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Permanent beds and rice-residue management for rice–wheat systems in the Indo-Gangetic Plain

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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

Editors: E. Humphreys and C.H. Roth

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Cover: Wheat directly drilled into combine-harvested rice residues on permanent raised beds in a farmer's field near Phillaur, Punjab, India, in January 2006. The wheat was sown with a Happy Seeder modified for permanent raised beds. Shown are H.S. Sidhu (left) from Punjab Agricultural University and J. Timsina (right) from CSIRO Land and Water. Photo: Manpreet-Singh.

Foreword

Rice–wheat (RW) cropping systems are critical for food security and livelihoods in South Asia. This is particularly so in India where 10 million hectares of rice and wheat are grown in sequence, providing 85% of the total cereal production and 60% of the total calorie intake. Over 150 million people are economically dependent on RW systems in South Asia.

The area and productivity of RW systems across South Asia increased dramatically between the 1960s and the 1990s, with the rate of increase in production surpassing the rate of population increase. This Green Revolution was enabled by the introduction of nutrient-responsive improved varieties, rapid expansion of irrigation and favourable government policies. However, the sustainability of RW systems is now in question, as evidenced by many factors including yield stagnation or decline of rice or wheat across the RW systems of South Asia, soil degradation, declining groundwater levels, severe air pollution from rice stubble burning, and declining terms of trade.

Around 2000 it was suggested by members of the Rice-Wheat Consortium of the Indo-Gangetic Plains, the Australian Centre for International Agricultural Research (ACIAR) and others that permanent raised beds could lead to increased productivity and resource use efficiency of RW systems. A system for retaining rice residues (instead of burning) was also dearly sought. ACIAR commissioned a large project—LWR/2000/089 ‘Permanent beds for irrigated rice–wheat and alternative cropping systems in north-west India and south-east Australia’—to address these questions. The project involved collaboration between Punjab Agricultural University (India), CSIRO Land and Water, and the New South Wales Department of Primary Industries. In the last months of this project (September 2006), the project team organised a small international workshop at Punjab Agricultural University, Ludhiana, to bring together the experience and learnings of researchers working on permanent raised beds and rice-residue management for RW systems across the Indo-Gangetic Plain.

The papers contained in these proceedings outline the work that was presented at the Ludhiana workshop. The proceedings provide a comprehensive compilation of the experience in permanent raised beds and direct drilling into rice residues for RW systems in the Indo-Gangetic Plain of South Asia. This research includes results from some of the longest running permanent raised bed RW systems experiments (up to 8 years) known to the workshop participants. The papers also present important breakthroughs in the challenge of direct drilling wheat into rice stubbles, avoiding the need for burning and the associated air pollution and loss of organic matter and nutrients.

This volume of proceedings should provide a timely stocktake of progress made to date and hopefully serve as a useful reference to other researchers working on permanent raised bed systems.

Peter Core
Chief Executive Officer
Australian Centre for International Agricultural Research

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Permanent beds and rice-residue management for rice–wheat systems in the Indo-Gangetic Plain: overview

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Introduction

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 million hectares (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 Plain (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). Almost all of Pakistan's rice production comes from RW systems, which are concentrated in the states of Punjab and Sindh. Conversely, in Bangladesh, almost all of the wheat is grown in RW systems.

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 fertilisers and other chemicals, and expansion of irrigation; and to support from 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 Mha 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% is under wheat in winter (GOP 2006b). In Pakistan rice production increased by a factor of 2.6 between 1965–70 and 1995–2000 due to expansion of the RW area and increasing rice yields (I. Masih, unpubl. data). In

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Bangladesh little wheat was grown before 1980 as it was not a part of the diet. However, in the 1980s and 1990s the area grew to almost 0.8 Mha of RW rotation before declining again in recent years to 0.5 Mha. Currently, wheat yields are consistently around 2.0–2.3 t/ha, showing that, despite being a 'marginal' environment for wheat cultivation, it can be and is grown.

Rice–wheat systems are practised on a range of soil types from sandy loam to clay. In the north-western 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 been expanded to coarse-textured, permeable soils more suitable for maize and groundnut production than traditional rice crops. While soils are generally finer textured in the eastern IGP (Gupta et al. 2003), RW systems also seem to be commonly grown on soils (sandy loams to clay loams) similar to those in the north-western IGP (Lauren et al. 2008; Talukder et al. 2008). Average annual rainfall increases from west to east, from 125 mm in RW areas in Sindh, Pakistan, to 400–700 mm in Punjab (Pakistan and India) to about 1,800 mm in eastern Bengal and Bangladesh. The majority of the rain falls during the monsoon (rice) season, while the winters are dry. Thus there is heavy dependence on irrigation for both crops in the west and for wheat in the east, whereas irrigation accounts for only a small proportion of the water input to rice in the eastern IGP (Ahmad et al. 2007; Humphreys et al. 2008; Jat et al. 2008; Lauren et al. 2008; Talukder et al. 2008). Irrigation water is sourced from both groundwater and surface water systems, with conjunctive use of surface- and groundwater in some regions (e.g. much of the RW area of Punjab, Pakistan), but in many regions groundwater is the predominant or only source of irrigation water (e.g. in much of the north-western IGP) (Hira and Khera 2000; Qureshi et al. 2004; Ahmad et al. 2007).

Since the late 1990s, rice and/or wheat yields have stagnated or declined across the IGP, partial factor productivity has decreased and there are now 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 in pace with population growth, are major concerns. Symptoms of environmental degradation, which vary depending on location, include declining soil organic matter content and nutrient availability and the emergence of multiple nutrient deficiencies; increasing soil salinisation; increasing weed, pest and pathogen populations; rapidly declining groundwater levels; 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 the RW systems of South Asia, especially in the north-western IGP, is water shortage. Groundwater levels are declining rapidly in north-western India (Pingali and Shah 1999; Hira and Khera 2000; Singh 2000; Hira et al. 2004) and water shortage during winter in Pakistan has been predicted to increase more than fourfold by 2017 (Qutab and Nasiruddin 1994; Kahlown et al. 2002). Lack of irrigation and drainage infrastructure is a major constraint to increasing production in the eastern IGP, where the ability to develop water resources for irrigation is economically limited. 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) that are 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 2 decades, spearheaded by the Rice-Wheat Consortium of the Indo-Gangetic Plains, and in collaboration with the National Agricultural Research and Extension Systems (NARES) (Gupta and Seth 2006). A range of technologies was developed and/or disseminated including 'zero tillage' (direct drilling), laser levelling, nitrogen management using the leaf colour chart, residue retention and raised beds.

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 fertiliser 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). Some disadvantages of raised beds for wheat were also reported, including increased powdery mildew

(Sharma, A.K. et al. 2004) and increased salinity on sodic and saline soils (Sharma et al. 2002; Yadav et al. 2002). 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 et al. (2002) and Connor et al. (2003) proposed PRB as a means of increasing the productivity and profitability of RW systems. They considered that PRB, in comparison with fresh beds, offered the potential additional advantages of reduced or zero tillage for 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). 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. Sharma et al. (2004) also found increased problems with termites for wheat on PRB.

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; Ahmad et al. 2007; Gupta and Seth 2006). The benefits of zero tillage 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; Gupta and Seth 2006; Ahmad et al. 2007). However, a prerequisite for successful implementation of zero-till wheat in the north-western IGP, where most rice is combine-harvested, is burning the loose rice residues. About 90% (17 Mt) of rice straw is burnt in Punjab, India, each year. In Punjab, Pakistan, more than 50% of the rice is currently combine-harvested followed by partial or complete burning, and the proportion harvested by combine is predicted to increase to 100% by 2030 (S. Kalwar, pers. comm.). 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.

