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Project final report

project

Permanent beds for irrigated rice–wheat and alternative cropping systems in north-west India and south-east Australia

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2 Executive summary

Rice-wheat (RW) cropping systems are critical for food security and livelihoods in South Asia. However the sustainability of RW systems in South Asia is now in question, faced with yield stagnation or decline of rice and/or wheat, soil degradation, declining groundwater levels, air pollution from rice stubble burning, and declining terms of trade. In Australia, the sustainability of rice-based systems is threatened by reduced availability and increasing price of water. ACIAR Project LWR/2000/089 sought to increase the sustainability, yield, resource use efficiency and profitability of RW and alternative irrigated cropping systems in Punjab, India and New South Wales (NSW), Australia, through the development of permanent raised bed (PRB) rice-based cropping systems and machinery capable of direct drilling wheat into rice residues.

The technical problems of direct drilling wheat into rice residues has been solved for conditions in Punjab with the development of the Happy Seeder, which cuts and picks up the residues in front of the sowing tynes, and deposits them as a mulch behind the sowing tynes. The machine is currently being manufactured by two commercial machinery companies in Punjab. The project has comprehensively demonstrated that wheat can be successfully established and grown by direct drilling into rice residues without burning or removal, on both flat fields and raised beds. Preliminary results suggest some water saving through reduced soil evaporation, but this requires further field and modelling work to quantify the savings more clearly. Whether the approach will be successful in the heavy rice straw loads (10-14 t/ha) in NSW is yet to be established. Preliminary financial analysis suggests that the Happy Seeder technology is more profitable for Punjabi farmers than both conventional tillage and direct drilling after burning the straw. However there are a number of assumptions in the analysis that can only be validated after prolonged testing (e.g. cost of repairs and maintenance, and potential reductions in herbicide, N fertiliser and irrigation water applications). Furthermore, there may be significant economic, environmental and social benefits, which need to be quantified, particularly as a result of reduced air pollution and reduced use of inputs subsidised by the government. The main needs now are to develop a smaller machine capable of being powered by the 35 h.p. tractors commonly used in Punjab, to develop management guidelines, to create a favourable policy environment to encourage adoption, and to implement a major program to demonstrate and disseminate the technology with farmers across the RW districts of Punjab, and across the north west Indo-Gangetic Plain.

The performance of RW systems on PRB on the sandy loam and loam soils commonly used for RW systems in Punjab was disappointing, and not viable with current technology. Contrary to expectations, yield of wheat on beds almost never exceeded yields with conventional tillage, and was sometimes significantly lower. The topsoil of the beds dried faster than the flat fields, and more skilled management may be required to ensure planting at optimal soil moisture and to avoid early water deficit stress on beds on these soils. Yield of transplanted rice on **fresh** beds (TRB) was usually similar to yield of puddled transplanted rice (PTR) with the same alternate wetting and drying irrigation scheduling (irrigating 2 days after the floodwater or furrow water had dissipated, which is recommended practice for PTR), however, yield of TRB declined relative to yield of PTR as the beds aged. The decline was even greater for direct seeded rice on permanent beds. The lower rice yields on beds were associated with cereal cyst nematode infestation, compaction of the beds, and iron deficiency in direct seeded rice. Three to four hand weedings were needed to control weeds on the beds. There was no benefit of mulching the beds with wheat and rice straw in terms of yield or nitrogen fertiliser requirement. Our findings were generally consistent with the findings of others in the north west Indo-Gangetic Plain (IGP), but in contrast with findings from the wetter environments and less mechanised systems of the eastern IGP. The reasons for the differences need to be investigated to help identify how to improve the performance of RW systems on PRB in

the north west, and in particular to determine whether compaction of the sides of the beds by the tractor tyres is a significant factor.

Irrigation water savings of 30–50% were achieved with furrow-irrigated TRB in comparison with continuously flooded PTR. However, field and modelling studies showed similar irrigation water savings when water management of PTR is changed from continuous flooding to the same irrigation scheduling as the beds (irrigate 2d after the furrow or floodwater has dissipated). The depth to which the furrows were filled, and age of the beds, also had a large effect on irrigation amount. Our studies demonstrate the importance of providing appropriate control treatments and sufficient contextual detail in reporting the results of comparisons of soil and water management for RW systems to enable sound interpretation and extrapolation of the results. Further detailed investigations are needed in farmer field sized blocks for a range of soil types, watertable conditions and irrigation management to understand the effects of raised beds on components of the water balance for RW systems, and to develop irrigation management guidelines for rice and wheat on PRB. Our field and modelling studies also demonstrated that deep drainage from PTR using recommended water management, and from beds, is excessive (~1,000 mm), raising the question of the suitability of sandy loam and loam soils for rice culture in this environment, and the need for lower water use alternatives. In contrast, deep drainage from wheat was negligible to less than one tenth of that from rice.

In our 3-year maize-wheat and soybean-wheat experiments in Punjab on a loamy sand with no history of rice cultivation, and under dry to average rainfall conditions, yields of maize, wheat and soybeans on PRB were comparable to yields with conventional tillage and direct seeding on the flat. The application of the technology in wetter conditions and on heavier soil types with a history of rice cultivation (and thus a well-developed hard pan) has not been assessed. It is likely that beds may be an advantage for non-rice crops on such soils due to reduced waterlogging of the beds, and this needs further investigation.

Comprehensive economic analysis showed that RW was slightly more profitable to farmers than maize-wheat (MW) cropping systems, and much more profitable than soybean-wheat (SW) systems, mainly due to the low yield of soybean. PRB were more profitable than all other layouts for MW and SW, but not for RW due to the yield decline in rice on PRB. If the rice yield decline could be reduced to 10%, there would be significant financial benefits of PRB over all other layouts except for zero-till wheat after PTR, which had similar net benefit. With no rice yield loss, PRB were superior to all other layouts, mainly due to reduced machinery costs. A 10% increase in wheat yield on PRB would also result in higher financial returns to PRB than any other layout, despite the rice yield decline on TRB.

In contrast to the situation in Punjab, direct seeded rice grew successfully on PRB on the heavy clay soil in Australia. Direct seeded rice was successfully grown in close rotation with winter cereals and other summer crops on PRB in terraced (zero grade), bankless channel layouts. Barley-soybean double cropping was also successful on PRB on this layout. Yields of wheat on beds and flats were similar, in contrast with past experience showing higher yields on beds due to improved drainage on the clay soils used for rice-based systems in Australia. Economic analysis showed that there were significant financial benefits in switching to PRB in terraced rice layouts due to reduced tillage costs and the opportunity to switch to more intensive cropping systems. Adoption of zero graded bankless terraced rice field irrigation designs potentially incorporating raised beds should be promoted now to rice growers in locations with suitable slopes and access to high irrigation flows. The evaluation of PRB for rice-based systems in NSW was undertaken during a prolonged period of very dry climatic conditions (drought). Monitoring in commercial fields during higher rainfall conditions conducive to waterlogging is needed to evaluate PRB terraced rice layouts in terms of crop performance, trafficability and damage to the beds under wetter conditions. Further work is also needed in commercial fields on irrigation distribution uniformity and the potential to save irrigation water.

The project has achieved many scientific, capacity building and community impacts to date. By far the most significant is the strong interest in promoting the Happy Seeder Technology in India and Pakistan by the Rice-Wheat Consortium of the Indo-Gangetic Plains, Punjab Agricultural University, the Indian Council of Agricultural Research, ACIAR and others. Happy Seeders are now made by two manufacturers in Punjab. Initiatives are underway to promote adoption of the technology through many demonstrations in farmers' fields, together with the development of a smaller version of the Happy Seeder capable of being powered by a 35 h.p. tractor. In the future, widespread adoption of the technology will result in many benefits including improved air quality (and therefore health) and soil quality through retention of rice residues instead of burning, reduced water depletion (from reduced soil evaporation), and financial benefits to farmers from more timely wheat sowing and reduced inputs (herbicides, water, fertiliser).

Another highly significant impact of the project is enhanced capability of PAU researchers to work in multi-disciplinary, cross-department teams and with the private sector, partnerships which continue today. Four of the project's Research Fellows are now undertaking PhD programs, three of these as John Allwright Fellows. The fourth is completing his PhD in collaboration with the world leading hydrology group at Charles Sturt University.

The project has also made many important findings in relation to knowledge of the performance of rice and wheat on permanent raised beds, including components of the water balance. Through presentations and publications, the project has influenced discussion on what constitutes real water savings within the RW region. Much of this knowledge, together with that of other RW researchers in the IGP, is documented in "Permanent beds and rice residue management for rice–wheat systems in the Indo-Gangetic Plain", the proceedings of a workshop organised by the project team at Ludhiana in September 2006 (ACIAR Proceedings No. 127). To date the project team has published 14 papers in prestigious scientific journals and books, 35 conference and workshop papers, 13 articles in farmer publications and a range of other publications.

3 Background

Rice-wheat systems in north west India

Rice-wheat (RW) systems are of immense importance for food security and livelihoods in South Asia (Timsina and Connor 2001; Gupta et al. 2003). Rice and wheat are grown in sequence annually on about 10 Mha in India, 2.2 Mha in Pakistan, 0.8 Mha in Bangladesh and 0.5 Mha in Nepal (Ladha et al. 2000). About 85% of the RW area in South Asia is located in the Indo-Gangetic Plains (IGP). RW systems provide 85% of the total cereal production and 60% of the total calorie intake in India, where the states of Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal are the heartland of RW cropping systems (Yadav et al. 1998). In the late 1990s, the small states of Punjab and Haryana contributed about 50 and 85% of the government procurements of rice and wheat, respectively (Singh 2000). In 2004-05, Punjab (only 1.5 % of the geographical area of India) contributed 37.1% of the rice and 55.4% of the wheat supplied to the central Government of India pool (GOP 2006a).

The area and productivity of RW systems in the IGP increased dramatically between the 1960s and 1990s due to the introduction of nutrient responsive improved varieties, increased use of fertilizers and other chemicals, and the expansion of irrigation, supported by favourable government policies (Kataki et al. 2001; World Bank 2003). In India, the contribution of Punjab and Haryana to total national food grain production increased from 3% before the ‘Green Revolution’ to 20% in the late 1990s (Singh, 2000). In Punjab, the area of rice increased more than 10-fold, from a minor crop grown on 0.23 Mha to the dominant summer crop grown on 2.65 Mha between 1960-61 and 2004-05, while the area of wheat increased from 1.40 to 3.48 Mha over the same period (GOP 2006a). Rice now occupies 60% of the total land area of Punjab in summer, while 80% of the land area is under wheat in winter (GOP 2006b).

Rice-wheat systems are practised on a range of soil types from sandy loam to clay. In the north west IGP soils tend to be coarser textured, and RW is predominantly grown on sandy loam to loam soils (Gupta et al. 2003). In Punjab, India, rice growing has even expanded to coarse textured, permeable soils more suitable for maize and groundnut production than traditional rice soils. Average annual rainfall in Punjab increases from west to east and ranges from 400-700 mm. The majority of the rain falls during the monsoon (rice) season, while winters are dry. The optimum date for transplanting rice is 2-3 weeks prior to the onset of the monsoon when evaporative demand is very high (up to 14 mm/day). Furthermore, the monsoon rains are usually erratic and poorly distributed relative to crop water use requirements. Thus there is heavy dependence on irrigation for both crops. Irrigation water is sourced from both groundwater and surface water systems, with conjunctive use of surface and groundwater in some regions (e.g. south west Punjab), but groundwater is the predominant or only source of irrigation water in much of the RW belt in Punjab (Hira and Khera 2000).

Since the late 1990s, rice and/or wheat yields have stagnated or declined across the IGP, “partial factor” productivity has decreased, and there are large gaps between potential yields, experimental yields and farmers’ yields (Gill 1999; Ladha et al. 2003). The environmental sustainability of RW systems, let alone the ability to increase production to match population growth, are major concerns. Symptoms of environmental degradation, which vary depending on location, include rapidly declining groundwater levels, declining soil organic matter content and nutrient availability and the emergence of multiple nutrient deficiencies, increasing soil salinisation, increasing weed, pest and pathogen populations, and particulate and greenhouse gas air pollution from stubble burning (Sondhi et al. 1994; Malik et al. 1998; Gulati 1999; Pingali and Shah 1999; Singh 2000; Byerlee et al. 2003). One of the biggest threats to sustaining and increasing the productivity of RW systems of South Asia, especially in the north west IGP, is water shortage. Groundwater levels are declining rapidly in north west India (Pingali and Shah 1999; Hira and Khera 2000; Singh 2000; Hira et al. 2004). On top of this, the cost-price squeeze of agricultural commodities has a serious impact on the livelihoods of the millions of farmers, labourers and others (>150 million in total) economically dependent on RW systems in South Asia (Ladha et al. 2000). Therefore there has been considerable research and extension effort to increase the productivity, profitability and environmental sustainability of RW systems over the past two decades, spearheaded by the Rice-Wheat Consortium of the Indo-Gangetic Plains, in collaboration with the National Agricultural Research and Extension Systems (NARES) (Gupta and Seth 2006).

Raised beds were introduced to RW systems of the IGP in the mid 1990s, initially for wheat, inspired by the success of irrigated maize-wheat on permanent raised beds (PRB) in Mexico (Sayre and Hobbs 2004). Since then, many advantages of growing wheat on beds have been reported, including increased yields, reduced lodging, opportunities for mechanical weeding and improved fertilizer placement, irrigation water savings, reduced waterlogging, reduced seed rate, and opportunities for intercropping (Hobbs et al. 1997; OFWM 2002; Talukder et al. 2002; Hobbs and Gupta 2003; Gupta et al. 2003; Sayre and Hobbs 2004; Ram et al. 2005).

In the initial work on beds in RW systems, the beds were usually destroyed after wheat harvest prior to puddling and transplanting rice on the flat. Hobbs and Gupta (2003) and Connor et al. (2003) proposed permanent raised beds (PRB) as a means of increasing the productivity and profitability of RW systems. They considered that PRB, as opposed to fresh beds, offered the opportunity for reduced or zero tillage of both crops, with large savings in diesel, labour and machinery costs. Other potential benefits included improved soil structure for wheat through controlled traffic and minimum tillage. Importantly, permanent beds also offered the opportunity for diversification to waterlogging sensitive crops like oilseeds and pulses, where substantial yield gains can be realised (Singh and Sharma 2005), and rapid response to market opportunities. However, Connor et al. (2003) also cautioned that bed systems may not be suited to some situations such as coarse-textured soils because of exacerbated losses by percolation in the absence of puddling. They also foreshadowed that, while PRB were likely to result in greater water and nutrient use efficiency, there would be new problems relating to weed control, and new issues concerning nutrient, residue and water management, and plant type.

Around the same time that PRB were being proposed, an unprecedented revolution in adoption of “zero till” (direct drilled) wheat after rice was underway across the IGP (Ahmad and Gill 2004; Malik et al. 2004; Gupta and Seth 2006; Ahmad et al. 2007). The benefits of zero till included increased profitability due to fuel and time savings, increased yield (through more timely sowing and better control of *Phalaris minor*) and reduced irrigation amount (Chauhan et al. 2000, 2003; Malik et al. 2004; Ahmad et al. 2006; Gupta and Seth 2006). However, a prerequisite for successful implementation of zero till wheat in the north west IGP, where most rice is combine-harvested, is burning the loose rice residues. For example, about 90% (17 Mt) of rice straw is burnt in Punjab, India. The result is terrible air pollution, affecting human and animal health, disrupting vehicle and air traffic, and causing accidental burning of property and remnant ecosystems. To avoid the need to burn the rice straw, improved technology with the capability of direct drilling into the standing and loose residues is needed.

Rice-based cropping systems in Australia

Wheat is also grown in rotation with rice in southern NSW, Australia, a cool temperate region with hot, dry summers and low (average 30-40 mm every month, but highly variable) rainfall. Prior to the onset of a prolonged drought in 2002 (and which has not yet ended at the time of writing in October 2007), around 0.15 Mha of rice were grown each year, with yields among the highest in the world, averaging 10.4 t/ha of paddy rice in 2003. Large areas of winter cereals (especially wheat) and a wide range of other summer and winter crops are grown in rotation with rice, but on a much less intensive scale than in the RW systems of the IGP. Wheat and other winter crops can be sown shortly after rice harvest, however by the time the winter crops are harvested, it is too late to sow rice in the same year. The sustainability of many regional communities is highly dependent on rice-based farming systems (Linnegar and Woodside 2003).

