible to plant into heavy stubble loads (eg by using the Happy Seeder), the issue of residual effects of large amounts of rice straw on N turnover, disease build-up and allelopathy will become increasingly important.
3. Optimisation of bed configuration.
   As discussed, bed configuration is often driven by machinery specifications rather than clearly defined optimum crop spacings and bed:furrow geometry as a function of soil hydraulic properties. There is probably enough data available to address this issue using a modelling approach, and a new ACIAR activity to tackle this issue this is planned for the near future.
4. Nutrient and solute management.
   Optimisation of fertiliser placement and adequate management of possible salt build-up require further work, which could be done in conjunction with the modelling approach proposed above to optimise bed configuration.

Machinery issues

5. Development of multi-purpose bed-planters.
   Many prototypes and some commercial options already exist. However, the ability to concurrently manage heavy stubble loads (see points 2, 3 and 4 above), precision drill seeds of different sizes, and band fertilisers, has not been successfully incorporated into many of the prototypes being tested in Asia, in particular those for single-axle or small, 20HP dual-axle tractors.
6. Bed maintenance and mechanical weeding.
   Again, a variety of potential solutions exist for larger tractors, but the need is greater for planter and bed renovators adapted to PRB systems in Bangladesh and China, where small tractors are still prevalent.

Environmental issues

7. Water, salt, carbon and nutrient balances.
   To better substantiate claims about water and nutrient savings and reductions in greenhouse gases, in particular net savings or reductions, it will be necessary to conduct more complete (not partial) balances. In some areas salt balances will also be affected, as many PRB systems are altering soil hydrology in areas of saline soils and aquifiers.
8. Scaling up of on-farm effects to catchment or irrigation scheme level.
   Even if it can be proven that on an individual field or even farm basis, PRB systems are able to generate true water savings, little is known about the extent to which the aggregation of PRB effects may have beneficial, neutral or detrimental effects on landscape health and the conservation of irrigation water resources.

Wherever possible, addressing the above research gaps should be undertaken in such a way as to rigorously enable differentiation of the contribution made by permanent beds per se, compared to the effects of zero-till or minimum tillage per se on the parameters being tested. Only in this way will it be possible to better justify in which conditions PRB systems are superior to zero-till or minimum tillage on the flat.

While addressing the above technical research gaps is an important part of increasing the likelihood of farmer adoption, arguably it is the socio-economic determinants and, in many cases, the governing institutional arrangements (eg water and energy pricing) that ultimately predispose farmers to adopt or not. Encouragingly, many of the studies reported in these proceedings have attempted to provide some level of economic analysis. However, as we point out in the section on benefits and risks, above, it is important that cost–benefit analyses do not just constrain themselves to evaluating all the individual components of PRB systems, but rather take into full account the economic decision-making process of farmers. This process tends to be at a farm level and have strong elements of risk assessment and response to market externalities, which are often completely disregarded in economic analysis of farming systems. In other words, in order to maximise adoption, the full context in which farmers operate needs to be better understood (eg markets, conflicting opportunities, access to credit, risk), otherwise the best of technologies will remain unadopted. Consequently, there is also a need for more socio-economic research:

Socio-economic issues

9. Economic benefits.
   More comprehensive cost–benefit analyses are required in many of the systems being developed. An example of the approach that could be taken is given by Singh and Beecher.
10. Farmer motivation.
   Apart from providing better cost–benefit data to underpin farmer adoption, it is necessary to also better understand the main determinants of farmer decision-making both within the farmer environment and in the broader context of institutional arrangements. This should be done using farmer participatory action research approaches.

Wherever there are clear and significant benefits for farmers, be it in yield increases, cost reduction, increased operational flexibility, labour reduction, or combinations of these, significant uptake can be observed when technical constraints have been addressed. This can be further reinforced, if additional policy drivers underpin the need for change. Until water scarcity expresses itself in reduced access to cheap irrigation water, water savings benefits will be something that scientists promote, but farmers don’t place much value on. Therefore, engaging policy makers and resource planners is possibly as important as working with farming communities. If policy makers are made aware of the existence of technically and economically feasible technologies, the political costs of policy reform decrease, and consequently, it becomes more likely that changes will be enacted. This means that the traditional role of agricultural researchers is rapidly changing from a linear research–extension–adoption mode to one of increasingly direct and active engagement with, and involvement of, farmers. As well, researchers are recognising that their innovations have to be packaged in many different ways to suit a broad range of end-users, including policy makers and planners.

The two decades or so of PRB research, some of which has been brought together in these proceedings, are a strong technical basis from which to continue. We believe that not only in Mexico and Australia, where PRB farming has gained significant traction with wheat, maize and cotton farmers, but increasingly in some of the Asian countries, the next decade is poised to see rapid adoption of PRB farming.