The beginning of the 21st century saw new major endeavours to develop and evaluate PRB for RW, and machinery capable of drilling wheat into rice residues. These included the Cornell University USAID-funded Soil Management Collaborative Research Support Program (CRISP), which began upscaling PRB in Rajshahi, Bangladesh, in 2001; and ACIAR project LWR/2000/089 'Permanent beds for rice–wheat and alternative cropping systems in north-west India and south-east Australia'. This project commenced in 2002 and involved collaboration between Punjab Agricultural University (India), CSIRO and the New South Wales Department of Primary Industries. In the last year of the project (September 2006) a small international workshop was held at Punjab Agricultural University, Ludhiana, to bring together the experience of researchers working on PRB and rice-residue management for RW across the IGP. The objectives of the workshop were:

- to report performance of permanent bed RW systems, with particular focus on the north-west IGP
- to report performance of technologies for direct drilling wheat into rice residues without burning in the north-west IGP
- to synthesise the findings and to identify future needs and priorities for research and development and extension.

The focus of the workshop was on the north-west IGP, where the issues of soil degradation, groundwater depletion and air pollution from stubble burning are most severe. However, the workshop also included the findings of long-term studies on PRB in the eastern IGP, where PRB seem to have been more successful to date than in the north-west. The papers from the workshop are presented in these proceedings in two parts—part 1 on PRB for RW systems and part 2 on direct drilling wheat into rice residues.

Outline of the proceedings

Part 1 of the proceedings includes eight papers on the performance of PRB for RW. Four of these relate to the work of the ACIAR project in Punjab, India (Dhaliwal et al.2008; Humphreys et al. 2008; Kukal et al. 2008; Yadvinder-Singh et al. 2008a), including comprehensive papers on water dynamics (Humphreys et al. 2008) and financial analysis (Dhaliwal et al. 2008). The other four papers (Jat et al. 2008; Ladha et al. 2008; Lauren et al. 2008; Talukder et al. 2008) report experience in western Uttar Pradesh, Bangladesh and Nepal, focusing on crop performance but including some data on irrigation water use. Three of these papers include results from PRB RW systems up to 4–8 years old (Jat et al. 2008; Lauren et al. 2008; Talukder et al. 2008), probably the oldest PRB RW experiments for which data are available. Section 1 also includes a paper by Malik and Yadav (2008) on the prospects for rice establishment using zero-till transplanting and direct seeding in RW systems. While the focus of their paper is on 'flat' layouts rather than beds, developments in these technologies are highly relevant to successful development of direct-seeded and transplanted rice on permanent beds.

Part 2 includes four papers from India on direct drilling wheat into rice residues—two on machinery development and crop performance in Haryana and Punjab (Sharma et al. 2008; Sidhu et al. 2008), a detailed financial analysis of the Happy Seeder for conditions in Punjab (Singh et al. 2008) and a paper on irrigation and nitrogen management for wheat mulched with rice residues in Punjab (Yadvinder-Singh et al. 2008b).

A brief summary of the main findings of each paper is presented here, followed by a general discussion of the similarities and contrasts in the findings, and recommendations on future research needs.

Permanent beds for RW systems

The first four papers by Kukal et al. (2008), Humphreys et al. (2008), Yadvinder-Singh et al. (2008) and Dhaliwal et al. (2008) report the agronomic, water use and financial performance of RW on PRB in Punjab, India. The biophysical experiments were conducted in replicated small plot experiments on two soil types (two sandy loam sites and one loam site) over 4 years, and in a farmer's field on loam soil on beds up to 3 years old. All crop residues were removed prior to sowing each crop. All tillage and wheat and rice seeding operations were done using four-wheel (35–50 hp) tractors. Yield of wheat on beds relative to yield of conventionally tilled wheat (CTW) was maintained as the beds aged. On the loam average yields of wheat on PRB and CTW were similar, but on the sandy loam yield on PRB tended to be lower than yield of CTW, with some significant differences. The beds dried faster than the flats, more so on the coarser textured sandy loam, and this may have impaired establishment or tillering on the beds relative to the flats in some years (Kukal et al. 2008). The results suggested that more skilled management (and modified irrigation guidelines) are probably needed for wheat on beds than on flats, especially in ensuring good establishment on coarse-textured soils of low water-holding capacity that drain rapidly.

Yield of transplanted rice on fresh beds was usually similar to yield of puddled transplanted rice (PTR) with the same irrigation scheduling (irrigating 2 days after the floodwater/furrow water has dissipated—PTR-2d). However, relative yield of transplanted rice on permanent beds with the same irrigation scheduling (TRB-2d) was only 40–70% of yield of PTR-2d. This occurred on both soil types and in both the small plots and large blocks in the farmer's fields, despite the fact that soil matric potential in the topsoil (10, 20 cm) was similar in the beds and puddled flats. On the sandy loam severe cereal cyst nematode infection was observed in TRB-2d in some years, the first time this problem had been recorded in Punjab. However, when infection was low or absent (e.g. after soil solarisation of the sandy loam, and on the loam where no cysts were observed), yield of TRB-2d was also lower than that of PTR-2d. In the small plot experiments at two sites, the relative yield of TRB declined as the beds aged, but in the farmer's field on loam the yield was reduced to 50% of PTR, starting with the first rice crop (second crop on the beds). With direct-seeded rice on beds (DSRB), the decline in yield as the beds aged was more pronounced, declining to 21–23% of the yield of PTR-2d in the third year on both soils in the experiments of Kukal et al. (2008), despite daily irrigation of the beds for the first 50 days after sowing in that year. Iron deficiency was a major problem for DSRB every year and was not overcome with frequent sprays of iron sulphate starting soon after emergence. Iron deficiency symptoms were worse on the loam, and the problem increased on both soils as the beds aged. Weed control was also a major problem on the beds, with three to four hand weedings required.

The experiment of Yadvinder-Singh et al. (2008a) included treatments in which the beds were mulched with 6 t/ha of wheat or rice straw immediately after planting rice or wheat, respectively. Over the 4 years there was no effect of mulching on yield or nitrogen use efficiency of wheat or transplanted rice on beds. However, mulching caused a significant reduction in yield of DSRB in 3 of the 4 years. Mulching was associated with higher levels of cereal cyst nematode infection in both TRB-2d and DSRB-2d. In the year in which there was no effect of mulching on yield of DSRB, the soil had been solarised prior to sowing.

The small plot and farmer's field experiments showed large irrigation water savings of 30–50% for TRB-2d in comparison with continuously flooded PTR (PTR-CF). However, irrigation amount was similar or higher for TRB-2d compared with PTR-2d (at the same irrigation frequency) (Humphreys et al. 2008). The results suggest that it was the method of irrigation (intermittent ponding) that reduced irrigation amount rather than whether the fields were puddled flats or raised beds. The depth to which the furrows were filled had a large effect on irrigation amount, with 37% higher irrigation water application in the farmer's field when the furrows were completely filled at each irrigation compared with half-filled furrows. However, there was a yield penalty of 20–25% when irrigation depth was decreased from full to half furrow on both fresh and permanent beds. Age of the beds also affected irrigation amount—with the same furrow depth and irrigation scheduling, applications to permanent beds were higher than applications to fresh beds, probably because of greater macropore development on the permanent beds. Irrigation applications to wheat on PRB and flats were similar because irrigation timing and amount were based on the ratio of irrigation amount (IW) to net cumulative pan evaporation (CPE-rain), and the same ratio of IW/(CPE-rain) was used for both beds and flats in each experiment. Humphreys et al. (2008) concluded that field experiments and model applications comparing PRB and flats for a range of values of IW/(CPE-rain) are needed to determine the magnitude and nature of any potential water savings on beds, and to develop irrigation scheduling guidelines.