Prior to the onset of the current drought, Australian farmers were already under great pressure to increase the water use efficiency of rice-based systems to remain profitable and to avoid soil salinisation. In particular, profitability was threatened by decreasing water availability and certainty of supply, and increasing water price, as a result of environmental policies and the National Competition Policy (Humphreys and Robinson 2003). It is now also recognised that Australia is experiencing a shift in climate to drier conditions (Khan 2007), and that global climate change is a reality that will further threaten the viability of rice-based systems.

Rice culture in the semi-arid rice growing regions of south eastern Australia requires considerable quantities of irrigation water. Rice growing is restricted to heavy textured clay soils, often with high surface and/or subsoil sodicity and on generally flat slopes (1:1500 to 1:6000). While these conditions are well suited to ponded rice culture, they often pose severe limitations to the growth of upland crops under irrigated conditions (Muirhead and Humphreys 1984). Conventional rice growing layouts and practices have several disadvantages for upland crop production: soil structural degradation during the rice phase and during harvest (especially in wet years), poor water management and waterlogging of drill sown rice and for crops grown in rotation with rice, and restricted cropping sequence flexibility. Conventional rice irrigation layouts in southern NSW minimise the impact of cold temperature on rice floret fertility by allowing deep water protection (25 cm depth) to be applied during the pollen microspore stage.

Conversion from contour layouts to better drained border check or raised bed layouts for non-rice crops is inconvenient, expensive and is not normally practised where rice is grown regularly in the ‘rotation’. This essentially limits the non-rice component of rice-based farming systems to relatively waterlogging tolerant, low-value bulk commodity crops. The benefit of raised beds for non-rice crops in the rice growing regions of southern NSW has been described by Beecher et al (1997).

Rice growers have recently adopted bankless channel systems as an irrigation layout (Beecher *et al.* 2000). Combining bankless channel layouts in a terraced system (zero grade in the bays) with permanent raised beds offers the opportunity to move from rice to other crops without the need to change irrigation layouts. Such layouts allow the opportunity to furrow or flood irrigate or even incorporate sub surface drip irrigation. The system allows ponded water depth to be manipulated to protect rice against low temperature damage.

Thompson *et al.* (2003) grew rice on raised beds in small plots on rice suitable soils using furrow irrigation with saturated soil culture (SSC) in southern NSW. They showed irrigation water savings of about 14% using beds compared to flat layout, at the cost of 12% yield decline. Field and modelling research by Humphreys *et al*. (2001) and Smith and Humphreys (2001) suggested that growing crops immediately after rice harvest provides significant benefits for watertable management (resulting in net groundwater discharge of about 1ML/ha) and water productivity. From a rice-based farming systems perspective, there may be significant advantages to be derived from growing rice on raised beds within a common irrigation layout.

ACIAR project LWR/2000/089 was therefore conceived with the aim to improve the productivity, profitability and sustainability of the irrigated rice-wheat (RW) cropping systems of north-west India and the rice-based systems of southern Australia. The introduction of permanent beds symbolized a radical change from conventional flooded and puddled rice systems on the flat. It offered large savings in energy in land preparation by minimizing tillage, protection from waterlogging for non-rice crops on heavy soils, and irrigation water-savings in rice grown on lighter soils. Permanent beds, it was proposed, would provide a soil environment conducive to crop diversification, and the opportunity to increase profitability through greater energy, water, labour and nutrient use efficiency of all crops in the rotation.

4 Objectives

The overall goal was to increase the sustainability, yield, resource use efficiency and profitability of the RW systems of the IGP, and of the cropping systems in the rice growing areas of Australia, through improved soil, water and nutrient management using permanent beds.

This goal was tackled through seven subprojects with the following objectives.

4.1.1 Subproject 1. Preliminary field experiments in India to evaluate layout and agronomic options for permanent bed systems, with particular emphasis on rice

Objective 1

To evaluate planting, water management, N management and stubble management options for permanent bed systems in India, with particular emphasis on rice.

4.1.2 Subproject 2. Field evaluation of permanent bed and conventional RW/rice-based cropping systems of Punjab and NSW

Objective 2.1

To quantify crop growth, development, yield and system productivity on permanent bed and conventional systems

Objective 2.2

To quantify soil physical properties, including changes over time, for permanent bed and conventional systems

Objective 2.3

To quantify components of the water balance, changes in soil water content over time, and water use efficiency (e.g. t/ML, ML/ha, losses) for permanent bed and conventional systems

Objective 2.4

To determine P, K and other nutrient balances for permanent bed and conventional systems (N is covered in subproject 4)

4.1.3 Subproject 3. Field evaluation of permanent beds for alternatives to RW (maize-wheat, soybean-wheat)

Objective 3.1

To quantify crop growth, development, yield and system productivity on permanent bed and conventional systems

Objective 3.2

To quantify soil physical properties, including changes over time, for permanent bed and conventional systems

Objective 3.3

To quantify components of the water balance, and water use efficiency (e.g. t/ML, ML/ha, losses) for permanent bed and conventional systems

4.1.4 Subproject 4. Nitrogen use efficiency in RW cropping systems in Punjab (with IAEA)

Objective 4.1

To determine nitrogen balances and N fertilizer use efficiency using 15N techniques, and to study nitrogen dynamics for permanent bed systems with and without mulching

4.1.5 Subproject 5. Development and application of models to identify management options for maximising the productivity of RW cropping systems in Punjab and the IGP, and of rice-based systems in NSW

Objective 5.1

To develop calibrated and validated models for bed and conventional RW cropping systems

Objective 5.2

To use the results of model simulations and the field experiments to evaluate layout, planting, irrigation and nitrogen management strategies on the productivity of permanent bed RW systems

4.1.6 Subproject 6. Economic impact assessment of permanent bed systems in Punjab

Objective 6

To determine the economic impacts of RW systems on permanent beds

4.1.7 Subproject 7: Development of the Happy Seeder for direct drilling into rice stubble

Objective 7.1

To rebuild, refine and fine tune the Happy Seeder for direct drilling of any crop into any residue in rice-wheat rotations under bed and flat layouts.

Objective 7.2

To undertake on-farm evaluation, demonstration and popularisation of the Happy Seeder.

5 Methodology

Subproject 1. Preliminary field experiments in India to evaluate layout and agronomic options for permanent bed systems, with particular emphasis on rice

Three experiments were conducted:

- Evaluation of rice varieties under different methods of plant establishment
- Evaluation of mechanical interculture for rice on beds
- Effect of irrigation frequency on water use and yield of transplanted and direct seeded rice on beds.

Evaluation of rice varieties under different methods of plant establishment

The hypothesis was that shorter duration direct seeded rice may have benefits of reduced irrigation requirement compared with longer duration varieties, through being able to delay time of sowing closer to recommended time for transplanting in early June. Earlier sowing extends the period of time that the crop is growing under conditions of extremely high evaporative demand prior to the onset of the rainy season.

Three varietal types were compared:

- PR106 (long duration)
- PR115 (short duration)
- Sonali (medium duration hybrid)

Using four methods of planting:

- puddled transplanted rice on the flat (PTPR)
- permanent beds (renovated) with transplanted rice (TPRB)
- direct seeded rice on the flat (DSRF)
- direct seeded rice on renovated beds (DSRB)

On sandy loam at PAU, sown (DSR) or transplanted (TPR) 20 June 2002.

The crop was irrigated frequently to try and avoid water deficit stress – daily for the first 2 months and on alternate days after that. The weather was unusually dry (there was no monsoon and rainfall was half the average for the rice season), and Dr Dhillon felt that there was some water deficit stress.

Evaluation of mechanical interculture for rice on beds

This was an unreplicated pilot trial in which mechanical interculture was applied 20 days after transplanting and soil drying for 4 days.

Effect of irrigation frequency on water use and yield of transplanted and direct seeded rice on permanent beds

The objective was to help identify the optimum irrigation scheduling for rice on beds by determining the effect of irrigation frequency on rice performance and water use. The experiment was established on 2 year old permanent beds (first established with rice in 2000) on a sandy loam with 4 irrigation frequencies (every 1, 3, 5, 7 days).

5.1.1 Subproject 2. Field evaluation of permanent bed and conventional RW/rice-based cropping systems of Punjab and NSW

Punjab

Field experiments comparing RW on permanent beds, fresh beds and conventional layouts/tillage over 4 years on 2 soils (sandy loam, loam)

Humphreys et al. (2004, 2007), Kukal et al. (2007, 2008), Nayyar et al. (2004), Prashar et al. (2004)

The performance of rice and wheat grown in rotation on permanent raised beds (PRB) was compared with performance on conventionally tilled flat layouts and with wheat on fresh beds following puddled transplanted rice (PTR). The experiments were conducted over 3-4 years in small plot, replicated experiments and in large (60 m long) blocks on sandy loam and loam soils in Punjab, India. The first crop was wheat sown in November 2002. All crop residues were removed at harvest. In the replicated experiments, there were two rice establishment methods on the PRB – direct seeding and transplanting. Also, there were two water management treatments for PTR - continuous flooding (PTR-CF) and frequent alternate wetting and drying (PTR-2d, irrigated 2 d after the floodwater had dissipated, the recommended practice). Irrigation scheduling for furrow-irrigated rice on beds was the same as for PTR-2d. Irrigation management of wheat on both flats and beds was based on net cumulative pan evaporation (CPE-rain), commencing after a common irrigation at crown root initiation (CRI).

Baseline soil properties were determined (e.g. pH, particle size, hydraulic properties, bulk density). Monitoring included crop establishment, growth, development and yield, profile soil water at planting and harvest and irrigation amounts. Wheat root development was measured in selected treatments in 2 years. Detailed soil water monitoring was undertaken using tensiometers, neutron counts, and granular matrix sensors (logged) in selected treatments/crops. Bulk density and hydraulic conductivity on beds and flats were compared after several crops.

New South Wales

A replicated large plot experiment comparing permanent bed and flat layouts for range of cropping systems suited to each layout

Beecher et al. (2004, 2005, 2006a,b, 2007a,b), Mathews et al. (2004, 2005a,b, 2006)

A replicated, large plot (11 m x 150 m) was installed on a typical, heavy clay soil used for rice growing in Coleambally, NSW. Furrow and sub-surface drip irrigated permanent raised beds (1.83 m wide) were compared with traditional flat layouts. The performance of several crop sequences used in rice-based farming systems was compared. The experiments commenced with rice on all layouts in 2002/3, and rice was again grown on all layouts in 2005/6. Three broad types of crop sequence were selected to include both traditional (low intensity rice-wheat-fallow sequences) sequences and novel crop sequences (double cropping of winter (barley or wheat) and summer crops (rice or soybeans) each year). Stubbles were burnt prior to the establishment of each crop. All crops were drill sown at recommended row spacings. Nitrogen rate treatments were applied to some crops, especially the initial and final rice crops.

Crop monitoring included crop establishment, crop growth and development at key growth stages including panicle initiation, anthesis and physiological maturity (PM). Monitoring of crop dry matter accumulation, nitrogen uptake, tiller number, yield and yield components of all crops was undertaken. Harvests were both small hand harvest and at PM mechanical harvest of 2 beds * 10m length. Irrigation applications to all treatments were measured by logging water depth in flumes to each plot throughout each irrigation. Soil moisture monitoring was undertaken using neutron probe counts, soil capacitance measurements and ganular matrix sensors in selected treatments.

Soil samples were taken to rootzone depth at various times including pre-sowing and harvest through the various crop sequences for determination of electrical conductivity, soil pH, soil organic carbon, mineral and total N, soil water content and bulk density for neutron probe calibration.

The potential financial benefits and costs of PRB compared with common irrigation layouts used for rice-based farming systems were estimated using a whole-farm benefit cost framework.

5.1.2 Subproject 3. Field evaluation of permanent beds for alternatives to RW (maize-wheat, soybean-wheat)

Ram (2006)

The two field experiments evaluated tillage, bed and flat layouts, and straw management in maize-wheat and soybean cropping systems on a loamy sand. The experiment was laid out in a randomized complete block design with four replications. Eight treatments were applied to both the cropping systems. The treatments included combinations of conventional tillage (CT), zero tillage (ZT), fresh beds (FB), permanent beds (PB) and wheat straw retention as mulch.

Monitoring included:

- soil temperature (0-5 cm) from sowing to emergence
- photosynthetically active radiation interception at key growth stages
- plant height at key growth stages
- yield and yield components
- soil water content (gravimetric) in the profile at the time of planting and harvest
- irrigation applications.

All treatments were irrigated on the same day, with less irrigation water applied to the beds than the flats.

5.1.3 Subproject 4. Nitrogen use efficiency in RW cropping systems in Punjab (with IAEA)

Yadvinder-Singh et al. (2003, 2004, 2005, 2007)

A field experiment was conducted over 4 years in Punjab, on a sandy loam soil, to compare conventional and permanent bed RW cropping systems, with and without retention of crop residues, in terms of crop performance and nitrogen use efficiency (NUE). Two methods of rice establishment (transplanting and dry seeding) were included on both beds and flats with 4 N rates (0, 80, 120, 160 kg N/ha). The experiment commenced with rice established in June 2002.

Crop growth and yield were monitored, and also N uptake at key growth stages. 15N-labelled fertiliser was applied to microplots for determination of recovery of fertiliser N in the plants and soil. Baseline soil organic C and total N and K were determined, and again after 8 crops.

5.1.4 Subproject 5. Development and application of models to identify management options for maximising the productivity of RW cropping systems in Punjab and the IGP, and of rice-based systems in NSW

Wheat – Punjab

Timsina et al. (2008)

DSSAT-CSM-CERES-Wheat modelling capability under irrigated conditions was extended by developing and including code to apply irrigation automatically based on: (1) growth stage, i.e., at CRI, booting, flowering, and grain filling, either as a single irrigation at one growth stage only, or in various combinations, and (2) cumulative net evapotranspiration since the last irrigation (ET-rain). Routines were also developed to generate additional outputs such as the duration from sowing to anthesis and from anthesis to physiological maturity, intercepted photosynthetically active radiation during various growth stages, and grain filling to end of maturity, components of the water balance, and crop water productivity.

The model was calibrated for PBW343 and was evaluated using independent data sets from 13 crops over the five year period from 2002 to 2006 (sub-projects 2, 3, 4). The model was then used to estimate yield, components of the water balance, and water productivity for PBW343 for a range of sowing dates and irrigation management on the sandy loam and loam soils of the PAU Farm and Phillaur in Punjab.

Potential yield, as affected by temperature, solar radiation and genotypic characteristics, was simulated for a range of sowing dates (at 15 day intervals from 10 October to 10 January) using 36 years of weather data at Ludhiana (1970-71 to 2005-06).

The effect of irrigation management on yield and components of the water balance and water productivity was investigated for various sowing dates for two soils. Three irrigation scheduling methods were used: SWD-based, growth stage-based, and ET-based. For the SWD-based scheduling, the irrigation management depth was set to 75 cm with irrigation scheduled when SWD increased to ≥50% and irrigation was applied to replace 100% of the deficit. For growth stage-based scheduling, irrigation was applied either only once at one of the key growth stages (CRI, booting or BT, flowering or FL, and grain filling or GF), twice (two stages in various combinations), thrice (three stages in various combinations), or four times (all four stages). Irrigation at CRI was applied when SWD at 0-25 cm depth was ≥25%, while for all other stages irrigation was applied when SWD over 0-75 cm depth was ≥25%. The irrigation water applied was the amount required to replace 100% of the deficit in the specified soil depth. For ET-driven irrigation, the first irrigation was scheduled at 21 DAE (approximately CRI) when SWD at 0-25 cm depth was ≥50%. Further irrigations were scheduled based on cumulative net ETo (ET0-rain) since the previous irrigation, for a range of net ETo (25, 75, 125, 150, and 175 mm). The irrigation water added was the amount needed to replace 90% of net ETo. Five main irrigation schedules, (1) SWD-based, (2&3) ET-driven with irrigation after accumulation of either 75 mm of ET (ET75) or 125 mm of ET (ET125), and (4&5) stage-based with irrigations applied at CRI plus booting, or at CRI plus booting plus flowering stage for crops sown on 10 November were chosen for detailed analysis of yield, irrigation water requirement, and CWP.