The work of Jat et al. (2008) and Ladha et al. (2008) in western Uttar Pradesh was in a reasonably similar environment (climate, soils) and with similar cultural practices to that of the work in Punjab. As in Punjab, yield of wheat on PRB up to 3 years old was similar to or significantly lower than yield of CTW grown in rotation with PTR in both small plots and farmers' fields. However, in a long-term replicated experiment, yield of the eighth wheat crop on PRB was significantly higher (by 11%) on the beds (data for earlier years were not presented) (Jat et al. 2008). Jat et al. (2008) and Ladha et al. (2008) also found significantly lower yields of transplanted and direct-seeded rice on PRB irrigated with the same intermittent flooding scheduling rules as PTR, although the decline was not as great as that observed in Punjab. The decline commenced with the first rice crop on PRB (second crop), with yields of TRB and DSRB of 92% and 86% of the yields of PTR, respectively (Ladha et al.). In the eighth rice crop on permanent beds, yield of DSRB was 74% of that of PTR (Jat et al. 2008). In farmers' fields, yield of TRB on permanent beds also declined as the beds aged, from 90% of PTR in the first year to 77% of PTR in the third year. In contrast with the work in Punjab, Jat et al. (2008) found that mulching wheat on beds with rice residues significantly increased wheat yield (by 13%) in the first wheat crop (second crop), with an associated 6% increase in irrigation application. They also found that mulching DSRB with wheat straw had no effect on yield in the first rice crop on fresh beds, whereas it consistently reduced yield of DSRB in Punjab, except when the soil was solarised prior to planting (Yadvinder-Singh et al. 2008a). Comprehensive financial analysis of PRB for RW in comparison with conventionally tilled flats and a range of other layouts or establishment methods in between these two extremes was undertaken by Dhaliwal et al. (2008). The inputs were based on the results of the field experiments in Punjab (Humphreys et al. 2008; Kukal et al. 2008; Yadvinder-Singh et al. 2008a) and assumed a decline in yield of TRB-2d from 0% in the first crop (fresh beds) to 25% in the fifth crop, a 30% reduction in irrigation amount in TRB-2d compared with continuously flooded PTR (PTR-CF) and a 20% reduction in irrigation amount for wheat. The analysis was undertaken for a period of 30 years, using a discount rate of 7% per year. The PRB RW system was only marginally more profitable than conventional practice (PTR-CTW) due to the decline in rice yield and thus income, which negated the cost savings of PRB through reduced tillage and labour for irrigation. The analysis suggested that if the rice yield decline could be reduced to 10%, there would be significant financial benefits of PRB over the other layouts, except for zero-till wheat after PTR-CF where the net benefit was similar. With no rice yield loss, PRB were superior to all other layouts. A 10% yield increase in wheat on PRB would also result in higher financial returns to PRB than any other layout, despite the rice yield decline on TRB.

In contrast with the work in Punjab, Jat et al. (2008) and Ladha et al. (2008) found reductions in irrigation water applications of about 10% on beds compared with PTR in their small plots. They also found reductions of about 25% in irrigation water applications to wheat on beds.

The results of the work of Talukder et al. (2008) and Lauren et al. (2008) in Bangladesh and Nepal were quite different from those in north-western India, with significantly higher yields of transplanted rice (by up to 29%) on PRB compared with PTR grown in rotation with CTW. Lauren et al. also found that PRB were more responsive to increasing rates of N than conventional tillage for both rice and wheat in the rice–wheat–mung system at Nashipur and Rajshahi in Bangladesh. However, this was not the case in the rice–wheat–maize experiment of Talukder et al. (2008) at Nashipur. While crop yields were consistently higher on PRB than conventionally tilled plots, crop responses to increasing N levels were similar for PRB and conventional practice. Talukder et al. (2008) and Lauren et al. (2008) both found that straw mulch significantly increased crop yields after only one to two cropping cycles in their rice–wheat–mung and rice–wheat–maize cropping systems in Nepal and Bangladesh. The findings of Talukder et al. (2008) suggested that N rate on PRB could be reduced with 50% or 100% straw retention, in contrast with the findings in Punjab where straw retention did not lead to higher yields at low N rates (Yadvinder-Singh et al. 2008a). Thus, PRB greatly increased the productivity of RW systems in Bangladesh and Nepal, and reduced irrigation amounts to rice and wheat by 14–38% (Lauren et al. 2008).

The reasons for the contrasting results on PRB in the north-western and eastern IGP are unclear, and need to be explored to help identify constraints to poor performance in PRB in the north-west and how to overcome them. Soil types were often similar (usually sandy loam or silty loam), as was the geometry of the beds—all narrow, with 65–75-cm spacing mid-furrow to mid-furrow, furrow depth about 15 cm, and usually two rows of rice or wheat per bed with a row spacing on the beds of 20–30 cm. The main differences appeared to be variety, the degree of trafficking with heavy machinery, the location of the transplanted rice on the beds, and the hydrological regime at the time of rice establishment and during the rice season. At the three experimental sites in Bangladesh, bed formation, reshaping and sowing were done manually or with two-wheel tractors, whereas in north-western India reshaping and seeding were done using a two-bed planter powered by four-wheel 35–50 hp tractors. Thus, the beds in north-western India were usually trafficked with a large tractor twice a year after pre-irrigation when the soil was moist. The tractor wheels were in the furrows; however, the standard tyres used pressed against the sides of the beds and may have compacted them, exactly where the rice was transplanted in latter years. In Bangladesh and Nepal the rice was always transplanted on the top of the beds. However, in Nepal four-wheel tractors were also used for bed formation, reshaping and sowing. Further investigations are urgently needed to determine whether compaction is a factor in causing the generally disappointing performance of RW on PRB in the north-western IGP.

The other main difference between the eastern and north-western IGP is the fact that the rice on beds was established and grown under much wetter conditions in the east. Annual rainfall was two to three times that in the north-western IGP. At the time of rice transplanting in the east, there had already been considerable rainfall, evaporative demand was relatively low and watertables were probably shallow, thus providing favourable conditions for rice on beds. In contrast, in the north-west the optimum time for rice transplanting is 2–3 weeks before the rains commence, at a time when evaporative demand is very high (pan evaporation of up to 14 mm/day), while watertables are deep (up to about 10 m). Under these conditions it is impossible to keep the sandy loam / loam beds saturated, let alone ponded (for efficient herbicide use, and for soil reduction and release of micronutrients including iron), even with daily irrigation with the furrows filled to the top of the beds.

Malik and Yadav (2008) summarised the findings of numerous trials of zero-till direct-seeded and zero-till transplanted rice on the flat in farmers' fields over the past few years in Haryana, north-western India. The main findings from this work included the following observations:

- Puddling is not essential for high yields.
- Yield of direct-seeded rice was variable relative to PTR while yield of zero-till transplanted rice was always comparable to yield of PTR.
- There was a need to avoid prolonged ponding during establishment of direct-seeded rice.
- There was a need to sow direct-seeded rice earlier (20–30 days prior to transplanting time).

While zero-till transplanting maintained yield while eliminating puddling from the system, an important constraint to adoption of zero-till transplanted rice was greater danger and difficulty for the labourers to transplant into non-puddled soil, and therefore greater cost. Use of the zero-till drill to create a slot for the transplants, or dry tillage, made the task easier. Similarly, Kukal et al. (2008) used knife tines on the bed planter to aid manual transplanting on PRB. Malik and Yadav (2008) showed that yield of zero-till direct-seeded rice tended to be less than yield of zero-till transplanted rice, but direct-seeded rice was more profitable because of the lower establishment cost. However, weed control was a major issue for direct-seeded rice. Potential solutions included the use of sequential herbicide applications, but maintenance of ponding for several days was a prerequisite for successful weed control. This was consistent with the problems of weed control on PRB in Punjab, where ponding could not be maintained (Kukal et al. 2008; Yadvinder-Singh et al. 2008a). Poor weed control in transplanted rice on beds was reported for 17 multi-locational farmers' field trials in Haryana and was attributed to lack of ability to pond water, exacerbated by unusually low rainfall and shortage of electricity for pumping (Malik and Yadav 2008). Malik and Yadav (2008) also reported that integrated weed management (sowing sesbania with the rice and use of a selective herbicide 30–40 days after sowing to kill the sesbania to provide a mulch) reduced the need for hand weeding. This technique should also be explored on beds as it has potential benefits of weed suppression, reduction of soil evaporation and addition of organic matter.

Direct drilling wheat into rice residues

Sharma et al. (2008) compared five types of machines for direct drilling wheat into rice residues after combine harvesting in Haryana and western Uttar Pradesh—the standard 'zero-till' drill with inverted T tines; a double disc coulter; the star wheel punch planter; the Rotary Disc Drill with a powered fluted or straight edge disc in front of double discs; and the Combo Happy Seeder. The Rotary Disc Drill is the only machine also capable of direct drilling into sugarcane ratoons with full trash retained at the surface. The Combo Happy Seeder essentially combines a forage harvester with modified chute and a seed drill into a single machine (Sidhu et al. 2008). The forage harvester cuts and picks up the straw in front of the seed drill, enabling the tines to engage bare soil. The straw is then deposited behind the seed drill as a mulch.

In thin rice stubbles (3–4 t/ha), yield of wheat sown with all machines was comparable, except for much lower yields with the star wheel (Sharma et al. 2008). With average straw loads (6–7 t/ha), highest yields were achieved with the Rotary Disc Drill and Happy Seeder. The other machines had problems of accumulation of the loose residues and blockages, and the double disc coulter had problems with placement of seed and fertiliser because it did not have sufficient weight to cut through the rice residues. Using the Combo Happy Seeder in rice residues of 5–8 t/ha, Sidhu et al. (2008) and Yadvinder-Singh et al. (2008b) found plant density and yields similar to those for wheat established after straw removal and conventional tillage. However, Sharma et al. (2008) reported that there were still some problems with both the Rotary Disc Drill and the Combo Happy Seeder at high straw loads. Sidhu et al. (2007) found that yield declined at stubble loads above 9 t/ha for wheat sown at the optimum time, but with late sowing yield declined for stubble loads above 7.5 t/ha. The Combo Happy Seeder has now been superseded by the Turbo Happy Seeder (Sidhu et al. 2008). The latter machine chops the straw finely in front of the tines and feeds it past the tines, producing much less dust and leaving the sowing lines exposed. It is anticipated that exposure of the sowing lines will assist establishment through increased radiation (heat, light) in comparison with the complete coverage of sowing lines by mulch with the Combo Seeder. The mulch reduced maximum soil temperature in the seed zone by 1–2 °C during establishment, reduced soil evaporation and suppressed weeds (Sharma et al. 2008; Sidhu et al. 2008; Yadvinder-Singh et al. 2008b), which is consistent with the findings of others in RW and other systems (e.g. Rahman et al. 2005; Sidhu et al. 2007). Sharma et al. (2008) found a significant increase in soil organic C after 2 years (four crops) with full residue retention, either as a mulch or incorporated. Talukder et al. (2008) and Yadvinder-Singh et al. (2008a) also found significant increases in soil organic C after 4 years of mulching in RW systems on PRB. Stubble retention as a mulch may have implications for nitrogen and irrigation management. Yadvinder-Singh et al. (2008b) found that drilling urea at sowing gave better yields than broadcasting. Irrigations scheduled using matric potential were always delayed, leading to a delay of 24 days for the third irrigation, suggesting that mulching could save an irrigation in some years.

A comprehensive financial analysis of the Happy Seeder in Punjab found that, assuming a 20-year machine life, the technology is more profitable than both conventional tillage and use of the zero-till drill after burning (Singh et al. 2008). The assumptions in the analysis included the same yield for all establishment methods, a reduction in fertiliser N requirement of 10% starting in the sixth year with mulching, a 50% reduction in herbicide use and a 30% irrigation water saving.

Conclusions

The performance of permanent bed RW systems in the north-western IGP has generally been disappointing to date, mainly due to poor yields of both transplanted and direct-seeded rice on beds, with problems of weed control and nematodes, and iron deficiency in the case of direct-seeded rice. Nor has the performance of wheat on PRB in the north-west reached the expectations of generally higher yields. In contrast, PRB RW systems in the eastern IGP consistently produced significantly higher yields of both rice and wheat. The main differences between the west and east are the much higher rainfall prior to and during the rice season in the east, and a greater level of machinery traffic using 35–50 hp tractors in the north-west. Further work is needed to properly determine the causes of the poorer performance of PRB in the north-western IGP and the means to overcome this. While PRB may reduce irrigation amounts in many situations, this is not always the case, as it is influenced by factors such as age of the beds, depth of water in the furrows and irrigation scheduling. It is still unclear how much, if any, real water saving is achieved through adoption of PRB in comparison with conventional tillage. Clear guidelines are needed on irrigation management for PRB to optimise yield and water use.

In recent years considerable progress has been made in the development of machinery capable of direct drilling wheat into combine-harvested rice residues, in particular the Happy Seeder and the Rotary Disc Drill. While there are likely to be long-term financial benefits to farmers using the Happy Seeder or the Rotary Disc Drill, adoption of the technology will be at an initial cost to the farmer in comparison with burning and zero tillage. Therefore, there is an urgent need for a major program to promote and facilitate adoption, together with development of a complete management package including guidelines for nutrient, weed and irrigation management.

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Part 1:

Permanent raised beds for rice–wheat cropping systems

Permanent beds for rice–wheat systems in Punjab, India. 1: Crop performance

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Abstract

The performance of rice and wheat grown in rotation on permanent beds over 3–4 years in small plots, replicated experiments and large (60 m long) blocks was evaluated on sandy loam and loam soils in Punjab, India. 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. 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, in contrast to findings in the eastern Indo-Gangetic Plain (IGP) where yields of transplanted rice on permanent beds were higher than in PTR. The different performance of permanent beds in the eastern and western IGP needs further examination to understand the reasons and to develop successful permanent bed systems for 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 is to be maintained at the levels achieved with PTR.

Introduction

Permanent raised bed rice–wheat (RW) systems have been proposed as a means of increasing the productivity, profitability and sustainability of RW systems in the Indo-Gangetic Plain (IGP), principally as a result of improved soil structure and drainage for wheat, direct drilling of both crops and reduced irrigation requirements for both crops through furrow irrigation (Hobbs et al. 2002; Connor et al. 2003). This paper reports the performance of rice and wheat grown on permanent beds over 3–4 years (up to eight crops) in small-plot replicated experiments and in large farmer-field blocks in Punjab, India. Water use, water productivity and soil water dynamics are presented in Humphreys et al. (2008).

Methods

Sites

Experiments on the small-plot and farmer-field scales were conducted at two sites in Punjab, India, from 2002 to 2006. One site was on the experimental farm of Punjab Agricultural University (PAU) at

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Ludhiana, and the second site was in a farmer's fields near Phillaur, about 20 km from PAU. Both sites had deep alluvial soils with very low organic C (4.2–4.7 g/kg at 0–15 cm) and had been under a continuous RW cropping system for at least 20 years. The soil at PAU was sandy loam (pH 6.7) overlying loamy sand, while the soil at Phillaur was loam (pH 8.3) overlying silty loam. The depth to the groundwater was more than 10 m at each site. More detailed information on the sites, treatments, management and monitoring are presented in Yadvinder-Singh et al. (2008b).

Small plot experiments

Treatments

Replicated experiments were established in November 2002 at both sites to compare four flat and bed treatments for a RW sequence over 4 years (8 crops). The treatments ranged from conventionally tilled flat layouts for both crops to fresh beds following puddled transplanted rice (PTR) to non-tilled permanent beds (Table 1). There were four replicates and plot size was 10.7 × 12 m on the loam and 6.7 × 12 m on the sandy loam, with earth bunds around each plot.