Rice - Punjab

We used the model CSM CERES–Rice V4.0 to simulate rice yield, components of the water balance and water productivities for a range of seasonal conditions, soil types and irrigation management.

Data from two experiments at PAU, Ludhiana were used to determine genetic coefficients for the two rice varieties for use in the DSSAT-CSM-CERES-Rice model. Ten independent data sets from Ludhiana and Phillaur were then used to evaluate the model. The data sets were from 12 replicated field experiments at Ludhiana and Phillaur spanning 2003-2005 in sub-projects 2 and 4, above. The CSM CERES-Rice model was then used to investigate the impacts on rice yield, components of the water balance and water productivity for a range of seasonal conditions, soil types, irrigation management, planting date and varietal duration.

Genetic coefficients were determined for two rice varieties, PR115 and PR118. PR 115 is a short duration variety which reaches harvest maturity approximately 125 days after seeding. PR 118 is a longer duration variety which reaches harvest maturity approximately 150 days after seeding. The recommended transplanting schedule is the 20th-30th June for PR 115 and 10th-20th June for PR 118. The genetic coefficients were determined iteratively by adjusting the values of the coefficients until a reasonable fit was achieved for simulated and observed flowering and maturity dates and yield.

The parameters that were common for all simulations were:

- Weather:
  - 36 years of Ludhiana data 1970-2005, collected by the Department of Agronomy and Meteorological weather station at PAU, Ludhiana
- Fertility:
  - N limiting (broadcast in 3 splits – 1/3 at transplanting, 1/3 at 21 DATP and 1/3 at 42 DATP) total applied 126 kg/N/ha
- Infiltration rate:
  - 10 mm/day
- Daily irrigation:
  - First 15 days to a floodwater depth of 50 mm
- N in irrigation water:
  - 4.0 µg/l (as found in the groundwater at the experimental sites) which is equivalent to 4 kg/N/ML applied.

The parameters that were varied were:

- Variety:
  - PR 115 or PR 118
- Irrigation:
  - CF - continuously flooded
  - 1d - 1 day after floodwater has disappeared
  - 2d - 2 days after floodwater has disappeared
  - 4d - 4 days after floodwater has disappeared
  - 8d - 8 days after floodwater has disappeared
  - 16d - 16 days after floodwater has disappeared
- Soil type:
  - Sandy loam (PAU)

  - Loam (Phillaur)
  - Clay (Riverina)
- Transplanting date:
  - every 10 days from 30 April to 20 August
  - (28 day old seedlings).

Wheat – NSW

Timsina et al. (2005b)

We used the model (CSM)-Wheat V4.0 to evaluate management options for increasing the water productivity of wheat. CSM-wheat is derived from CERES-Wheat and CROPSIM-Wheat and embedded within the Decision Support System for Agro-technology Transfer (DSSAT V4.0).

Genetic coefficients for a current wheat variety (Chara) grown under irrigation were derived using field observations of crop development and yield on a Wilbriggie clay loam (sub-project 2). The model was used to evaluate the effect of sowing date and irrigation management for Chara on irrigation water productivity (IWP, g grain/kg irrigation water), crop water productivity (CWP, g grain/kg ET), irrigation water use, yield, and drainage losses. Cumulative probability functions were generated using 41 years of historical weather data at Griffith, NSW.

Rice – NSW

Timsina et al. (2004b)

The objectives of the study were: (1) to develop and test floodwater temperature and chilling injury routines for rice, (2) to incorporate these routines into CSM-CERES-Rice version 4.0, and (3) to use the model to predict the grain yield response of rice in southern NSW.

We adapted the soil temperature model of Krenz and Ritchie as used in the SALUS model (J. Ritchie, pers. comm.) for incorporation into CERES Rice. The SALUS soil temperature model is more responsive to short term changes in ambient temperature and solar radiation, and also better reflects the impacts of changes in soil water content on soil temperature, than the EPIC model used in DSSAT. The model uses the heat conductivity and heat capacity of each layer of soil to predict heat transfer and temperature changes.

At the start of the pollen microspore stage, final spikelet number cannot be estimated since culm weight at anthesis will not be known. As a surrogate for spikelet number, the model estimates a potential spikelet number from the size of biomass and tiller numbers at PI. This is used to derive an index describing the likely impact of assimilate availability on pollen cell efficacy. This index is calculated each day during the microspore duration and will ultimately be used to determine the proportion of spikelets which will be fertile.

The microspore duration (or the cold sensitive phase) depends on the physiological age of florets on various tillers and within panicles. The extension of microspore duration may result in delayed heading by as much as 90 degree days. The model first determines the proportion of pollen cells which may be vulnerable to low temperature damage on any one day and the extent to which they are “damaged”. During the pollen microspore stage, if the floodwater minimum temperature on any day is below the critical value for a variety, a pollen-chilling damage index is calculated for that day. Using the floodwater minimum temperature, a further index for the direct effect of chilling on pollen cell survival is derived. This index is sensitive to variety and defines the threshold below which chilling injury occurs. Then the fraction of fertile microspores is determined as a function of the above stresses (assimilate, cold, and N) and the fraction of microspore available on that day for pollination. If the rice crop is exposed to low enough temperatures, i.e, if the minimum floodwater temperature is less than the critical temperature for given cultivar, then the spikelet fertility is reduced by cold temperature.

The nitrogen status of the crop at PI stage and during the microspore duration interacts with cold temperature to influence the spikelet fertility. The N-induced chilling injury is most severe when the plant has high N status during the PI stage and also during the microspore stage. The N stress functions allow the model to capture the greater susceptibility of plants with high N status to chilling injury. The model also simulates the greater chilling injury risk with early (pre-permanent flood) N application than with late N application at PI.

The genetic coefficients for Amaroo and Calrose were determined using data from the conventional combine-sown treatments in experiments at Coleambally (Beecher et al. 2006) and at Whitton (Muirhead et al. 1989). Independent validation data sets for crop performance and floodwater temperature as affected by water depth were from experiments at Deniliquin and Yanco (Williams and Angus 1994; Beecher et al. 1994; Farrell 2004).

5.1.5 Subproject 6. Economic impact assessment of permanent bed systems in Punjab and Australia

Punjab

Dhaliwal et al. 2007

A financial analysis was undertaken using a partial budgeting approach in which the additional and foregone annual costs and benefits of the options were compared. The analysis sought to ascertain the attractiveness of the options from the perspective of a farmer, using financial values for all relevant inputs and outputs. ‘Financial values’ are the prices/benefits actually received by farmers for outputs or actually paid by them for inputs or losses. For example, the value of a 10% decline in rice yield is a financial loss to a farmer.

The period over which the benefits and costs of adoption of the PRB technology were determined was 30 years. A discount rate of 7% per annum was used, assuming that all future costs and benefits will be measured in relation to the current purchasing power of the money, and ignoring the effect of inflation on future costs and benefits. The 7% discount rate was higher than the 4% discount rate normally used for economic assessments in India to allow for the facts that there is some risk involved in investments in agriculture, and that individuals acting independently take a shorter view than society. The 4% discount rate is based on the prevailing 8.25% p.a. interest rate on long term bank deposits of up to 10 years minus inflation at 4.5% p.a. All benefits and costs were expressed in 2006 Indian Rupees (Rs), which required all future returns and costs to be discounted to 2006 values.

The financial benefits of adoption of PRB were assessed using the net present value (NPV) of the investment. NPV is the difference between the present value of costs associated with the investment and the present value of benefits accruing from the investment. The proposal is deemed to have a positive impact if NPV exceeds zero.

Australia (additional undertaking not in original project proposal)

Beecher et al. 2007b; Singh and Beecher 2007

The financial of four field layouts currently being used by rice growers to grow different summer and winter crops were compared with permanent beds in a terraced, zero grade, bankless channel layout. There is no one crop sequence suited to every rice-based layout. The study identified a typical crop sequence for each of the irrigation layouts to for the comparison. The details of the cropping sequences under different layouts are:

Layout	Crop sequence
1. non-landformed natural contour	RRRF(OW)WWPPP
2. laser landformed natural contour	RRRF(OW)WWPPP
3. laser landformed square contour	RRRF(OW)WWPPP
4. laser landformed square contour alternating with raised beds	RRRFS/BSF
5. Laser landformed lateral permanent raised beds (zero-graded, bankless, terraced rice field irrigation design)	RRB/SB/S
6. Laser landformed lateral permanent raised beds (zero-graded, bankless, terraced rice field irrigation design)	RRRB/SB/S

R = rice, F = fallow, OW = opportunity wheat (immediately after rice harvest), W = wheat, B = barley, S = soybean,

The study used a crop sequence gross margin analysisi to estimate the potential financial benefits to farmers of adoptiong PRB in terraced, zero slope bankless channel layouts. The financial merit of adopting permanent raised beds was assessed using the net present value (NPV) of benefits over costs over a 30 period, using a 4% discount rate. The proposal is deemed to have a positive impact if NPV exceeds zero.

The study used financial values for all relevant inputs and outputs - ‘financial values’ are the prices/benefits actually received by farmers for outputs or actually paid by them for inputs or losses). The costs of some inputs or operations such as irrigation water, fertiliser and machinery operations are different under different field designs. Increase in yield or price also leads to increase in the 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 were estimated separately for different irrigation designs and cropping rotations. The costs of conversion to lateral permanent raised beds considered in the analysis include: initial cost of survey design, earthworks, landforming, capital costs and annual maintenance (reshaping) costs over the lifespan of the system on a medium slope country. The machinery costs for preparing lateral permanent raised beds were contract rates charged by local machinery contractors.

5.1.6 Subproject 7: Development of the Happy Seeder for direct drilling into rice stubble

Blackwell et al. (2004) ; Sidhu et al. (2007a,b), Singh et al. (2007), Yadvinder-Singh et al. 2007, Humphreys et al. (2005)

Development of machinery (the Happy Seeder) for direct drilling wheat into rice residues, in collaboration with private Punjabi machinery manufacturer.

In brief, 3 versions of the Happy Seeder were developed – the original machine with modified forage harvester and seed drill linked together, the Combo Happy Seeder which was a smaller single unit which combined both functions, and finally the Turbo Happy Seeder which included a straw chopper at the front and feeds the straw between the tynes instead of through a chute over the top.

The Happy Seeder concept was tested extensively in several replicated field experiments, and in farmers' fields under farmer management. The majority of this testing was carried out using the Combo Happy Seeder, with and without strip tillage.

In addition, there were:

- two replicated experiments evaluating the effect of rice straw load (0-12.5 t/ha) and sowing date, for direct drilled wheat mulched with rice residues – included monitoring of establishment, growth, yield and yield components.
- a replicated experiment on a loamy sand examining soil water dynamics and irrigation scheduling for wheat direct drilled wheat into rice residues (7.3 t/ha) with the Happy Seeder in comparison with residues removed. There were four irrigation schedules based on recommended practice, the ratio of irrigation water to cumulative pan evaporation minus rainfall (IW/CPE) and soil matric potential (SMP). Irrigation amounts, soil water content to depth prior to each irrigation, and crop establishment and yield were monitored.
- a replicated experiment evaluating fertiliser N management options for wheat direct drilled into rice residues with the Happy Seeder. Urea was applied at the recommended rate (120 kg N/ha to all treatments except one unfertilised treatment. There were 8 N management treatments for the wheat mulched with rice straw, including the recommended practice (half broadcast before sowing, half broadcast before the first irrigation after sowing). There was also a non-mulched control treatment with N applied using recommended practice. Crop growth, N uptake, yield and yield components were monitored.

Financial analysis of the Happy Seeder

Singh et al. (2007)

The analysis was conducted for a 20 year period, assuming a 20 year life of the machine, with discounting back to 2006 values using the real discount rate of 7%. The Happy Seeder was compared with conventional tillage and use of the zero till drill following stubble burning.

6 Achievements against activities and outputs/milestones

6.1.1 Subproject 1. Preliminary field experiments in India to evaluate layout and agronomic options for permanent bed systems, with particular emphasis on rice

Objective 1

To evaluate planting, water management, N management and stubble management options for permanent bed systems in India, with particular emphasis on rice.

no.	activity	outputs/ milestones	completion date	comments
1.1 PC	preliminary replicated experiments to aid selection of rice varieties & irrigation scheduling for rice for medium term RW experiments in Sub-projects 2 and 4	Draft reports; results summarised in Annual Report 2002	2002	1. 3 rice varieties were evaluated leading to selection of PR115 for the medium term experiments. However after 2 years we changed to a longer duration variety (PR118) following observations in farmers' field that PR118 did better than PR115 in adjacent replicated experiment, and the poor performance of PR115 2. several irrigation schedules for beds were evaluated – we selected the schedule "irrigate 2d after floodwater dissipated" for future experiments as there was no yield penalty compared with more frequent/higher irrigation water use treatments

PC = partner country, A = Australia

6.1.2 Subproject 2. Field evaluation of permanent bed and conventional RW/rice-based cropping systems of Punjab and NSW

Objective 2.1

To quantify crop growth, development, yield and system productivity on permanent bed and conventional systems.

Objective 2.2

To quantify soil physical properties, including changes over time, for permanent bed and conventional systems.

Objective 2.3

To quantify components of the water balance, changes in soil water content over time, and water use efficiency (e.g. t/ML, ML/ha, losses) for permanent bed and conventional systems.

Objective 2.4

To determine P, K and other nutrient balances for permanent bed and conventional systems (N is covered in subproject 4).

no.	activity	outputs/ milestones	completion date	comments
2.1 PC A	Crop growth and development	Completed for RW on 2 soils in India (4 years, 8 crops) and for range of rice-based sequences over 4 years in Australia	2003 2004 2005 2006	P Humphreys et al. (2004) P Kukal et al. (2007a) A Beecher et al. (2004, 2005, 2006a,b, 2007a,b) A Mathews et al. (2004) Causes of disappointing crop performance on beds (both crops) and yield decline with transplanted rice on beds in India needs further investigation
2.2 PC A	Soil physical properties	Selected baseline properties at all sites in India and Australia were determined; detailed soil water monitoring at all sites; hydraulic conductivity and bulk density comparisons in India	2006	P Humphreys et al. (2004) P Humphreys et al. (2007) P Kukal et al. (2007b) Some data analysis still pending for Australia
2.3 PC A	Water balance and water use efficiency	Comprehensive and intensive measurements were undertaken at all sites in India and Australia	2006	P Humphreys et al. (2004) P Humphreys et al. (2007) A Beecher et al. (2004, 2005, 2006a,b, 2007a,b) A Mathews et al. (2004) Excessive seepage from small plots confounded water balance results for rice in India
2.4 PC A	Nutrient balances other than N		Not undertaken at any site	

PC = partner country, A = Australia

6.1.3 Subproject 3. Field evaluation of permanent beds for alternatives to RW (maize-wheat, soybean-wheat)

Objective 3.1

To quantify crop growth, development, yield and system productivity on permanent bed and conventional systems.

Objective 3.2

To quantify soil physical properties, including changes over time, for permanent bed and conventional systems.

Objective 3.3

To quantify components of the water balance, and water use efficiency (e.g. t/ML, ML/ha, losses) for permanent bed and conventional systems.

no.	activity	outputs/ milestones	completion date	comments
3.1 PC	Crop performance	Completed on loamy sand – 3 years (6 crops)	2006	Ram (2006)
3.2 PC	Soil physical properties	Initial and final measurements of selected properties	2006	Ram (2006)
3.3 PC	Components of water balance	Completed	2006	Ram (2006) Soil water data from only 1 replicate; no estimates of deep drainage, if any

PC = partner country, A = Australia

6.1.4 Subproject 4. Nitrogen use efficiency in RW cropping systems in Punjab (with IAEA)

Objective 4.1

To determine nitrogen balances and N fertilizer use efficiency using 15N techniques, and to study nitrogen dynamics for permanent bed systems with and without mulching.

no.	activity	outputs/ milestones	completion date	Comments
4.1 PC	N balances and N fertilizer efficiency	Completed – experiment run for 4 years (8 crops) with 4 N rates and 2 mulching treatments	2006	Yadvinder-Singh et al. (2003, 2004, 2005, 2007)

PC = partner country, A = Australia

6.1.5 Subproject 5. Development and application of models to identify management options for maximising the productivity of RW cropping systems in Punjab and the IGP, and of rice-based systems in NSW

Objective 5.1

To develop calibrated and validated models for bed and conventional RW cropping systems.

Objective 5.2

To use the results of model simulations and the field experiments to evaluate layout, planting, irrigation and nitrogen management strategies on the productivity of permanent bed RW systems.

no.	activity	outputs/ milestones	completion date	comments
5.1 PC A	Model calibration and validation	Completed for individual crops of wheat (India and Australia) and rice (India) on conventional flat layouts	2006	PC, A Timsina et al. (2004a,b; 2005a,b) PC Timsina et al. (advanced draft) PC Smith et al. (early draft) PC, A Timsina et al. (2006a,b) A Timsina et al. (2007)
5.2 PC A	Model applications	Completed for individual crops of wheat (India and Australia) and rice (India) on conventional flat layouts	2006	PC, A Timsina et al. (2004a,b; 2005a,b) PC Timsina et al. (advanced draft) PC Smith et al. (early draft) PC, A Timsina et al. (2006a,b) A Timsina et al. (2007)

6.1.6 Subproject 6. Economic impact assessment of permanent bed systems in Punjab

Objective 6

To determine the economic impacts of RW systems on permanent beds.

no.	activity	outputs/ milestones	completion date	comments
6.1 PC	Economic impacts of RW for PRB in India	Financial analysis completed for RW, MW and SW	2006	PC Dhaliwal et al. (2007)
	Additional output – Financial impacts of PRB for rice-based systems in Australia	Financial analysis completed for comparisons of raised bed and conventional flat systems	2007	A Singh and Beecher 2005? A Singh, RP et al 2007 A Beecher et al 2007

6.1.7 Subproject 7: Development of the Happy Seeder for direct drilling into rice stubble

Objective 7.1

To rebuild, refine and fine tune the Happy Seeder for direct drilling of any crop into any residue in rice-wheat rotations under bed and flat layouts.

Objective 7.2

To undertake on-farm evaluation, demonstration and popularisation of the Happy Seeder.

no.	activity	outputs/ milestones	completion date	comments
7.1 PC	Development of Happy Seeder	Completed – successful for wheat into rice and mungbean into wheat (PC), and for soybeans into barley and barley into maize (A)	2006	PC Humphreys et al. (2006) PC Sidhu et al. (2007a,b) Combo seeder well-tested but superseded by development of Turbo seeder in late 2005 – this machine is little tested Smaller versions of the machines need to be developed to be powered by 35 h.p. tractors
7.2	On-farm evaluation of Happy Seeder	Completed – for wheat into rice at several locations in Punjab over 4 seasons	2006	PC Sidhu et al. (2007a) Further participatory farmer evaluation and testing needed
	Additional activities – To develop irrigation and N management strategies for direct drilling wheat into rice residues	2 replicated experiments – one on irrigation scheduling, one on N management	2006	PC Yadvinder-Singh et al. (2007) Further experimentation and modelling studies needed to evaluate options and develop guidelines

7 Key results and discussion

7.1.1 Subproject 1. Preliminary field experiments in India to evaluate layout and agronomic options for permanent bed systems, with particular emphasis on rice

Evaluation of rice varieties under different methods of plant establishment

Yields ranged from 5.1-9.5 t/ha and increased as duration decreased across all treatments except for transplanted rice on beds (TRB) where they were similar (~7.4 t/ha) for all varieties. Yields of PTR were always at least 10% higher than all other planting methods. Yields of direct seeded rice on beds (DSRB) were considerably less than yields of TRB for the longer duration hybrid and in-bred varieties, but comparable (7.2 t/ha) for the short duration variety. Leaf spot was a problem in direct seeded rice on both beds and the flat and may have reduced yields. Iron deficiency was also very severe in direct seeded rice on both beds and flats – FeSO4 (1%) was sprayed 10 times on the DSR and twice on the TRB. Based on these results, PR115 was selected for the experiments in sub-projects 2 and 4 as it was the best variety with direct seeding on beds, and comparable to the other varieties for transplanted rice on beds. Furthermore, irrigation water requirement would be less for a shorter duration variety, and harvest would be earlier, enabling timely sowing of wheat. However, performance of PR115 declined as the beds aged in sub-project 2, and after two years it was replaced with a recently released long duration variety PR118 based on its good performance on beds in the farmers' field on the loam in 2004, much better than that of PR115 on the loam in the adjacent sub-project 2 plots.

Evaluation of mechanical interculture for rice on beds

There was a yield increase of 31% compared with the unweeded area (5.7 cf. 4.3 t/ha). Further development of interrow culture equipment is needed, but was not undertaken in this project.

Effect of irrigation frequency on water use and yield of transplanted and direct seeded rice on beds

DSRB showed symptoms of Fe and N deficiency in early growth stages, and N deficiency was more prominent with daily irrigation, suggesting higher N losses. Four hand-weedings were done due to heavy weed infestation – economic methods of weed control are needed for intermittently irrigated permanent beds.

Yields of TRB were consistently higher than DSRB. Yields of TRB were comparable (4.8 t/ha) for irrigation every day or every third day, however water use (irrigation plus rain) was reduced by 152 cm out of a total of 341 cm. Yields were reduced a little to 4.3 t/ha for lower (after 5 and 7 days) irrigation frequencies, and total water use was further reduced by about two-thirds from 341 to 111 and 90 cm.

In contrast to TRB, yields of DSRB declined from 4.3 to 3.8 t/ha with reduction in frequency from 1 to 3 days, with little difference in yield between 3, 5 and 7 day intervals but reduction in water use by over two-thirds.

On fresh beds in the same field, DSRB (6.5 t/ha) and TPRB (6.2 t/ha) performed much better - possibly due to consolidation of the permanent beds. There was also less weed infestation of fresh beds.

7.1.2 Subproject 2. Field evaluation of permanent bed and conventional RW/rice-based cropping systems of Punjab and NSW

Punjab

Yield of wheat on fresh and permanent beds in both small plots and large blocks was usually similar to yield of conventionally tilled wheat (CTW) on the loam, but tended to be lower on the sandy loam (Humphreys et al. 2004; Kukal et al. 2007; Yadvinder-Singh et al. 2007a). There was no evidence of a decline in wheat yield on the beds relative to CTW as the beds aged. Yield of both transplanted and direct seeded rice on beds on both soils declined significantly relative to puddled transplanted rice (PTR) as the beds aged. The direct seeded rice on beds suffered from iron deficiency, despite several sprays of iron sulphate. The problem became worse as the beds aged, and was also worse on the loam soil than on the sandy loam. The transplanted rice on beds was also affected by cereal cyst nematodes on the sandy loam, but no cysts were observed on the loam. Weed control was also a major issue, as it was impossible to pond water for long enough for herbicides to be effective, so 2-4 hand weedings were required. Mulching had a significant negative effect on DSRB, and was associated with increased incidence of nematode cyst counts on the roots (Yadvinder-Singh et al. 2007a).

In situ exposure of root profiles on permanent beds revealed that the horizontal spread of roots was more towards the furrow-side than the bed-side (Kukal et al. 2008). The root mass density in 0-30 cm profile was significantly lower on permanent beds than on fresh beds. The bulk density of side-slopes of the permanent beds was significantly higher than that on the fresh beds. Since the permanent beds were reshaped prior to establishing rice each year, the pressure exerted by the tractor-tyres (with width similar to that of the top of the furrow) on the side-slopes of the beds may have compacted the soil and hindered the spread of the roots particularly towards the beds. This could have resulted in declining rice grain yield on permanent raised beds with time.

Irrigation applications to PTR with continuous flooding (PTR-CF) ranged from 3,300-4,300 mm in the small plots, and around 2,200-2,300 mm in the large blocks (Humphreys et al. 2007a). Irrigation water use was much higher in the small plots due to disproportionately large seepage losses. This led to overestimation of the potential saving in irrigation water by changing from continuous to alternate wetting and drying (PTR-2d). However, underbund seepage was also a major component of the water balance in the large farmer field blocks, and accounted for 60% of the irrigation input in PTR-CF. Total deep drainage (in-field percolation losses and underbund seepage) in the large block with PTR-CF was 2,120 mm (90% of the irrigation input), and was roughly halved with alternate wetting and drying. Thus even with recommended water management, deep drainage (~1,000 mm) was very high in the farmer's field, raising the question of the suitability of such free-draining soils with deep watertables for rice culture.

Water management had a large effect on rice irrigation amount. Switching from continuous flooding (PTR-CF) to intermittent flooding (PTR-2d) reduced irrigation amount in the large blocks by over one-third (~800 mm). A similar reduction was achieved by switching from PTR-CF to transplanted rice on fresh or permanent beds (TRB-2d) with the same irrigation scheduling as PTR-2d. The results suggested that the reduction in irrigation amount in changing to rice on beds is due to changing to intermittent irrigation rather than changing to beds.

Depth of water in the furrows also had a large effect on rice irrigation amount on both fresh and permanent beds. Irrigation amount with a full furrow at each irrigation was much higher than with a half furrow depth of water, however there was a yield penalty in reducing furrow water depth from full to half. The amount of irrigation water applied to TRB-2d with a full furrow exceeded that applied to PTR-2d, probably because of higher permeability of the soil in the unpuddled furrows, and greater macropore development on the permanent beds. Consistent with this, irrigation amount on permanent beds irrigated with a full furrow depth of water was about 600 mm (20%) higher than on fresh beds with the same irrigation scheduling.

Total irrigation amounts for wheat (212-383 mm) were about one tenth of the irrigation amounts for rice. The amount of water applied at each irrigation was usually less on the beds than on the flats because of the volumetric limitation of the furrows. However, there was no effect of layout on total irrigation application to wheat, in either the small plots or large blocks, because irrigation management was based on the same ratio of irrigation amount to net cumulative pan evaporation (CPE-rain) for both beds and flats, meaning that the beds were irrigated more frequently after CRI.

Deep drainage from wheat was very small in comparison with that from rice, in both flat and bed layouts. Deep drainage from wheat was sometimes negligible and usually less than 100 mm, compared with up to ~2,000 mm from rice.

Our studies demonstrate the importance of providing sufficient contextual detail in reporting the results of comparisons of soil and water management for RW systems to enable sound interpretation and extrapolation of the results. In particular, they highlight the importance of appropriate controls in understanding the potential irrigation water savings in switching from puddled transplanted rice to beds. They also show the need for caution in interpreting the results of rice water balance studies in small plots unless adequate measures have been undertaken to prevent disproportionately high seepage losses, especially from continuously flooded rice. Further detailed investigations are needed in farmer sized blocks, for a range of soil types, watertable conditions and irrigation management, to understand the effects of raised beds on components of the water balance for RW systems, and to develop irrigation management guidelines for rice and wheat on PRB.

Our findings of the performance of rice and wheat on PRB were generally consistent with those of others in the western IGP (e.g. Bushan et al. 2007; Jat et al. 2007), but in strong contrast to findings in the eastern Indo-Gangetic Plains (IGP). In Bangladesh and Nepal, the performance of transplanted rice and wheat on PRB is superior to results with conventional tillage, improves with mulching, and mulching reduces the need for N fertiliser (Lauren et al. 2007; Talukder et al. 2007). The different performance of permanent beds in the eastern and western IGP needs further examination to elucidate the reasons and to develop successful permanent bed systems for the western IGP. Major differences include the much wetter conditions in the eastern IGP, and the much greater mechanisation with 4-wheel tractors in the western IGP. The results of our work suggest that, with current technology, permanent bed RW systems in Punjab, India, are not viable if rice yield and production are to be maintained.

NSW

Rice crop performance on PRB was as successful as that achieved by rice on conventional flat systems when the crop was protected by deep water during the pollen microspore growth stage. Adequate weed control was achieved in the raised bed layouts with existing weed control strategies.

The possibility of cold temperature conditions during the early pollen microspore stage of crop development inducing floret sterility when using current rice varieties remains a significant hazard (viz 2003/4 and 2004/5 rice crop performance when deep water was not applied). It is necessary to ensure the impact of these conditions is minimised/managed by the use of deep water conditions (Williams and Angus 1994) for all rice growing layouts including raised beds. The terraced, zero grade, bankless channel layout with large banks around each bay enables ponding with deep water to provide cold protection during the pollen microspore stage. This layout provide the capability of being able to achieve uniform water depth control across each bay compared to a 5-10 cm water depth variation across the bay in conventional graded field layouts. This has implications for improved and more uniform crop establishment, for the more efficient and effective use of herbicides, and it reduces the volume of water required to be held in the bay at any point in time.

Other crops (wheat, barley and soybeans) were successfully grown in rotation with rice on raised beds in zero graded layouts.

Raised beds did not provide the yield advantages for wheat or barley compared to flat irrigation layouts that have been clearly demonstrated in other work (Thompson and North 1994) and which were anticipated in this experiment. This could have been due to how water was supplied to and drained from the plots in experiment, or more likely reflects the absence of winter rainfall conditions conducive to development of waterlogged conditions during the experimental period. Winter rainfall was below average to average, with no major wet periods.

Winter cereal crop performance in the experiment was limited due to delayed sowing in mid to late May, significantly later than the late April – early May recommend date (Lacy 2006) to achieve high (8 t/ha) yields. Sowing time was constrained by growing wheat after rice (i.e. late harvest even with low rainfall during autumn of each season of the experiment and by low rainfall conditions generally). This was exacerbated by inability to access irrigation water during early September when soil moisture levels were depleted by lack of sufficient winter rainfall. Outbreaks of wheat stripe rust occurred during the experiment and although fungicides were applied rust may have also impacted on wheat yield outcomes.

Soybean growth and yield under both furrow and drip irrigation were highly satisfactory given the later than optimum sowing dates of soybean imposed by the double cropping regime. Double cropping barley and soybeans with current varieties, especially as barley stubbles need to be burnt prior to soybean sowing, leaves little time between harvest and sowing of the following crop. The feasibility of drilling soybeans into barley stubble was demonstrated using the Combo+ Happy Seeder in a commercial field, with potential benefits of earlier establishment in addition to the benefits of retaining the residues.

Growers are interested in the concept of PRB in terraced, zero grade, bankless channel layouts, and perceive many advantages. **BUT** they also want to see performance of the system under a range of conditions, especially in wet winters with waterlogged conditions.

These zero-graded basin layouts can be adapted to tram lining (controlled traffic – occurs axiomatically where beds are present, provided wheel spacings match furrow spacings.) This can provide advantages in terms of limiting soil compaction to particular furrows/ tramlines), improving machinery access along these trafficked tramlines following irrigation. Matching irrigation layouts to machinery (or vice versa) will also allow improvements in machinery efficiency to be achieved.

Growers see labour savings as a major advantage of this style of irrigation layouts. These systems have a significant advantage over conventional graded furrow systems in that there are no syphons to start, stop or shift, and no water to recycle except from the bottom bay. This style of layouts also lends itself to automation in terms of opening irrigation channel structures.

The experiment was conducted during period without significant winter/spring rainfall events so issues of compaction, waterlogging and machinery access were not encountered during the four--year experiment. Commercial situations need to be monitored during wet winter/spring periods as the situation arises and issues and solutions explored at that time.

Limitations imposed by the experiment need to accurately measure water on/off, and often poor access to large irrigation water flows, meant that the irrigation intake opportunity times were extended compared to what could happen in the commercial situation.

The degree of adoption of beds in zero graded layouts may be limited by two significant constraints: (1) existing land slope – land with flat to very flat grades may not allow the economic development of terraces with appropriate steps between irrigation bays (from one bay to the next down stream bay), and (2) lack of access to high irrigation flow rates, in balance with size of irrigation bays. Although substantial irrigation flow rates (greater than say 25 ML/day) can be achieved by riparian irrigators or irrigators with on farm storages, district irrigation infrastructure may limit the ability to adopt these irrigation layouts due to the inability to deliver irrigation flow rates of sufficient volume.

Adoption of increased cropping intensity (wheat immediately after rice) is constrained by the need to remove or otherwise handle rice stubble residues in all rice growing locations. Stubble is currently mulched and burnt in most situations. Limitations on the amount of stubble burning either due to concerns about greenhouse gas generation or from growers' desires to improve soil organic carbon levels may restrict adoption of double cropping systems unless technology such as the Happy Seeder can be adapted to achieve good establishment and early growth in the very heavy stubble loads (10-14 t/ha) of Australian rice crops. This may be a prohibitive given the large amount of stubble and it's effect on soil temperature and light and consequently on germination and early growth.