Wheat sown in November 2002 had only two treatments—conventional tillage on the flat (CTW) and fresh beds (WFB)—as it was the first crop. This was followed by three methods of rice establishment in June 2003—PTR, transplanted rice on permanent beds (TRB) and direct/dry-seeded rice on permanent beds (DSRB). Direct-drilled wheat on permanent beds (DDWB) commenced with the second wheat crop (2003–04). In the fourth and final rice crop (2006) one of the PTR treatments was converted to transplanted rice on fresh beds (TRFB) and DSRB was converted to TRB.

Crop management

All stubbles were removed manually at ground level at harvest. After rice harvest there was a short bare fallow of 3–5 weeks followed by pre-irrigation, cultivation (where required) and wheat sowing. Most cultivations and sowings were done using implements drawn by four-wheel tractors (35–45 hp). Recommended sowing and fertiliser practices were used at both sites. Wheat (PBW343) was sown at 100 kg/ha on the flats and 75 kg/ha on the beds at about 5 cm depth in early to mid November. The width of the beds (mid-furrow to mid-furrow) was 67 cm, with 30-cm-wide flat tops of the beds and 15 cm furrow depth. Two rows of wheat were planted on top of each bed with 20 cm between the rows; thus, there was a 47 cm spacing between the rows on adjacent beds. Total N application rate was 120 kg/ha in the first 2 years in a 50:50 split application and 150 kg/ha in the last 2 years. Half of the N fertiliser was applied at sowing (23 kg N/ha as diammonium phosphate drilled with the seed, and the remainder as urea broadcast prior to sowing) and the other half broadcast (urea) prior to the first irrigation after sowing. Weeds were well controlled by spraying sulfosulfuron within a week after the first post-sowing irrigation. The wheat was harvested in early to mid April each year, leaving the fields with bare fallow for about 8 weeks.

Table 1. Treatments[a] in the small plot replicated rice–wheat experiments on two soils over 4 years (8 crops, starting with wheat in November 2002)

Layout	Wheat	Rice
Flat	CTW	PTR-2d
Fresh bed / flat	WFB	PTR-CF[b]
Permanent bed	DDWB	TRB-2d
Permanent bed	DDWB	DSRB-2d[c]

[a] CTW = conventionally tilled wheat; WFB = wheat drilled on fresh beds; DDWB = direct-drilled wheat on permanent beds; PTR = puddled transplanted rice; TRB = transplanted rice on permanent beds; DSRB = direct-seeded rice on permanent beds; CF = continuously flooded; 2d = irrigated 2 days after the floodwater / furrow water had dissipated

[b] Converted to fresh beds for rice (TRB-2d) for the fourth (last) rice crop

[c] TRB-2d for the fourth (last) rice crop

The plots were pre-irrigated for rice in early June, then the furrows were cleaned and the beds reshaped using the tractor and bed planter. In the beds to be transplanted with rice, narrow tines were also run through the shoulders of the beds (outside the former wheat rows) to loosen the soil for hand transplanting. On the puddled transplanted plots there were several dry cultivations prior to puddling. Rice was direct seeded (40 kg/ha) on the beds in early June, two rows per bed at about 4 cm depth, on the outside of the former wheat rows. Transplanting on flats and beds took place within 1 week after direct seeding using recommended planting, fertiliser and biocide management. TRB was established by manually transplanting 24–33-day-old rice seedlings (two seedlings per hill) in two rows spaced at 25–30 cm, with 10 cm between the plants in each row on the beds (30 hills/m^2), compared with a spacing of 20 × 15 cm (33.3 hills/m^2) on the flats. In 2006 the plants were placed halfway down the bed shoulders to locate them in a more favourable (wetter) zone. A short duration variety (PR115) was grown in the first 2 years, and was replaced with a longer duration variety (PR118) in 2005 and 2006. All treatments received a basal fertiliser application of 12 kg N/ha, 13 kg P/ha, 25 kg K/ha and 15 kg Zn/ha as diammonium phosphate. Potassium chloride and zinc sulphate were broadcast prior to bed reshaping or pre-puddling irrigation, and 113 kg N/ha as urea was top-dressed in three or four split applications in the transplanted and direct-seeded rice, respectively, with the first application shortly after transplanting. In 2005 farmyard manure (15 t/ha) was broadcast across both sites prior to the first cultivation or bed reshaping. Weeds were well controlled in PTR using butachlor 6–7 days after transplanting. Sofit® was applied to TRB and DSRB 5–6 days after sowing, followed by several hand weedings.

Irrigation management

The plots were irrigated, one at a time, with groundwater (0.8–0.9 dS/m) and volume was measured with a Woltman® helical turbine flowmeter.

Wheat. The amount of irrigation water (IW) applied was based on the amount required to fully flood the flat plots to a depth of about 60 mm, or the amount required to fill the furrows without overtopping the beds. Each year, all plots were irrigated prior to wheat sowing and again 2–4 weeks after sowing, usually around the time of crown root initiation. Further irrigations were scheduled based on net cumulative pan evaporation (CPE-rain) using the recommended ratio IW/(CPE-Rain) = 0.9 to 1.0, where IW is the amount of irrigation water applied (Prihar et al. 1974, 1976, 1978a, 1978b). As irrigation amounts in the bed plots were usually less than in the flat plots (because of the volume limitation of the furrows), the beds were usually irrigated more frequently. In 2002–03 the irrigations were applied at fixed values of CPE-rain (80 mm for flats, 40 mm for beds). In other years the irrigation interval was calculated from the amount applied at the previous irrigation and the above ratio.

Rice. All plots were irrigated prior to cultivation and/or transplanting or direct seeding. After transplanting or sowing, the plots were irrigated daily for the first 15–21 days to try to maintain continuous ponding of the flats and furrows. Thereafter, the plots were irrigated 2 days after the floodwater had disappeared from the surface of the plots/furrows, the recommended practice for PTR. This meant that the plots were usually irrigated every third or fourth day (except after significant rainfall), other than PTR-CF which was irrigated daily (except after rain) to maintain continuous flooding of 50–80 mm. In 2003, 2004 and 2006 the furrows were filled to near the top of the beds during each irrigation. In 2005 only, the furrows were only half-filled, and the '2d' irrigation scheduling of PTR and TRB was based on soil matric potential (SMP), with irrigation when SMP reached –15 kPa at 15–20 cm depth (Kukal et al. 2005). In 2005 DSRB received daily irrigation (except after rain) for the first 8 weeks, prior to commencing irrigation based on SMP. Irrigations ceased about 2 weeks before the crop reached harvest moisture content.

Monitoring

A range of crop and soil parameters were monitored during the rice and wheat cropping season (Yadvinder-Singh et al. 2008b). At maturity grain yield was determined on an area of at least 25 m^2 in the middle of each plot. Total air-dried weight of grain was measured in the field using spring balances, and grain moisture content was determined by drying subsamples at 70 °C or by using a grain moisture meter. Soil matric potential was monitored in two wheat treatments (CTW and DDWB) using tube tensiometers installed at six to eight depths in the 10–140 cm range in four replicates at both sites.

Farmer-field scale experiments

Bed and flat treatments

Fresh and permanent beds were compared with conventional tillage on the loam at Phillaur in large, unreplicated blocks running the full length (~60 m) of a farmer's field (typically square 1-acre (0.4-ha) blocks) (Table 2). The dimensions of the beds were the same as in the small plots. Twenty-two beds were established in block 1 prior to sowing wheat in November 2003. The beds were maintained as permanent beds for six consecutive crops, with rice transplanted halfway down the bed shoulders, and wheat direct drilled on the bed tops. The adjacent flat block (no. 2) grew CTW and PTR. In 2005 this block was split in two, with PTR-CF in one-third and water management by the farmer in the larger section (PTR-farmer; CF for the first 40 days followed by weekly irrigation). In 2006 the latter block was split in two, with PTR-2d in half and transplanted rice on fresh beds (TRFB) in the other half. A third block (no. 3) was set up in 2005, with TRFB followed by DDWB with rice residues retained in 2005–06. The wheat was sown with a Combo+ Happy Seeder (Sidhu et al. 2008) modified to sow on beds. Prior to rice in 2006, block 3 was split into fresh and permanent (3rd crop) beds with transplanted rice. The fresh beds were formed after wheat harvest by knocking the beds down with a disc plough and then forming new beds.

Irrigation treatments

Rice. Three irrigation treatments were compared for rice on permanent beds in block 1 in 2005, and for rice on permanent and fresh beds in blocks 1 and 2b in 2006. The treatments were: (i) irrigation with a full-furrow depth of water 2 days after the furrow water had dissipated, (ii) irrigation with a half-furrow depth of water 2 days after the water had dissipated and (iii) irrigation with a half-furrow depth when soil matric potential at 20 cm depth in the beds reached –15 kPa. In 2005 these bed treatments were compared with PTR-CF and PTR-farmer. In 2006 the beds were compared with PTR-CF and PTR-2d.

Wheat. In 2005–06 three irrigation schedules were compared for wheat on the permanent beds (2nd crop) in block 3 sown with the Happy Seeder with rice residues retained: IW/(CPE – rain) = 0.9 and 1.2, and SMP = –35 kPa at 40 cm depth in the beds (Table 3). In blocks 1 and 2 irrigation of CTW was scheduled using the recommended practice (IW/(CPE – rain) = 0.9), while irrigation of the fresh and permanent beds was scheduled using IW/(CPE – rain) = 1.2, based on observations that the beds dried faster than the flats.

Crop management and monitoring

All crops were managed using recommended practices similar to those in the small plot experiments. Each block was irrigated separately and all irrigations were measured by flowmeter (as above) using the same flowmeter. Grain yield was determined by harvesting four areas of approximately 30 m^2 in each block.

Weather

Rainfall was measured using a rain gauge within each experimental field for each crop at both sites. Other weather data were collected from the meteorological station on the PAU farm at Ludhiana, about 1.5 km from the sandy loam site. Weather conditions over the 4 years are presented by Yadvinder-Singh et al. (2008b).

In brief, monthly mean minimum temperatures were usually above the long-term averages, by up to 3.5 °C, throughout the 4 years. Monthly mean maximum temperatures fluctuated about the long-term mean. February 2006 was unusually warm, with mean minimum and maximum temperatures 4.5 °C and 4.1 °C above the long-term averages, respectively. The 2003–04 wheat season was also warmer than average throughout the reproductive period (February–April), with the March mean maximum temperature 4.3 °C above the long-term average. January 2003 was unusually cool, with a mean

Table 2. Treatments in the farmer-field scale (~60 m long) blocks

Block	Width (m)	Treatment	2003–04[a]	2004[a]	2004–05[a]	2005[a]	2005–06[a]	2006
1	16	Permanent beds	WFB	TRB (2)	DDWB (3)	TRB (4)	DDWB (5)	TRB (6)
2a	15	Flat (rice), fresh beds (wheat)		PTR	WFB	PTR-CF	WFB	PTR-CF
2a	11	Flat	CTW		CTW	PTR-CF	CTW	PTR-CF
2b	8.5	Flat				PTR-farmer		PTR-2d
2b	20	Flat				PTR-farmer		TRFB (1)
3a	10	Fresh beds for rice only				TRFB (1)	DDWB (2)	TRFB (1)
3b	10	Permanent beds						TRB (3)

[a] Age of beds (number of consecutive crops) in parentheses; CTW = conventionally tilled wheat; WFB = wheat drilled on fresh beds; DDWB = direct-drilled wheat on permanent beds; PTR = puddled transplanted rice; TRB = transplanted rice on permanent beds; TRFB = transplanted rice on fresh beds; CF = continuously flooded; 2d = irrigated 2 days after the floodwater / furrow water had dissipated; farmer = continuously flooded for 40 days after transplanting, then weekly

maximum temperature 4.3 °C lower than the long-term average. This was associated with particularly foggy weather in January 2003 and 50% reduction in sunshine hours compared with the long-term average. Sunshine hours were also unusually low in February 2005; otherwise, the monthly mean sunshine hours did not vary remarkably for the same month across years.

Total rainfall during the wheat season (November–April) ranged from 55 mm in 2005–06 to 201 mm in 2002–03, compared with the long-term average of 108 mm. Monthly rainfall didn't vary greatly across years for the same month during the wheat season, except for unusually high rainfall of 135 mm in February 2003, most of which fell over 3 consecutive days in mid February. Rainfall during the rice season (June–September) ranged from lows of 316 mm in 2004 to 597 mm in 2005, compared with the long-term average of 580 mm. In contrast with the other weather parameters, there was little variability in pan evaporation for the same month across years, except for much higher evaporation during the unusually dry month of July 2004.

Statistical methods

Data were analysed using analysis of variance (ANOVA) by IRRISTAT v.5.0 and Genstat v.7.1. The comparison of treatment means was made by least significant difference (LSD) at P = 0.05.

Results

Small plot experiments

Wheat

The plots were generally uniform, with good weed control and no significant pest or disease damage (Figures 1 and 2). Yields (dry) of CTW over the 4 years were in the range 3.8–4.8 t/ha on the sandy loam and 3.6–4.9 t/ha on the loam (Yadvinder-Singh et al. 2008b). In 3 out of 4 years on the sandy loam, yields were consistently lower on both fresh and permanent beds than CTW, with significantly lower yield on all bed treatments in 2002–03 and 2004–05, and on DDWB (after DSRB only) in 2003–04. On the loam, yields on beds and CTW were statistically similar, except for higher yields on fresh beds in 2003–04 and lower yields on all beds in 2004–05. The lower yields on beds in 2004–05 at both sites were associated with relatively low plant density on the beds (60–80 plants/m2) (Yadvinder-Singh et al. 2008b), possibly due to sowing at suboptimal soil moisture content due to too long a delay between irrigation and sowing. This was exacerbated on the beds, which dried faster than the flats (more so prior to canopy cover), particularly soon after sowing and on the sandy loam (Figure 3). In 2002–03 establishment on the beds was adequate, and the lower yields on the sandy loam appeared to be associated with water deficit stress due to more rapid drying on the beds during the vegetative stage (Figure 3). There was no

Table 3. Dry yield (±st dev) of wheat on beds and flats in farmer-field scale blocks

Block	Treatment	2003–04[a,b]		2004–05[a,b]		2005–06[a,c]		
		Layout	Wheat yield (t/ha)	Layout	Wheat yield (t/ha)	Layout	Irrigation treatment IW/(CPE – rain)	Wheat yield (t/ha)
1	Permanent beds	WFB (1)	5.1	DDWB (3)	4.6±0.1	DDWB (5)	1.2	4.0±0.1
2a	Fresh beds			WFB	4.7±0.4	WFB	1.2	4.2±0.2
2a	Flat	CTW	5.4	CTW	5.1±0.2	CTW	0.9	4.3±0.2
3a	Beds—rice straw removed					DDWB (2)	0.9	3.7±0.3
3b	Beds—rice straw retained					DDWB (2)	0.9 1.2 SMP= –35 kPa	4.2±0.3 4.4±0.3 4.3±0.1

a Age of beds (number of consecutive crops) in parentheses; CTW = conventionally tilled wheat; WFB = wheat drilled on fresh beds; DDWB = direct-drilled wheat on permanent beds; SMP = soil matric potential

b Wheat in 2003–04 and 2004–05 irrigated using IW/(CPE-rain) = 0.9, except for the first irrigation after CRI in DDWB in 2004–05 for which the ratio was 1.2

c DDWB was planted on 11 November 2004 compared with 29 October 2004 for WFB and CTW (lower yield on DDWB probably due to later sowing) trend in yield of wheat relative to yield of CTW as the permanent beds aged (Figures 4, 5).