Double cropping in soybean-barley rotations is currently restricted in the Murray Valley due to strict bans on stubble burning for wildfire control in summer. This means that alternative approaches of handling barley crop residues to burning are needed. Opportunities for this may be the use of the Happy Seeder approach. Manipulation of seed row spacing and inter row sowing of succeeding crops which could be achieved on raised bed layouts or with precision guidance steering systems may offer another alternative.

The adoption of raised beds is problematic on properties where livestock and cropping enterprises are jointly undertaken. Beds/furrows and livestock are considered incompatible due to the increased possibility of livestock becoming cast (unable to stand if caught in an unsuitable position in the furrow).

Substantial irrigation water savings during rice growing through the use of raised beds compared to conventional flat layouts are unlikely to occur on the heavy clay, low permeability soils used for rice culture in Australia. Where reduced water applications are made it is likely that yields will also be reduced (Thompson et al. 2003).

7.1.3 Subproject 3. Field evaluation of permanent beds for alternatives to RW (maize-wheat, soybean-wheat)

Yields of maize, wheat and soybeans on fresh and PRB on a loamy sand with no history of rice cultivation were similar to yields with conventional tillage and direct drilling on the flat, over 3 seasons, for each crop (Ram 2006). Yields were maintained on permanent beds while applying less irrigation water, however this needs qualification as it is unknown if the same yields could have been achieved on the flats with the lower irrigation amounts as applied to the beds, nor whether there were significant differences in deep drainage or residual soil water at the end of the season.

Seasonal rainfall for each crop ranged from relatively dry (about half the seasonal average) to around the seasonal average. There were no unusually wet summers or winters during the 3 years, so the potential advantage of beds in reducing waterlogging has not been assessed. Furthermore, the application of the technology on heavier soil types with a history of rice cultivation (and thus a well-developed hard pan) has not been assessed. Other studies in the region have shown that beds are an advantage on such soils due to reduced waterlogging of the beds (Ram et al. 2005).

Permanent beds were more profitable than all other layouts for MW and SW, due to reduced costs of tillage, labour, and wheat seed, although PRB were only slightly more profitable than double zero tillage on the flat (Dhaliwal et al. 2007). RW was slightly more profitable than MW for respective layouts, and that both systems were much more profitable than SW, mainly due to the low yield of soybean. However, both maize and soybean have additional social, economic and environmental benefits as a result of much lower electricity consumption due to much lower irrigation requirement than rice (~15% of the requirement for rice using conventional tillage for both crops). However, diversification from RW to MW or SW cropping systems would require more research and extension efforts and better marketing infrastructure to enable them to compete with the Government of India (GOI) procurement scheme for rice and wheat.

7.1.4 Subproject 4. Nitrogen use efficiency in RW cropping systems in Punjab (with IAEA)

Rice grain yield increased significantly as N rate increased up to 160 kg N/ha, irrespective of method of rice establishment (Yadvinder-Singh et al. 2007a). Puddled transplanted rice (PTR) was always superior to all other establishment methods in terms of biomass, yield and NUE, consistent with the findings of sub-projects 1 and 2. At 120 kg N/ha, yield of transplanted rice on permanent beds (TRB) was 29% lower than yield of PTR, while yield of direct seeded rice on permanent beds (DSRB) was even lower (44% lower than yield of TRB). Wheat straw mulch further reduced yield of DSRB by 26% on average, whereas there was no effect of mulching on yield of TRB. Dry-seeded rice on flats and beds was prone to severe iron deficiency and root nematode infestation. Yield of DSRB relative to yield of PTR declined as the beds aged, however there was no trend in relative yield of TRB. Recovery of fertiliser ^{15}N in the straw plus grain was 30% in PTR compared with only 14% for TRB and 17% for DSRB. The majority of the crop N uptake (65-83%) was derived from the soil in all treatments, despite the application of urea at 120 kg N/ha. Total N losses from the urea N applied to rice ranged from 52 to 60% in TRB and DSRB compared with 38% in PTR.

Wheat yield increased with N rate up to 120 kg N/ha, with further significant response to 160 kg N/ha in 2 of the 4 years. Wheat grain yield on permanent beds after TRB and DSRB was 75-96 % of that of conventional tilled wheat (CTW), with no trend in relative yield over time as the beds aged. Grain yield of wheat was similar in CTW and direct drilled (“zero till”) wheat on the flat DDW. The ^{15}N recovery in the wheat plants in all flat and bed treatments was similar. Straw mulch had no effect on yield or NUE of wheat. Recoveries of applied N in the wheat plants and soil (58-51%) were much higher than in rice. Total fertilizer N losses were much lower in wheat (mean 14-21%) compared with rice (mean 38-60%).

After 8 crops, soil organic C, total N and available K were significantly higher with straw mulch compared with no mulch. Permanent beds for RW seem to have limited potential under the soil and climatic conditions of Punjab, India, with current technology, even with full residue retention for both crops. Further research on PRB should focus on the selection of rice and wheat cultivars better suited to beds, soil health issues such as nematodes and iron deficiency, weed control, nitrogen, water and residue management and machinery (development and practices).

7.1.5 Subproject 5. Development and application of models to identify management options for maximising the productivity of RW cropping systems in Punjab and the IGP, and of rice-based systems in NSW

Wheat - Punjab

There was a good agreement between measured and simulated grain yields (5.3-5.4 t/ha) (Timsina et al. 2008). Mean observed straw yields (7.0-7.1 t/ha), on the other hand, were 20% higher than simulated straw yields (5.5-5.6 t/ha). As a result, the total top weight at maturity was underestimated by about 10%. Simulated seasonal total above-ground biomass accumulation during the season also agreed well with the observed values. There was generally a good agreement between the model predictions and observed data, within the bounds of experimental error. The model predicted grain yield on the loam at Phillaur and on the loamy sand at PAU quite well, but tended to over-predict on the sandy loam at PAU. The model also predicted the yields for the four N rates ranging from 0 to 160 kg/ha on the sandy loam at PAU over three seasons quite satisfactorily, suggesting that the model is able to capture the yield response to N. Across all data sets from all experiments examined together, prediction for grain yield was best (absolute RMSE=617 kg/ha; normalised RMSE= 15%; D-index= 0.92) while that for HI was not so good (absolute RMSE=0.14; normalised RMSE= 35%; D-index= 0.34). There were greater standard deviations about means for observed values than for the simulated values.

Potential yield varied across years and sowing dates, with mean yield ranging from 5.2 t/ha (October 10 sowing) to 6.4 t/ha (November 10 sowing). Potential yields were greatest for sowings between 25 October to 25 November (mean 6.3-6.4 t/ha), and least for 10 October and 10 January sowings (mean 5.2-5.5 t/ha). Yield variation due to seasonal weather variation was greater than variation across sowing dates. On both the loam and sandy loam soils, yields under SWD-based irrigation were also greatest for 10 November sowing, albeit close to those for 25 October and 25 November sowings. Differences in yields across sowing dates were much greater than between soil types. The effect of sowing date on yield with irrigation based on SWD was similar to that of potential yield as the crops with SWD-based irrigation were never stressed. As for potential yield, yield with all irrigation scheduling methods varied greatly with seasonal conditions.

Yields of crops sown on 10 November on a loam with growth stage-based irrigation scheduling ranged from 0.9 to 7.2 t/ha. With one irrigation, yields were highest when the crop was irrigated at booting (mean 3.8 t/ha) and least when irrigated at grain filling (mean 2.8 t/ha). With two irrigations, yields were highest when irrigated at CRI and booting (mean 4.9 t/ha) and least when irrigated at flowering and grain filling (mean 2.8 t/ha). With three irrigations, yields were highest when irrigated at CRI, booting, and flowering, or at CRI, booting and grain-filling (mean 5.0 t/ha). Irrigation at three stages gave higher yields than at two stages in about 60% of years. Yields with three irrigations were similar to those with irrigations at all four stages. Yields with three and four irrigations were always considerably less than that with SWD-based irrigation.

Crop water use and irrigation amount varied greatly with seasonal conditions and frequency of irrigation. Mean ET for the November 10 sowing ranged from 226 mm for a single irrigation to 342 mm for four irrigations. Mean irrigation amount ranged from 40 to 245 mm for the same treatments. In comparison, irrigation amount with SWD-based irrigation was considerably higher (mean 361 mm) for the same sowing date. Mean CWP ranged from 1.0 g/kg (for two irrigations at flowering and grain filling) to 1.2 g/kg with three irrigations (CRI, booting, flowering) to 1.6 g/kg for two irrigations at CRI and booting.

Grain yields of PBW343 sown on 10 November with irrigation scheduled according to net ETo were much higher with more frequent irrigation (i.e., after accumulation of net ETo of

25 and 75 mm) compared to less frequent irrigation (i.e., after accumulation of 125, 150, and 175 mm net ETo). Yield with ET75 was similar to that with SWD-based irrigation, and considerably higher than yield with growth stage-based irrigation. Yield declined more rapidly on the sandy loam than on the loam as irrigation interval increased, probably reflecting the greater initial PAWC.

In conclusion, the scenarios tested using 36 years of weather data and the seasonal analysis option of the DSSAT software showed how to better schedule irrigation to increase yield, optimize irrigation amount with selection of proper irrigation method, and increase CWP. Simulation results suggest that irrigation should be scheduled based on the atmospheric demand and soil water status and not on growth stage.

Rice - Punjab

Model evaluation

Agreement between the model predictions and the field observations (yield, anthesis and maturity dates) was generally reasonable and provided confidence that the model is doing a reasonable effort in simulating processes.

Simulation experiment 1 – irrigation management, CF, 1d, 2d 4d, 8d and 16d after disappearance of floodwater (all with 10th June transplanting).

The key finding is that irrigation management had very little effect on water depletion (i.e. it did not save water where deep drainage can be recycled) at frequencies for which yields were maintained close to maximum. Maximum yields were obtained with the most frequently irrigated treatments (CF, 1d and 2d), which also had higher water productivity of ET (WP_{ET}) than the less frequently irrigated treatments (4d, 8d and 16d). Changing from CF to 2d reduced irrigation amount by 25%. The CF treatment had the lowest irrigation water productivity (WP_I) whereas the 16d treatment had the highest $WP_{I.}$ However, there are yield tradeoffs in opting for a longer irrigation interval to save irrigation water, while there are other benefits in terms of reduced power/energy in pumping irrigation water. Deep drainage accounted for approximately two-thirds of the irrigation application. Taking into account water productivities, water use and yield, the 1d and 2d irrigation treatment rank very highly, although the 1d option may not be practical in terms of time management and irrigation water availability (power restrictions). The recommended practice is for a 2d irrigation option and from the simulations this seems to be a reasonable recommendation.

Simulation experiment 2 – 12 transplanting dates from 30th April – 20th Aug with 2d irrigation management and the long duration variety

The key finding is that date of transplanting has a very large effect on water depletion, while yield of PR118 was maintained across a wide range of dates (30 April-20 July). The later the transplanting date, the more potential there is to save water. Transplanting on 20th July transplanting had the highest WP_{ET}, whereas the 20th June transplanting date had the highest $WP_{I.}$ There are tradeoffs in opting for a delayed transplanting date to save water. The primary one is the timely harvest of the rice crop and vacation of the field for sowing wheat on time. The 30th June transplanting date reaches physiological maturity (in 50% of years) on day of year (DOY) 290 (17 Oct) and would be harvested by approximately 31 Oct (in 50% of years), compared with the optimum sowing window for wheat of late October to November. The other 50% of years would be harvested after 31 Oct (up to approx 10th Nov). This timeframe is impinging on the optimal sowing window for wheat. Taking into account water productivities, water use, yield and the vacation of the field for timely sowing of a wheat crop, the 20th June transplanting date (with a 2d irrigation treatment) ranks very highly. The recommended practice for this variety is for a transplanting date in the second fortnight of June (i.e. 15th - 28th June) with a 2d irrigation option and from the simulations this seems to be a reasonable recommendation.

Simulation experiment 3 – Comparison of variety – PR 115 and PR118 on a sandy loam, 2d irrigation,10th June transplanting, N is non-limiting

The key finding is that varietal duration has a very large effect on water depletion. By growing PR 115 rather than PR 118 there is potential to save real water (>125 mm in all years), however, the simulations suggest that there is always a yield penalty of around 2 t/ha from growing the short duration variety. PR 118 had the highest $WP_{ET,}$ and the highest $WP_{I.}$ To sustain and maximise yield, PR 118 appears to be the best option. If nitrogen is limiting and applied as per recommended practice to the two varieties, taking into account water productivities, water use and yield, the 10th July transplanting date with a 2d irrigation treatment for PR 115 ranks very highly, although there appears to be a wide transplanting window for this variety from the 10th June–10th July with minimal consequences for water productivity, water use and yield. The recommended practice for PR115 is for a late transplanting date (i.e. > 28th June) with a 2d irrigation option and from the simulations this seems to be a reasonable recommendation, however there appears to be no evidence from the simulations as to why this variety could not be planted as early as 10th June onwards.

Simulation experiment 4 – Comparison of soil type – PR 118 on a sandy and heavy clay soil, 2d irrigation, 10th June transplanting, N is non-limiting

The key message here is that soil type has very little effect on water depletion (i.e. it does not save water where deep drainage can be recycled). The sandy loam had the higher $WP_{ET,}$ whilst the clay soil had the higher $WP_{I.}$ There are some positive tradeoffs in opting for a clay soil. Irrigation requirement will be reduced substantially (by up to 800 mm) with minimal or no decline to yield but huge benefits in terms of reduced power/energy in pumping irrigation water to satisfy evaporative demand. Taking into account water productivities, water use and yield, growing rice on a heavy clay soil is to be recommended if at all possible. To save irrigation water (and pumping/power requirements), alternative methods/practices and technology may be investigated and adopted in an attempt to reduce deep drainage as this is the largest single loss in the rice system.

Wheat – NSW

Irrigation and crop water productivity varied greatly depending on seasonal conditions, through their influence on both yield and crop water use requirement (Timsina et al. 2005). Starting with a wet soil profile, yield and CWP of rainfed Chara were higher for April and May sowings (means ~ 3 t/ha and 0.9 g/kg ET, respectively), declined as sowing was delayed to June and July, and increased greatly by starting with a wet soil profile. Irrigation greatly increased CWP by 42 to 141% depending on sowing date.

For irrigated Chara, CWP varied from 0.4 to 1.6 g/kg, and was highest when sown on 10 May, averaging 1.3 g/kg. This is similar to the values for irrigated wheat from 13 countries across 5 continents (range 0.6 to 1.7, mean 1.09 g grain/kg ET) (Zwart and Bastiaanssen 2004).

The variation in IWP due to seasonal variation in rainfall was much greater than the variation in CWP, and ranged from 0.9 to 2.3 g/kg with July sown Chara to 0.9 to 4.7 g/kg with April sowing. In most years, IWP of Chara was highest with May 10 sowing, exceeding 2 g/kg in about 55% of years. The results suggest that there is large scope for maximising CWP and IWP by sowing at the optimum time. However, most growers do not currently schedule irrigations based solely on soil water deficit or crop water use, due to limited availability of irrigation water. Many growers are more likely to plan for one or two irrigations at key stages, seeking to maximise yield and IWP. There is currently no facility in DSSAT V4.0 to enable automatic growth stage dependent irrigations, which limits the development of meaningful simulations for growers. Furthermore, there is no facility for interaction with groundwater in the model, whereas deep drainage (and upflow) are affected by shallow watertables, which are common in parts of the irrigation areas of the SMDB.

While CWP was similar with flood and sprinkler irrigation, IWP was consistently about 23% higher for sprinkler irrigation regardless of seasonal conditions, due to slightly higher yields and lower irrigation amounts. The flood irrigated wheat left more water in the profile at harvest (by up to 29 mm) available for crop use or loss depending on subsequent landuse. This highlights the importance of analysing the impacts of irrigation management strategies on irrigation requirement and water productivity for cropping systems rather than single crops.

In summary, the simulations suggested that:

- yield and water productivity of both irrigated and rainfed wheat vary greatly with seasonal conditions
- there is scope for maximising yield and water productivity by timely sowing: for rainfed Chara earlier sowing (Apr/May) was best, while May/Jun sowing was best for Chara irrigated to avoid SWD
- irrigation always greatly increased yield and crop water productivity
- sprinkler irrigated wheat had higher irrigation water productivity than flood irrigated wheat due to slightly higher yield, lower irrigation amount, and lower deep drainage losses.

Rice - NSW

Floodwater temperature and chilling injury routines were developed and incorporated into CSM-CERES-Rice ver. 4.0, and the resulting model ver 4.0C (C for cold) was tested against data from five experiments from southern NSW (Timsina et al. 2004b). Simulated daily mean flood water temperatures were 5-10% higher than the measured data in shallow and deep water. In shallow water, the simulated minimum temperatures matched the measured data well, however the model overestimated the daily minimum floodwater temperature in deep water throughout the 39 days of measurement in early 2000 in an experiment at Yanco. Conversely, daily maximum temperatures in deep water were simulated well except for some overestimation during the later stage, but in shallow water, the maximum temperatures were consistently overestimated. CSM-CERES-Rice ver. 4.0C simulated the grain yield satisfactorily across 4 data sets from southern NSW, except for a late planted (31 October) crop at Deniliquin. Simulated grain yield response to shallow and deep water was within 10-20% of measured data for early planting (26 September 1991) at Deniliquin, but agreement was poor for late planting (31 October). Sensitivity analysis suggested greater cold damage with pre-flood N than PI N, consistent with observations from many experiments in southern NSW.

Initial attempts to develop and test the floodwater temperature and chilling injury routines for the simulation of yield loss in rice due to cold injury in southern NSW are promising. Refinement of both floodwater temperature and chilling injury routines and the collation and scrutiny of data for model validation are in progress. More and better data sets, and further refinement and testing of the model, are required to accurately simulate the effects of low temperature, and deep water and N management on chilling injury and grain yield of rice.

7.1.6 Subproject 6. Economic impact assessment of permanent bed systems in Punjab and Australia

Punjab

Permanent beds led to significant reductions in tillage, labour and wheat seed costs for RW, but the profitability of PRB was similar to or less than that of the other layouts due to the large decline in rice yield as the beds aged (increasing to 25% in the fifth year) (Dhaliwal et al. 2007). The PRB RW system was only marginally more profitable than conventional tillage for both crops and was less profitable than fresh beds for rice followed by direct drilled wheat on the beds, and puddled transplanted rice followed by direct drilled wheat on the flat or fresh beds. However PRB for RW would have additional social, economic and environmental benefits as a result of much lower electricity consumption with lower irrigation requirement of rice on the beds.

NSW

The results of the benefit cost analysis suggests that PRB in terraced, zero grade layouts are financially viable, and more profitable than other designs currently used for rice-based farming systems (Singh and Beecher 2007). The results of the sensitivity analysis show that the NPV of benefits are highly sensitive to change in the discount rate used in the analysis and to a decline in rice yield compared to any change in the yield of soybean or barley. An increase in yield of crops grown on the beds would further increase the benefits from lateral permanent beds, and this is likely in winter crops in wet years. t

7.1.7 Subproject 7: Development of the Happy Seeder for direct drilling into rice stubble

The development of the Happy Seeder commenced in 2001 and has included 3 major prototypes to date (Blackwell et al. 2004; Humphreys et al. 2005; Sidhu et al. 2007a, b). The first two versions cut and lift the standing stubble and loose straw ahead of the sowing tynes, which thus engage bare soil, and deposit the stubble as mulch on the sown area behind the seed drill. The first version, the Trailing Happy Seeder, consists of a forage harvester with a modified chute, with a seed drill attached behind by three point linkage. It has the advantage of flexibility in that the seed drill can be readily interchanged, but has poor manoeuvrability and visibility of the seed drill. The Combo Happy Seeder, developed in collaboration with Dasmesh Mechanical Works combines the straw handling and sowing units into a single, lightweight, compact machine, while the Combo+ Happy Seeder includes strip tillage in front of the inverted T sowing tynes. In the Combo machines, only an 8 cm strip in front of each tyne (tyne spacing 20 cm) is cut, instead of the full width. However, like their predecessor, the Combo machines generate considerable dust, and accurate lining up of adjacent passes is difficult due to inability to see the sowing lines under the mulch. The Turbo Happy Seeder solves the problems of excessive dust and visibility of sowing lines by eliminating the chute and chopping the straw finely in front of the tynes and feeding it past the tynes.

Considerable testing of the Combo Happy Seeders in farmers' fields has shown that wheat yields are increased by 10-15% on average, and never decreased, with direct drilling into rice stubble in comparison with the farmers' practices of straw burning followed by tillage or direct drilling (Sidhu et al. 2007a). The Turbo Happy Seeder has undergone limited testing to date, and there is a need for comparative evaluation of the Combo and Turbo approaches for a range of straw loads and soil types and conditions (moisture).

In the one year experiment investigating the interactions between irrigation scheduling and mulching, wheat grain yield was not significantly affected by mulching or irrigation scheduling treatment (Yadvinder-Singh et al. 2007b). Nor was the total amount of irrigation water influenced by mulching within any irrigation scheduling treatment.

However, using soil matric potential-based scheduling, irrigations of the mulched treatment were always delayed, by up to 24 days, compared with the non mulched treatment. The results suggested that mulching reduced soil evaporation, and could save an irrigation in some years, depending on the incidence and amount of rainfall. Further field experimentation and modelling studies are needed to develop irrigation scheduling guidelines for wheat sown into rice residues, and to determine the impact of the mulch on irrigation and total crop water use.

In the experiment studying N fertiliser management for wheat sown into mulch, 3 splits (50% drilled at sowing + 25% broadcast before the 1st and 2nd irrigations) resulted in significantly higher grain yield, agronomic efficiency and N recovery efficiency than all other treatments (Yadvinder-Singh et al.). In the presence of mulch, drilling the urea at sowing gave higher yields and efficiency than broadcasting. Further field and modelling investigations are needed to develop N management guidelines for wheat sown into rice residues.

The financial evaluation of the Happy Seeder suggested that the HS technology is more profitable than the conventional cultivation or use of the zero till drill after burning, and that it is viable for farmers from a financial perspective. The net present value (NPV) of the benefits is highly sensitive to yield, with a 5% increase in yield doubling the NPV in comparison with conventional tillage. The NPV is also quite sensitive to changes in herbicide use, and less sensitive to changes in irrigation water saving and discount rate. The financial evaluation needs to be refined as further information becomes available on the costs and benefits of this new technology. Furthermore, there are likely to be substantial economic, community and environmental benefits from adoption of the technology.

8 Impacts

8.1 Scientific impacts – now and in 5 years

Note: impacts in italics denote potential impacts.

- RWC/CIMMYT through its coordinator Dr Raj Gupta and other State Agricultural Universities have purchased 15 Happy Seeder units and distributed to other research teams in the RWC for comparative and on-farm field testing.
- PAU has endorsed the HS concept as an official recommended practice.
- ICAR through DDG Dr J. Samra has made the HS concept a priority for promotion across India.
- FAO through Dr Theo Friedrich has indicated a strong interest in the HS concept and intends acquiring and testing at least one HS unit in Syria.
- Water savings review paper by Liz Humphreys et al. presented at the 4th ICSC in Brisbane 2004 has influenced the discussion on what constitutes water savings within the RWC.
- GTZ funded a 4 year IRRI project on straw management x soil health though links with Dr JK Ladha following his exposure to the HS concept.
- Murray Irrigation Limited has funded a NSW DPI project (lead by Sam North, research agronomist/hydrologist at Deniliquin) in Murray Valley to look at hydrology of different irrigation layouts based on the results of the Coleambally trial of the ACIAR project.
- PAU has initiated investigations on PRB for other crops e.g. pigeon pea-barley, sesame-chickpea, moong-wheat-summer moong etc, as a result of maize-wheat and soybean-wheat ACIAR project findings.
- CRC IF has funded Michael Grabham to do a PhD on beds in bays as a result of seeing the work on RBS on beds in bays at Coleambally.
- Maize-wheat and soybean-wheat for PRB and fresh beds for rice have been approved in principle as recommended PAU recommendations subject to testing starting in 06/07.
- Dissemination of the project's model development and modelling work through the DSSAT network is likely to result in the more widespread use of the improved DDSAT-CSM-CERES model produced by the project; the cold damage routine has been incorporated into the standard version of the rice model.
- ACIAR funded a 3-year project in Pakistan to develop and promote the Happy Seeder technology there.
- ACIAR funded a new 3-year project to refine and disseminate the Happy Seeder technology in Punjab India.
- ACIAR funded a new policy linkages project to stimulate the development of policy to facilitate rapid adoption of the Happy Seeder technology.
- The Proceedings of a workshop organised by the project team, Permanent beds and rice residue management for rice–wheat systems in the Indo-Gangetic Plain. Proceedings of a workshop held in Ludhiana, India, 7–9 September 2006. ACIAR Proceedings No. 127, is an important compilation of current achievements and knowledge of PRB for RW and direct drilling wheat into rice residues across the IGB.

8.2 Capacity impacts – now and in 5 years

- The project has enhanced the capacity of the PAU Dept. of Farm Power and Machinery in conducting research in partnership with the private sector and in training of Dr H Sidhu in research management through a John Dillon Fellowship.
- Dr H Sidhu has been appointed to the Govt. of Punjab taskforce on burning of agricultural wastes and will thus have an opportunity to influence key policy makers.
- Dr Yadvinder Singh is chair and Dr H Sidhu is a member of the of PAU residue management committee.
- 3 research fellows have been awarded John Allwright Fellowships to undertake PhDs in Australia (Balwinder Singh, Navneet Kaur, Sudhir Yadav), and another to undertake his PhD at PAU (Sudhir Thaman); Hari Ram completed his PhD at PAU as part of the ACIAR project.
- Sudhir Thaman has received two opportunities to undergo training and work experience with Shahbaz Khan’s hydrology group at Wagga Wagga (for 2 months in 2005 and 7 months in 2007/8).
- Training of 12 researchers from Nepal conducted in the use of DSSAT Rice and Wheat in courses in Australia (2) and Nepal (10-20 in 2 workshops in 2005 and 2007) in association with the Crawford Fund.
- The project has enhanced PAU ability to work in multi-disciplinary / cross departmental teams (Farm Power and Machinery, Soil Science, Agronomy, Economics).
- CSIRO & NSW DPI developed stronger collaborative relationships and synergies as a result of the project.
- ACIAR project attracted funding of Indian component by the International Atomic Energy Agency (IAEA), and of the Australian component by RIRDC and GRDC, and in-kind support from Coleambally Irrigation, the Coleambally Demonstration Farm, Murrumbidgee Irrigation and IAEA.
- Research Fellow Tejpal Singh received training in *“Financial and Economic Research Methods for Natural Resource Managers”.*
- Research Fellow Sudhir Thaman received training in experimental design and statistical analysis.

8.3 Community impacts – now and in 5 years

8.3.1 Economic impacts

- The Happy Seeder machine is commercially available and manufacture and sale of a total of up to 25 units to September 2006 has generated flow-on employment and revenue for Dashmesh Ltd.
- In 05/06, 3-4 farmers tested the Turbo HS concept on an area of 100 acres in collaboration with Dasmesh and PAU; the Combo Happy was tested with 15 farmers by PAU in 05/06.
- In Australia, at least 4 farmers have set up beds in bays for growing rice and other crops in rotation through interactions with the project.

Twynam Pastoral Co. invested $106k to build the Oz Happy based on the Combo Happy Seeder concept.

Transplanted rice on fresh beds is now a PAU recommendation for farmers on heavy textured soils. The results of our studies influenced the recommendation for fresh beds and heavy textured soils only, as our ACIAR project work shows that we do not yet have the technology for successful production of transplanted rice on PRB on the coarser textured soils used for rice growing in Punjab. Our work shows that the performance of rice on beds declines as the beds age.

- Adoption of HS technology may have the potential to increase farm profitability through more opportunities for diversification, improved timelines, increased cropping intensity and input savings.
- Future adoption of HS concept has the potential to significantly reduce smoke related animal health problems and reduce animal productivity losses.
- Reduced highway and airport closures through reduced smoke pollution following adoption of Happy Seeder.
- Adoption of PRB for rice-based systems in Australia has potential to increase farm profitability and productivity.
- Adoption of PRB for maize-wheat and soy-wheat has the potential to reduce irrigation amounts (through switching from rice to maize or wheat, and from reduced irrigation times on beds) and this reduce demand for electricity, with benefits to industry as a result of reduced down-time and greater reliability of supply.
- Adoption of the Happy Seeder may save the first irrigation and thus reduce demand for electricity.

8.3.2 Social impacts

- Future adoption of HS concept has the potential to significantly reduce smoke related human health problems.

8.3.3 Environmental impacts

- The Punjab Science and Technology Council through its ED and the Punjab Pollution Control Board has identified the HS concept as one of several policy options to phase in enforcement of bans on residue burning over the next 24 months and is strongly supporting ACIAR to fund a HS policy analysis project.
- The Punjab Dept. of Agriculture through its Director of Agriculture, supported by the Punjab Farmers Commission, also has identified the HS concept as one of several policy options to phase in enforcement of bans on residue burning and intends purchasing 15 HS units for on-farm testing in the next wheat season, as a precursor to more widespread implementation of incentives to accelerate adoption of the HS concept.
- There is potential for the HS technology to improve air quality in combine-harvested RW growing areas (NW India, Punjab Pakistan and Australia).
- Residue retention as a result of applying the HS technology is likely to improve soil health.
- Widespread adoption of HS has potential to reduce weed infestation and herbicide use.
- Widespread adoption of HS has potential to reduce damage to remnant ecosystems through accidental burning.

8.4 Communication and dissemination activities

8.4.1 Workshops organised by the project:

1. February 2002. Modelling irrigated cropping systems, with special attention to rice-wheat sequences and raised bed planting. Small international workshop at CSIRO Land and Water, Griffith, NSW, Australia, 25-28 February 2002.
2. August 2002. Rice on beds workshop – field visit to new experimental site at Murrumbidgee Shire Community Experiment Farm followed by presentations and discussions on best bet management for growing rice on beds at Coleambally Bowling Club 23 August 2002.
3. July 2003. ACIAR project workshop at Yanco, with guests from Pakistan and Indonesia ACIAR bed projects.
4. September 2006. International workshop on PRB for RW and Direct Drilling Wheat into Rice Residues at PAU. Key workers from Bangladesh, India, Pakistan, USA.