Rice

Yield of PTR-2d was in the range 4.6–6.0 t/ha (5.3–7.0 t/ha at 14% moisture) on the sandy loam, and 4.9–6.2 t/ha on the loam, over the 4 years (Yadvinder-Singh et al. 2008b). Yields of PTR-CF and PTR-2d were similar in all 3 years in which they were compared on the sandy loam, but yields of PTR-2d were significantly lower (by 16–18%) on the loam in 2 of the 3 years. Yield of TRB-2d, with the same irrigation scheduling as PTR-2d, declined from 81–92% of yield of PTR-2d in the first rice crop to 41–43% in the third crop (Figures 6 and 7). There was no further decline in relative yield of TRB-2d in the fourth year. While yield of TRB-2d declined as the beds aged, yield of transplanted rice on fresh beds in 2006 was similar to PTR-2d. With DSRB, the decline in yield as the beds aged was even more pronounced, declining

Figure 1. Wheat plots on loam in February 2004. Foreground rep. 1: fresh beds (left), permanent beds (right); background rep. 2: permanent beds (left and centre), zero-till wheat (right)

Figure 2. Wheat plots on sandy loam in February 2005. Foreground rep. 1: permanent beds (left), conventional tillage (right); background rep. 2: permanent beds (left), zero-till wheat (right)

to 21–23% of the yield of PTR-2d in the third year despite daily irrigation for the first 50 days after sowing in that year. Many factors appeared to contribute to the lower yield of both TRB and DSRB, including weeds, nematodes and iron deficiency (Yadvinder-Singh et al. 2008b). The rice on beds required three to four hand weedings (Figure 8) compared with no hand weeding in either PTR-2d or PTR-CF. On the sandy loam the rice on beds had severe infestations of cereal cyst nematodes in the first and third years, but not in the second year when the soil was solarised prior to planting. Iron deficiency was a problem for DSRB, and became more severe as the beds aged (Figures 9 and 10). It worse on the loam and could not be overcome by frequent iron sprays (1% ferrous sulphate) starting shortly after establishment.

Farmer-field scale experiments

Wheat

Establishment and growth of wheat on flats and beds in the farmer's fields were excellent each year (Figures 11–13). The grain yield of wheat in the large blocks in 2005–06 was similar in all layouts regardless of age of beds (up to 5th crop) or irrigation scheduling (Table 3), which is consistent with the results from the small plots at the same site (see above). The generally lower yield on permanent beds compared with CTW in 2004–05 could be due to the later

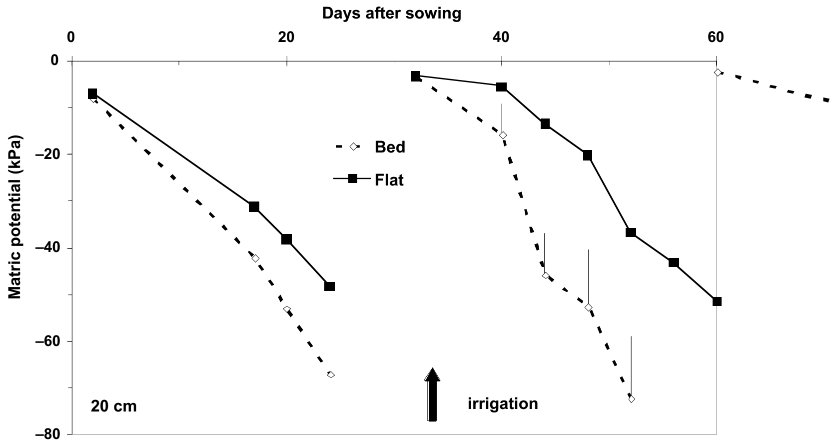

Figure 3. Soil matric potential on flats and beds on sandy loam in 2002; vertical bars are LSD (0.05)

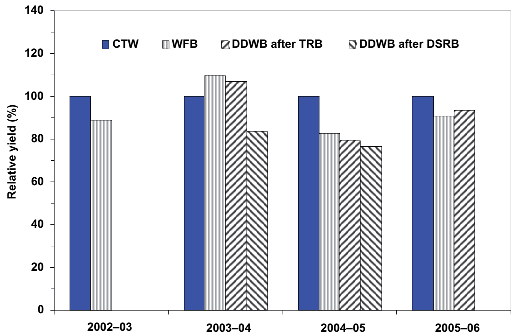

Figure 4. Relative yield (%) of wheat on fresh beds (WFB) and permanent beds (DDWB) compared with conventionally tilled wheat (CTW) on sandy loam

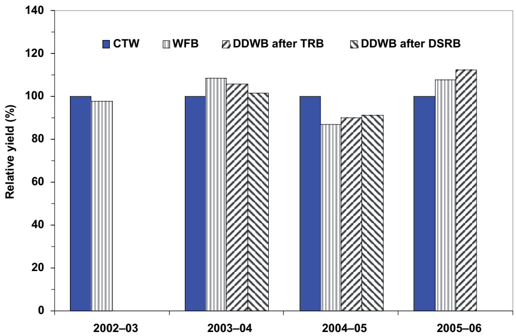

Figure 5. Relative yield (%) of wheat on fresh beds (WFB) and permanent beds (DDWB) compared with conventionally tilled wheat (CTW) on loam

sowing (11 November 2004) on the permanent beds compared with CTW (29 October 2004), although the fresh beds were also sown on 11 November 2004. The optimum sowing date for wheat in Punjab, India, is 5 November (Ortiz-Monasterio et al. 1994).

Rice

Rice growth on both fresh and permanent beds and in PTR was good each year (Figures 14–16). Yield on fresh beds was similar to yield of PTR in block 2 in both years, but not in block 3 (Table 4). However, rice yield on permanent beds was consistently about half that of PTR regardless of the age of the beds (third, fourth or sixth crop) or irrigation management.

There was a consistent trend for higher yield of rice on beds when irrigated with a full-furrow depth than with a half-furrow depth, with significant differences on both permanent and fresh beds in 2006 (blocks 1 and 2b, respectively). Yield on fresh beds with a half-furrow depth and SMP-based irrigation scheduling was 80–90% of yield of PTR-CF in both years.

Yield on permanent beds was about two-thirds that on fresh beds within each irrigation treatment, except in block 3 in 2006.

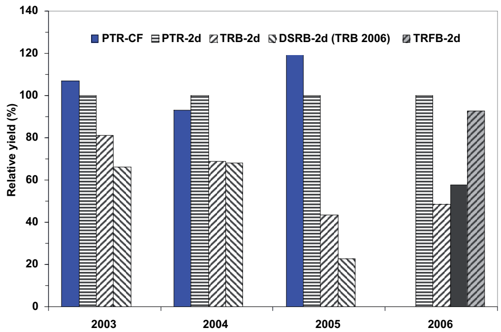

Figure 6. Relative yield (%) of transplanted rice on fresh beds (TRFB-2d), transplanted rice on permanent beds (TRB-2d) and direct-seeded rice on permanent beds (DSRB-2d) compared with puddled transplanted rice (PTR-2d) on sandy loam. All treatments irrigated 2 days after the floodwater / furrow water had dissipated (-2d)

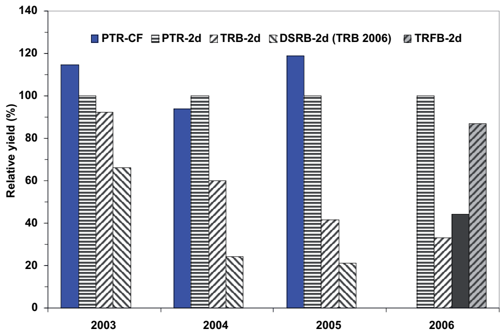

Figure 7. Relative yield (%) of transplanted rice on fresh beds (TRFB-2d), transplanted rice on permanent beds (TRB-2d) and direct-seeded rice on permanent beds (DSRB-2d) compared with puddled transplanted rice (PTR-2d) on loam. All treatments irrigated 2 days after the floodwater / furrow water had dissipated (-2d)