8.4.2 Presentations at workshops/conferences

2002

1. Beecher, G., Thompson, J., Dunn, B., Humphreys, E., Christen, E., Timsina, J., Smith, D. and Singh, R.P. (2002) Permanent beds for sustainable cropping systems on irrigated farms. Poster presented at RIRDC Rice Research and Development Committee “Research Seminar”. August 2002, Leeton, Australia.
2. Dhillon, S.S. (2002) The development of bed planting in the IGP. Technical Coordination Meeting of the RWC, Delhi, February 2002
3. Dhillon, S.S. (2002) Experience with bed farming in Punjab. International Workshop on Conservation Agriculture for Sustainable Wheat Production in Rotation with Cotton in Limited Water Resources Areas. Tashkent, Uzbekistan, 13-18 October 2002.
4. Humphreys, E. (2002) The ACIAR permanent beds project. Technical Coordination Meeting of the RWC, Delhi, February 2002
5. Humphreys, E. (2002) Rice-based cropping systems in Australia. 1st meeting of the FAO/IAEA Co-ordinated Rice-Wheat Project, Vienna, April 2002
6. Humphreys, E. (2002). Integrated approaches to increasing water use efficiency in rice-based systems in Australia. 1st International Rice Congress, Beijing, 16-19 September 2002.
7. Humphreys, E. (2002). Increasing water use efficiency in rice-based systems in Australia: institutions and policies. 1st International Rice Congress, Beijing, 16-19 September 2002.
8. Timsina, J. (2002). Monitoring and modelling rice-wheat cropping systems. APN/RWC/GCTE Workshop 8-10 October in New Delhi, India.
9. Yadvinder-Singh (2002) RW cropping systems in Punjab. 1st meeting of the FAO/IAEA Co-ordinated Rice-Wheat Project, Vienna, April 2002

2003

1. Dhillon (2003) Evaluation of rice on beds in 2002. ACIAR project workshop at Yanco
2. Gajri & Humphreys (2003) Results of comparisons of wheat on beds and flats in 2002/3. ACIAR project workshop at Yanco
3. Blackwell (2003) The Happy Seeder. ACIAR project workshop at Yanco
4. Dhillon (2003) Results of Happy Seeder trials sowing wheat into rice stubble in 2002/3. ACIAR project workshop at Yanco

5. Sidhu (2003) Future plans for refining and testing the Happy Seeder. ACIAR project workshop at Yanco
6. Beecher (2003) 2002/3 rice experiments in Australia. ACIAR project workshop at Yanco
7. Singh (2003) Economic evaluation of layouts on rice farms. ACIAR project workshop at Yanco
8. Timsina (2003) Progress in validating CERES Rice and Wheat. ACIAR project workshop at Yanco
9. Xevi (2003) Use of Hydrus 2D for design and management of bed layouts. ACIAR project workshop at Yanco
10. Beecher et al. (2003) Oral presentation of the Permanent beds for sustainable cropping systems on rice farms experiment was made at the IREC cropping seminars at Darlington Point on 30 July 2003
11. Beecher et al. (2003) Poster presentation of the Permanent beds for sustainable cropping systems on rice farms experiment was made at the RIRDC Rice R&D meeting. 4/5 August 2003
12. Beecher et al. (2003). ‘Strategies for Improving Rice Water Use in the Australian Rice Industry’ International rice conference “Modern Rice Farming”, 13-16 October, Alor Setar, Kedah, Malaysia. Oral presentation.
13. Beecher et al. (2003). Alternative Irrigation Methods For Rice-based Cropping Systems: Permanent Beds and Sub-Surface Drip. 3rd Temperate Rice Conference, Punta Del Este Uruguay, 10-13 March 2003. Poster.
14. Dhillon et al. (2003). Preliminary studies on raising rice on beds in comparison to conventional (flat) practice. ISTRO conference 13-18 July, 2003 held at Brisbane. Poster
15. Humphreys et al. (2003). Permanent beds for irrigated rice-wheat and alternative systems in north west India and south east Australia. Rice-Wheat Consortium 11th Regional Technical Coordination Meeting, Kathmandu, Nepal 4-6 March 2003. Oral presentation.
16. Humphreys et al. (2003). Productivity, water use efficiency and hydrology of wheat on beds in Punjab, India. IAEA Coordinated Research Project Meeting, Nanjing, China 8-12 September 2003. Oral presentation.
17. Yadvinder-Singh et al. (2003). Rice and wheat yields response to fertilizer N and straw management under a permanent bed planting system in Punjab, India. IAEA Coordinated Research Project Meeting, Nanjing, China 8-12 September 2003. Oral presentation.

2004

1. Sidhu (2004) Development of the Happy Seeder for simultaneous straw management and direct drilling in combine harvested paddy fields. 38th annual convention of Indian society of Agricultural Engineers, 16-18 Jan. Dapoli, India
2. Humphreys (2004) Results of Wheat 2002/3, preliminary results of Rice 2003 and Happy Seeder trial at Rice-Wheat Consortium meeting, 7-9 Feb. at Islamabad, Pakistan
3. Sidhu (2004) The Happy Seeder for simultaneous straw management & direct drilling of wheat at a National Workshop on Agricultural Mechanisation, Ludhiana

4. Sidhu 92004) The concept, work ,experience and results on Happy Seeder for simultaneous straw management & direct drilling of wheat at a Workshop on Managing Crop Residue for Healthy Soil in Rice Ecosystems, 20-22 Feb., New Delhi (India)
5. Blackwell (2004) The Happy Seeder. Commonwealth Royal Agricultural Society International Conference in Albury – this meeting was attended by the owner of Twynam Pastoral Co. Pty Ltd and led to the funding of the construction of the Twynam Happy Seeder
6. Beecher HG et al. (2004) Permanent bed rice based systems in Australia. Aust Soc Soil Science Riverina Branch meeting at Yanco
7. Humphreys (2004) Permanent bed rice based systems in India & the Happy Seeder. Aust Soc Soil Science Riverina Branch meeting at Yanco
8. Sidhu and Dhillon (2004) 5 presentations in Pakistan at Faisalabad Agricultural University, Provincial research institutes and the Farm Mechanisation Institute at NARC, and meetings with the Vice chancellor, 3 D.G's on bed planting and crop residue management.
9. Timsina (2004) Modeling chilling injury in rice. International Rice Cold Tolerance Workshop, 22-23 July 2004, Canberra.
10. Blackwell (2004) The Happy Seeder. GRDC irrigated cropping update at Griffith
11. Beecher HG et al. (2004) Permanent bed rice-based systems. GRDC Irrigated Cropping Update, Moama
12. Beecher HG et al. (2004) Permanent bed rice-based systems. RIRDC Rice Research and Development Seminars, Yanco
13. Dunn et al., Prashar et al. (2), Timsina et al., Humphreys et al. 4 poster papers and 1 oral presentation at 4th International Crop Science Congress (2004)

2005

1. Beecher HG et al. (2005). Successful Permanent Raised Beds in the irrigated farming systems of the Murrumbidgee / Murray Valleys of NSW, Australia. ACIAR Permanent Raised Beds International Workshop Griffith March 2005
2. Humphreys and Mathews (2005) Nitrogen management for rice on permanent raised beds in south east Australia. IAEA Coordinated Research Project on Integrated Soil, Water and Nutrient Management for Sustainable Rice-Wheat Cropping Systems. 3rd Research Coordination Meeting. 11-15 July 2005, Dhaka, Bangladesh.
3. Kukal and Yadvinder-Singh (2005). Water and N use efficiency of rice-wheat system vis-à-vis water quantity and quality in Indo-Gangetic Plains of India. Regional Asia-Pacific Workshop on water in Agriculture, 21-13 November 2005, Nanjing, China
4. Mathews SK and Timsina J (2005). Exploring yield potential and irrigation options for soybean using CSM-CROPGRO-soybean model for irrigated cropping systems in southern New South Wales. 13th Australian Soybean Conference, Barooga, NSW., 1-3 March 2005.
5. Mathews SK et al. (2005) Soybean performance on raised beds in a rice irrigation layout 13th Australian Soybean Conference, Barooga, NSW., 1-3 March 2005.
6. Singh RP and Beecher HG(2005) Economic Evaluation of Permanent Raised Beds for Sustainable Cropping Systems on Rice Farms. ACIAR Permanent Raised Beds International Workshop Griffith March 2005
7. Timsina et al. (2005). Evaluation of options for increasing water productivity of wheat using CSM-Wheat model. MODSIM05 Conference, 12-15 December, 2005, Melbourne.

8. Yadvinder-Singh (2005). Rice and wheat yields response to fertilizer N and straw management under a permanent bed planting system in Punjab, India. IAEA Coordinated Research Project on Integrated Soil, Water and Nutrient Management for Sustainable Rice-Wheat Cropping Systems. 3rd Research Coordination Meeting. 11-15 July 2005, Dhaka, Bangladesh.
9. Yadvinder-Singh and Kukal (2005) Permanent raised beds for rice-wheat and alternative cropping systems in NW India. ACIAR Permanent Raised Beds International Workshop Griffith March 2005

2006

1. Blackwell (2006) The Happy Seeder. GRDC irrigated cropping update. 2 August 2006, Griffith
2. Beecher HG et al. (2006) Permanent bed rice-based systems. RIRDC Rice Research and Development Seminars, 8-9 August 2006, Yanco
3. Humphreys et al. (2006) The Happy Seeder enables direct drilling into heavy stubbles. No Tillage Conference, 29-30 March, Tamworth
4. Humphreys et al. (2006) Increasing water productivity of rice-wheat cropping systems. International Rice Congress, 9-13 October 2006
5. Sidhu, H.S., Bector, V., Singh Manpreet, Singh Yadvinder, Humphreys Liz and Blackwell John. (2006). A break-through for direct-drilling of wheat into combine harvested rice fields. Oral and poster presentation at International Rice Congress held at NASC complex IARI, New Delhi , 9-12 October 2006.

8.4.3 Field days and visitors to field sites

India

23 Oct 2003	Happy Seeder discussion/demonstration at PAU Agricultural Machinery field day (approx. 30 farmers and manufacturers)
February 2004	Dr JK Ladha (IRRI), Dr RJ Buresh (IRRI), Prof. HU Neue (Head, Dept of Soil Science, UFZ Centre for Environmental Sciences, Leipzig-Halle, Germany), Dr. Elke Schulz (UFZ), Dr Andrees Berske (Martin-Luther University, Halle-Wittenberg, Germany) plus 2 Chinese scientists from the German funded international project on Managing Crop Residue for Healthy Soil in Rice Ecosystems
February 2004	Lal P. Amgain Tribhuvan University, Nepal
May 2004	Combo Happy Seeder displayed at Agrotech at Chandigarh; Punjab Director of Agriculture was present
September 2004	H.E. Ms Penny Wensley, Australian High Commissioner to India, Drs Kuhu Chatterjee and Christian Roth (ACIAR), Dr P.K. Sharma (Himachal Pradesh Agicultural University – project reviewer)
October 2004	Combo Happy Seeder displayed to Pakistani delegation
November 2004	Combo Happy Seeder displayed at farmers workshop
05 August 2005	Dr. B.S. Dhillon, Director of Research, PAU, Ludhiana
19 August 2005	Dr. R.A. Fischer and Mr John Cullen, Program Manager Crop Improvement, ACIAR 22 August 2005 Md. Murshedul Alam, IRRI-Bangladesh Liaison Officer, Dhaka
August 2005	~15 scientists from India, Nepal, Bangladesh and Pakistan visited the experiments under the RWC travelling seminar program.
30 Sept 2005	~40 participants from Kisan Cell Centre, Chandigarh, Shimla, Kulu, Srinagar
28 Dec 2005	12 Assistant Supervisors from Military Farm School and Centre, Meerut, UP

Sept 2005	The Combo+ Happy Seeder was demonstrated to hundreds of farmers at the farmer field days at PAU
27 Sep 2005	Mr. Chad R. Russell, Counselor for agricultural affairs, American Embassy, New Delhi
2005/6	Happy Seeder sites were visited by senior research managers and extension specialists of Punjab Agricultural University, who agreed to make it a recommended practice after compilation of the results from the current season.
2005/6	Other visitors to the Happy Seeder sites and/or to inspect the machines included the Vice President of South Africa with the Vice Chancellor of PAU
10 Jan 2006	Visit of French Agriculturists Group (Bourgogue 110)
20 Feb 2006	Visit of members of board of Regents, UAS, Bangalore
March 2006	Happy Seeder display at Farmer Fair at PAU (hundreds of farmers)
7 March 2006	Team from Ohio state University, USA to Happy Seeder /residue mgt projects
12 May 2006	Mr. Fayyaz Bashir, Secretary Agriculture, Punjab, Pakistan (Happy Seeder)
30 May 2006	Faculty of state Agriculture Management and Extension Training Institute Agricultural Training Center, Narendrapur, Kolkata
4 June 2006	Mr. Fayyaz Bashir, Secretary Agriculture, Punjab, Pakistan (Happy Seeder
20 June 2006	Korean delegation plus Theodor Friedrich, Senior Officer FAO, AGPC (Happy Seeder)

Australia

12 August 2002	GRDC southern panel members 23 August 2002 Project steering committee and a couple of other farmers
4 Nov 2002	Full RIRDC committee (including Colin Piggin from ACIAR)
? 2002	Murrumbidgee College of Agriculture students
12 Dec 2002	Malaysian Felcra plantation services, Malaysia
20 Dec 2002	~25-30 Coleambally farmers and agribusiness advisors (organized by NSW Agr. DA)
Jan 2003	Moulamein farmers – 5 members of Farming Systems group from Western Murray valley
26 Feb 2003	~50 members of the Rice CRC during the CRC Annual Symposium/ Annual Rice Field Days
11 March 2003	~40-50 farmers at Demonstration Farm field Day
20 March 2003	~10 members of Rice Breeding/Physiology team YAI
20 March 2003	~10 University of Sydney Agriculture Students
21 March 2003	NSW Agriculture Southern Farming System Irrigation Extension Team
24 March 2003	Dr Tony Fischer ACIAR – site inspection
26 March 2003	Chilean Rice industry delegation
July 2003	Presentation to NSW DPI Research/Extension review meeting
Sept 2003	Presentations to pre-season rice grower meetings at 7 locations – Yanco, Griffith, Coleambally, Hay, Finley, Deniliquin, Wakool
21 October 2003	Mr Manikum, Acting India High Commissioner to Australia, Mr Jain Secretary of Agriculture for India, Mr Verma Secretary of Agriculture, Rajasthan, Dr Sarswat, Indian Maize program
22 October 2003	Dr Kim Chung Kon, Dr Kim Yeon-Gyu, Dr Son Jong Rok, Korean Rice Industry
February 2004	Israeli Cotton Board growers
March 2004	Drs Tony Fischer and Christian Roth (ACIAR)
March 2004	Thai rice industry people, 25-30
March 2004	Coleambally farmers and agribusinesses
March 2004	~10 Uni of Sydney agriculture students,
March 2004	Dr Ken Fischer UQ

March 2004	Dr Upendra Singh (IFDC)
July 2004	Presentation to NSW DPI Research/Extension review meeting
September 2004	Presentation to Coleambally rice grower meeting
September 2004	>50 Uni of Sydney Agriculture, Agricultural Economics and Environmental Science students
October 2004	Drs Shiratsucji and Kitagawa, Japan, Dr Yadvinder Singh (PAU), Mr Lal Amgain (Nepal), Prof Zheng Jia Guo (China)
November 2004 -	>30 Coleambally growers, agribusiness/consultants and extension officers, Dr Bijay Singh
December 2004 -	~20 Murray Valley growers and NSW DPI extension officers
February 2005	Growers Field day Coleambally
February 2005	Queensland Cotton industry agribusiness personnel
March 2005	Annual Rice Field Day Coleambally (56 growers, 8 commercial agronomists)
March 2005	ACIAR Raised bed Workshop field Trip (15 international scientists from USA, China, Pakistan, India, Bangladesh, Philiippines, Indonesia plus about 25 from a range of organisations and locations across Australia)
March 2005	Lachlan Valley Agribusiness personnel
May 2005	Daljit Singh, collaborating farmer from Phillaur (with his now Australian uncle)
May 2005	GRDC Project Review
July 2005	Presentation to NSW DPI Research/Extension review meeting
2005	Presentation to RIRDC board at Yanco
August 2005	Presentation at RIRDC Rice R&D seminars
Sept 2005	Dr N. R. Devkota, Tribhuvan University, Nepal
October 2005	Dr Bob Ziegler, Director General IRRI
November, 2005	Field day (at Coleambally Bowling Club due to rain) ~20 growers/extension/agribusiness
November 2005	Professor Vo-Tong Xuan, Angian University, Vietnam
December 2005	Delegation of 5 scientists and research administrators for Sichuan Academy of Agricultural Science and Sichuan Ministry of Agriculture
December 2005	Jack McHugh and 3 Chinese from ACIAR beds project in Gansu Province
February 2006	~50 farmers, agribusiness, researcher participants in national maize conference
March 2006	Happy Seeder presentation at Rice Field day at McCaughey Institute (several hundred farmers, extension, agribusiness)
March 2006	Dr G Hoffman, USDA Salinity Lab.
July 2006	Shabbir Kalwar and Dr Nadeem Amjad from ACIAR Pakistan Happy Seeder project
July 2006	Presentation to NSW DPI Research/Extension review meeting

8.4.4 Media

India

November 2002	Several articles and photos in Indian newspapers in November 2002 associated with CSIRO visits to Ludhiana and National Agro Industries
July 2004	Sidhu & Dhilllon gave a TV talk to PTV World in a programme Kissan Manch anchored by Mushtaq Gill on RCTs and Straw Management during their visit to Pakistan
Sept 2004	several articles and pictures in Indian newspapers in English and Hindi during visit from Australian High Commissioner
August 2006	Ludhiana Tribune – VC PAU announces that Happy Seeder is a recommended practice

Australia

March 2002	Article and photo in The Area News associated with the modelling workshop at CSIRO Griffith
March 2003	The Land: Rice Field day presentation re Field Experiment
June 2003	Local Newspaper articles: re ACIAR project in connection with meeting at Yanco involving collaborators from India and Australia
June 2003	Interview (Sidhu) on Punjabi Sydney radio program on Happy Seeder
2003	Rice CRC Newsletter : re ACIAR project in connection with meeting at Yanco
2003	NSW Agriculture, Centre of Excellence, Yanco Agricultural Institute Web page
2003	Weekly Times “Potential in raised bed rice”
2004	Article prepared for GRDC Crop Doctor Series
2004	Articles for electronic newsletters such as Grainzone News and Rice CiRCle
Winter 2004	Article in Irrigation and Water Resources
2004	A couple of newspaper articles.
October 2004	Beds in bays broaden the irrigation crop mix. Groundcover 58 October / November 2005 pg. 19
2004	Radio Interview: Harvest Radio GRDC
2005	The Weekly Times – article on Happy Seeder
February 2006	The Land – article on Happy Seeder
4 Jan 2006	Weekly times “Easier crop switches”

8.4.5 PAU recommended practices

December 2005	Yadvinder Singh appointed as convenor of the PAU residue management committee; case prepared with Sidhu and team for getting Happy Seeder included in Package of Recommended Practices for 2006/7 season
March? 2006	Committee formed to develop case for transplanted rice on bed
August 2006	Happy Seeder approved as a recommended practice
August 2006	Permanent raised bed soybean-wheat and maize-wheat cropping systems approved as recommended practice

9 Conclusions and recommendations

9.1 Conclusions

9.1.1 Direct drilling into rice and other heavy stubbles

The project has comprehensively demonstrated that wheat can be successfully established and grown by direct drilling into rice residues without burning, on both flat fields and raised beds, in Punjab. Preliminary results suggest some water saving through reduced soil evaporation, but this requires further field and modelling work to quantify the savings more clearly. Whether the approach will be successful in the heavy rice straw loads in Australia (10-14 t/ha) is yet to be established.

The problem of direct drilling wheat into rice residues has been solved with the development of the Happy Seeder technology, which cuts and picks up the residues in front of the sowing tynes, and deposits the straw as a mulch behind the sowing tynes. Farmers in Punjab will no longer need to burn rice residues prior to wheat establishment. The machine is currently being manufactured by two commercial machinery companies in Punjab. Preliminary financial analysis suggests that the technology is superior to both conventional tillage and direct drilling after burning the straw. However there are a number of assumptions in the analysis that can only be validated after significant use of the technology (e.g. cost of repairs and maintenance, herbicide requirement, N fertiliser requirement). Furthermore, there may be significant economic, environmental and social benefits, which need to be quantified.

The main needs now are to build a smaller machine capable of being powered by the 35 h.p. tractors commonly used in Punjab, development of a package of management guidelines including irrigation and N fertiliser management, a favourable policy environment to encourage adoption, and a major program to demonstrate the technology with farmers across the rice-wheat districts of Punjab. Two new ACIAR projects have been initiated to address these needs, complemented by two PhD students supported by John Allwright Fellowships.

The Happy Seeder has also been used for successful establishment and growth of mungbean in 6 t/ha wheat straw in India. In Australia it was used for successful establishment of soybeans in 4.4 t/ha barley straw, and barley in 10 t/ha of maize straw. It did not perform well in establishment of wheat in damp rice straw in moist clay soil (blocking of the tynes with mud and straw), and thus needs further refinement if it is to perform well in all situations.

The potential benefits of direct drilling with residues retained are substantial, especially in the case of RW systems in Punjab, where air pollution from rice stubble burning is a major health hazard for humans and animals and accidental burning destroys remnant ecosystems and infrastructure, in addition to the loss of carbon and nutrients (especially nitrogen) with adverse effects on soil fertility (chemical, physical, biological).

9.1.2 Permanent raised beds for maize-wheat and soy-wheat cropping systems in Punjab

Permanent raised beds (PRB) are currently being considered for recommended practice for maize-wheat and soybean-wheat cropping systems in Punjab. This involves “adaptive trials” in several districts across Punjab. The ACIAR project was one of several studies which provided the basis for this development, this project being the only one with permanent beds for several years.

In our 3-year experiment on a loamy sand with no history of rice cultivation, yields of maize, wheat and soybeans on PRB were comparable to yields with conventional tillage and direct seeding on the flat. Seasonal rainfall for the summer crops ranged from relatively dry (about half the seasonal average) to well distributed rains around the seasonal average. Yields were maintained on permanent beds while applying less irrigation water, however this needs qualification as it is unknown if the same yields could have been achieved on the flats with lower irrigation amounts as for the beds, nor whether there were significant differences in residual soil water at the end of the season. As there were no unusually wet summers or winters during the 3 years, and the soil was a loamy sand with no history of rice cultivation and thus no hard pan, the potential advantage of beds in reducing waterlogging has not been assessed. Furthermore, the application of the technology on heavier soil types with a history of rice cultivation (and thus a well-developed hard pan) has not been assessed. It is likely that beds may be an advantage on such soils due to reduced waterlogging of the beds.

9.1.3 Permanent raised bed rice-wheat systems

India

Wheat yields on PRB almost never exceeded yields with conventional tillage, in contrast with our original hypothesis of improved performance of wheat on PRB. On a loam soil, wheat yields on PRB were similar to yields with conventional tillage over the duration of the experiments (7-8 crops), but were generally lower on PRB on sandy loam soils.

On both soil types the yield of transplanted rice and direct seeded rice on beds (TRB, DSRB) declined relative to the yield of puddled transplanted rice (PTR) as the beds aged. The reasons for the decline in yield over time are not known, but appear to be partly associated with increased incidence of cereal cyst nematode infection, and iron deficiency in the case of DSRB. Bulk density of the slopes of the permanent beds was much higher than of fresh beds, and may have impeded root proliferation on the permanent beds.

Direct seeded rice on beds, with current varieties, on sandy loam and loam soils, is not viable in this region. There is considerable variation in the performance of rice varieties direct seeded on beds and a need for breeding and selection of rice varieties suited to beds (for both transplanted and direct seeded rice). Cereal cyst nematode can be a major problem for intermittently irrigated rice (on puddled transplanted flats and even more so on beds). Current herbicides are ineffective for rice on beds on the sandy loam and loam soils, where it is impossible to maintain adequate inundation. Several hand weedings are needed.

Retention of both wheat and rice residues (5 or 6 t/ha of wheat or rice straw, respectively as mulch) resulted in a significant increase in organic C, total N and available K after 4 complete crop cycles (8 crops) on PRB. However, there was no interaction between residue management and N rate, even after 8 crops. Mulching with wheat straw had no effect on TRB, but significantly reduced growth and yield of DSRB. Both the mulch and direct seeding were associated with serious nematode infestation, the effect compounding in mulched direct seeded rice. The reasons are unknown. Residue retention reduced yield of unfertilised wheat on beds in the first 2 years, probably due to N tie up, otherwise there was no effect of mulching with rice straw on the performance of wheat. These findings are in contrast with the experience of permanent bed RW systems in Nepal and Bangladesh, and with maize-wheat systems in Mexico, where mulching was associated with significantly higher yields after the first few years.

Studies of the water balance in small plots can be seriously flawed by large edge effects (seepage), and the suggested irrigation water savings (reported in the literature) by changing from continuous flooding to intermittent irrigation may be greatly inflated due to high seepage rates from continuously flooded plots where adequate barriers have not been installed. Deep drainage (in-field and underbund) was the major component of the water balance in both small plots and farmers' fields – accounting for about 60% of the total water input in continuously flooded PTR. Deep drainage was roughly halved by switching from PTR-CF to PTR-2d. Deep drainage from wheat was comparatively small (negligible to <100 mm).

It cannot be assumed that growing rice on beds will always save irrigation water, contrary to common opinion and the experience of others. Our results in farmer length fields show that irrigation water use on beds depends greatly on irrigation management (both depth (e.g. full furrow vs half full furrow) and scheduling). The amount of irrigation water applied to TRB-2d with a full furrow exceeded that applied to PTR-2d, probably because of higher permeability of the soil in the unpuddled furrows and greater macropore development on the permanent beds. Reducing the irrigation application to half a furrow depth also reduced yield. Further studies of the water balance at the farmer field scale are needed to evaluate the impacts of water management on yield and components of the water balance of beds compared with recommended and farmer practice for PTR.

The topsoil in beds dries out faster than on the flat, more so on the sandy loam, due to the 40% higher surface area on the small beds typical of the NW IGP. Thus soil evaporation (and total water depletion as ET) may be greater on bed than flat layouts, in contrast to the common belief that water is saved using beds.

Australia

The project showed that on the heavy clay soil and wide beds in Australia, yield of direct seeded rice on PRB is comparable to yield on the flat provided that the furrow gap is not too wide (60 cm was too wide), and that the beds are ponded with deep water during early pollen microspore to protect the crop from cold damage (as in conventional practice). In 2005/6, with favourable seasonal conditions for rice, more N was required to achieve maximum yield on the beds than on the flats, and 15N and small plot studies suggested that split N application gave better results than applying all of the nitrogen at around the 3-leaf stage. Considerable periods of ponding are needed during the vegetative stage for effective control of weeds with herbicides, with the result that there is only a small reduction in irrigation amount with furrow irrigation of beds.

The project also showed that a range of crops (soybean, barley, wheat) can be successfully grown in rotation with rice on PRB in zero graded, terraced rice field irrigation designs. Beds within terraced, bankless channel systems are being adopted in the rice growing region. A range of crops are being grown under variations this style of layout including rice, wheat, maize, cotton, faba beans, chickpeas, barley, sunflowers. The area of adoption is not great at this stage but considerable attention is being paid to the performance of these commercial fields by other irrigators.

Further work needs to be undertaken on this style of irrigation layout to explore the distribution uniformity of irrigations and to explore the water saving possibilities of these designs at commercial scale (North 2007) and studies are currently being undertaken by Michael Grabham, NSW DPI, Griffith. Preliminary data indicates that these layouts are associated with shorter irrigation times, reducing the potential for deep drainage losses for crops other than rice.

The ongoing adoption of terraced, zero graded bankless channel rice layouts with PRB appears likely given the increased cropping choice and flexibility and the significantly reduced labour requirement made possible by this type of layout. The adoption of these layouts will be constrained to locations where existing land grades allow creation of zero graded layouts with appropriate terrace widths and high enough steps to allow adequate drainage without excessive landforming costs, and where access to large irrigation flows are available in order to achieve satisfactory short duration water on/water off times for crops other than rice. There may also be significant gains for pastures grown in rotation with rice in these layouts.

The potential of these PRB irrigation layouts fits with grower and grains industry desires to increase crop range and yield e.g. rice, faba beans, soybeans, canola, wheat, barley. The layouts are also well-suited to implementation of precision agriculture concepts – compaction control, tramlining, machinery efficiencies and uniform or varied input application. Adoption of permanent raised beds will help increase farmers' income through more intensive cropping and increased productivity; it will also help improve water productivity and sustainable use of land and water.

Crop modelling

The model processes developed for simulation of the effects of low temperature on cold damage (as reflected in floret infertility), and the buffering effects of deep water, have already been incorporated into the standard, publicly available version of the DSSAT crop modelling software.

The project also developed routines for use in DSSAT that allow selection of automatic irrigation management that more closely reflects recommended or farmer practice for both rice and wheat. It is now possible to (1) schedule irrigations for rice "x" days after the floodwater has dissipated, (2) irrigate wheat based on cumulative net ET (PAU recommendations are based on cumulative net pan), and (3) irrigate wheat based on growth stages. The code has been provided to the maintainers/developers of DSSAT, but not yet incorporated into the standard version.

Modelling studies for wheat in Punjab confirmed that the optimum date for planting wheat (PBW343) is from late October to mid-November, in terms of yield and water productivity. For a 10 November sowing, irrigation based on soil water deficit or cumulative net ET always exceeded yields with growth-stage based irrigation.

Modelling studies for puddled transplanted rice suggest that changing from continuous flooding to the recommended practice (irrigate 2 d after the floodwater has dissipated) does not "save" water in Punjab – ET is virtually unaffected, as is yield. However irrigation amount is greatly reduced due to reduced deep drainage. Where the groundwater can be recycled, as in much of the NW IGP, reducing deep drainage is not a water saving (however it is a beneficial energy saving). The modelling studies confirm that the recommended irrigation management for PTR is optimal in terms of maximising yield and irrigation water productivity. The modelling studies also confirmed that the recommended transplanting dates for long (2nd half of June) and short (early July) duration rice varieties is optimal, although this may lead to late harvest (and late wheat sowing) with the long duration variety in some years.

9.2 Recommendations

9.2.1 Refine and disseminate the Happy Seeder technology

Promotion

Farmer field demonstrations in each district are needed to help promote the Happy Seeder technology. All demonstrations should be combined with good records of farmer management and regular monitoring to:

- assess and explain crop performance and causes of poor performance (maybe due to factors other than the technology!)
- to identify problems encountered by farmers and how they overcame them

- to help develop guidelines based on practical experience.

Refinement of the HS & other technologies needed to facilitate adoption

- evaluation and refinement of the combine straw spreader in rice
- development of a bund former that works in the presence of rice straw
- development of a Happy Seeder that can be powered by 35 h.p. tractors.

Development of guidelines for irrigation and N management for wheat sown into rice residues with the Happy Seeder

- field experimentation and modelling studies are needed to assist this
- the guidelines should include information on financial performance of the HS in comparison with other technologies.

Development of a policy environment to promote uptake of the technology

Adoption of the technology will require an initial captal investment by contractors and farmers who purchase the machinery. Policies to promote adoption need to be explored. This needs to be underpinned by analysis of the economic benefits of the technology.

9.2.2 Investigate the causes of yield decline of rice, and relatively poor performance of wheat, on permanent beds on the sandy loam and loam soils in Punjab

It should be possible to improve the performance of rice and wheat on permanent beds by better understanding of the possible causes of poor performance and yield decline in rice, and by systematic comparison with performance in the eastern IGP, where PRB rice-wheat systems have been shown to be superior to conventional layouts. Solutions need to be developed to overcome the problems of iron deficiency (for direct seeded rice), nematode infestation and weed control. In particular, the hypothesis of impaired crop performance due to compaction of the beds during machinery operations (sowing wheat, reshaping beds prior to rice) needs further investigation – this problem could be relatively easily solved if indeed it is a major cause poor crop performance.

9.2.3 Develop guidelines for irrigation and N management for transplanted rice on fresh beds followed by direct drilled wheat

This practice has been recommended by PAU for “heavy” textured soils in Punjab; guidelines for irrigation and N management are needed for both rice and wheat on beds for a range of soil types, and also methods for effective weed control.

9.2.4 Evaluate PRB for RW and alternative crops on clay soils/ soils with a history of rice in Punjab

There is an urgent need for diversification away from rice to reduce water depletion. There may be a significant advantages for non-rice crops (e.g. maize, soybean, wheat) grown on beds on soils that have a history of rice culture, due to reduced waterlogging on the beds. Irrigation and crop water use of rice in comparison with non-rice crops also needs to be quantified in farmer-sized irrigation blocks.

9.2.5 Promote adoption of zero graded bankless terraced rice field irrigation designs in NSW rice growing areas

Adoption of zero graded bankless terraced rice field irrigation designs (basin layout) potentially incorporating raised beds (lateral beds) should be promoted to rice growers in locations with suitable slopes and access to high irrigation flows.

9.2.6 Develop zero graded bankless terraced rice field irrigation designs as part of the total irrigation system in NSW rice growing areas

Irrigators and surveyor/designers need to consider the field size in relation to potential water flows and implications for access to adequate flows if this style of layout is adopted more widely by farmers within irrigation areas and districts; consideration needs to be given for installation of on-farm storages to provide the opportunity to achieve the high irrigation delivery rates required.

9.2.7 Review performance of zero graded, terraced rice field irrigation designs in commercial fields in NSW in higher rainfall years

The evaluation of PRB for rice-based systems in NSW was undertaken during a prolonged period very dry climatic conditions (drought). Monitoring of the performance of the irrigation layouts in farmers' fields during higher rainfall and potentially waterlogging conditions needs to be undertaken when the opportunity arises.

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