Figure 8. Weeding transplanted rice on beds on sandy loam in July 2005

Figure 9. Iron deficiency in direct-seeded rice on beds on sandy loam in July 2005

Figure 10. Rice plots on sandy loam in July 2005. Foreground rep. 1: PTR-CF (left), DSRB (centre), PTR-2d (right); background rep. 2: DSRB (left), PTR-CF (centre), PTR-2d (right)

Figure 11. Wheat on fresh beds in the farmer's field on loam in February 2006

Figure 12. Wheat on permanent beds in the farmer's field on loam in February 2006

Figure 13. Conventionally tilled wheat in the farmer's field on loam in February 2006

Discussion

Wheat

On the loam, yields of wheat on fresh and permanent beds up to 4 years old in both small plots and large blocks were usually similar to yield of CTW, with no decline in relative yield as the beds aged. On the sandy loam, yields on beds tended to be lower than in CTW. There was no decline in yield on the beds relative to CTW as the beds aged on either soil type. The results on the sandy loam are consistent with the findings of Yadvinder-Singh et al. (2008a) on a similar soil in an adjacent field over the same period of time. In contrast, Lauren et al. (2008) found initially higher yields on beds than CTW, but the relative yield on the beds declined as the beds aged in a RW system on a similar sandy loam soil in Nashipur, Bangladesh.

In the present experiments the lower yield on the beds on both soils in 2004–05 was associated with suboptimal establishment, probably because sowing was delayed too long after pre-irrigation. This delay affected crops on beds more than flats because the beds dry more rapidly and the lower sowing rate provides less seedlings to compensate for loss. Beds probably dry more rapidly because of the 25% greater surface area of the small beds used in Punjab, and because of the concentration of roots in the bed tops (Yadvinder-Singh et al. 2008b). Other studies have also shown that the performance of wheat on beds is reduced relative to conventional sowing where early vegetative growth is set back or insufficient to close the gap between the outside rows on adjacent beds, for example with late sowing and with varieties unsuited to beds (less spreading plant types) (Fischer et al. 2005; Ram et al. 2005; Choudhury et al. 2007). In their review of raised bed planting for irrigated wheat in non-rice-based systems in Mexico, Fischer et al. (2005) concluded that the main factor determining whether yield on beds was maintained was the ability of the cultivar to capture the solar radiation falling in the gap between the beds. They also found that a gap of 44 cm could be compensated for in most cultivars, but not all, and that some varieties could tolerate a gap of up to 55 cm. Those losing 10% yield tended to be short, two-gene dwarf wheat bread varieties.

More skilled management is probably needed for wheat on beds than flats, especially in ensuring good establishment on coarse-textured soils of low water-holding capacity that drain rapidly. The risk of poor establishment on beds could be reduced by more precise irrigation management, increasing the sowing rate to that used for CTW instead of the recommended 25% reduction compared with CTW, and/or sowing three rows per bed (the trade-off being loss of ability to carry out inter-row culture and drilling of topdressed fertiliser). On a loamy sand in Punjab, Kaur (2003) found that a post-sowing irrigation improved establishment on beds and led to higher yield on beds than CTW. At Modipuram, Jat et al. (2008) found significantly higher yield of direct-drilled wheat on permanent beds (eighth crop) in comparison with CTW, using the same variety (PBW343) but with a sowing rate of 100 kg/ha for both beds and CTW. At

Table 4. Rice grain yield (dry, ±st dev) on beds and flats in the farmer-field scale blocks

Block	2005[a]			2006[a]		
	Layout	Irrigation treatment	Yield (t/ha)	Layout	Irrigation treatment	Yield (t/ha)
1	TRB (4)	Full-2d Half-2d Half-SMP	3.1±0. 5 2.8±0.1 3.8±0.7	TRB (6)	Full-2d Half-2d Half-SMP	4.4±0.2 3.5±0.2 3.2±0.3
2a	PTR-CF	CF	6.9±1.0	PTR-CF	CF	7.1±0.5
2b	PTR-farmer	CF for 40 days then weekly	6.7±0.2	PTR-2d	2d	7.5±0.5
2b				TRFB (1)	Full-2d Half-2d Half-SMP	6.9±0.3 5.2±0.6 5.8±0.8
3a	TRFB (1)	Half-SMP	6.1±0.3	TRFB (1)	Full-2d	4.2±0.6
3b				TRB (3)	Full-2d	3.5±0.3

[a] Numbers in parentheses are the age of the beds (number of crops); PTR = puddled transplanted rice; TRB = transplanted rice on permanent beds; TRFB = transplanted rice on fresh beds; CF = continuously flooded; 2d = irrigated 2 days after the floodwater / furrow water had dissipated; farmer = continuously flooded for 40 days after transplanting, then weekly; SMP = soil matric potential

Nashipur, Bangladesh, Talukder et al. (2008) also found significantly higher yields of wheat on permanent beds than flats (average over 4 and 2 years, respectively) sown at 100 kg /ha at low N rates, but similar yields at recommended and higher N rates. In Bangladesh and Nepal, Lauren et al. (2008) found similar or higher yields of wheat on beds on three soil types ranging from sandy loam to silty clay loam. The studies of Jat et al. (2008), Talukder et al. (2008) and Lauren et al. (2008) at Nashipur were all on sandy loam soils similar to the soil at PAU.

Figure 14. Transplanted rice on fresh beds in the farmer's field on loam in July 2005

Figure 15. Transplanted rice on permanent beds in the farmer's' field on loam in July 2005

In the above examples all crop residues were removed at harvest. However, there is evidence from maize–wheat systems in Mexico that residue retention is essential for maintaining or increasing yield on untilled permanent beds (Sayre et al. 2005). In that system significant benefits of residue retention did not occur until the fifth year but appeared to increase with time over the first few years. In RW systems on the sandy loam at Nashipur, Bangladesh, Talukder et al. (2008) and Lauren et al. (2008) found that straw mulch significantly increased wheat yields after only one or two cropping cycles. In contrast, in a permanent bed RW system on the sandy loam in Punjab, retention of rice and wheat residues (6 t/ha) as mulch after each crop did not affect yield of wheat on permanent beds over 4 years in comparison with non-mulched beds or CTW (Yadvinder-Singh et al. 2008a).

Figure 16. Puddled transplanted rice (CF) in the farmer's field on loam in July 2005

Rice

Yield of both transplanted and direct-seeded rice on beds on both the sandy loam and loam soils in Punjab declined substantially relative to PTR, with the same irrigation management, up to the third rice crop (sixth crop). Results in other studies are contradictory. At Modipuram, Singh et al. (2005) also found that relative yield of transplanted rice on permanent beds decreased progressively over the years, from 90% of PTR in the first rice crop to 77% of PTR in the third crop. Also at Modipuram, Jat et al. (2008) reported that yield of the fourth crop of direct-seeded rice on permanent beds was only 76% of that of PTR. In contrast, in Bangladesh and Nepal, Talukder et al. (2008) and Lauren et al. (2008) found yield increases in non-mulched transplanted rice on beds compared with PTR. The increases obtained by Talukder et al. (2008) were up to 29%. The reasons for the decline in yield over time in India, and the increase in yield in Bangladesh and Nepal, are not yet understood. Nor is the variable performance of DSRB and TRB relative to PTR in different locations. The sandy soils were reasonably similar at all sites but there are important differences in site conditions and management. In Bangladesh, for example, it is likely that high rainfall and shallow watertables, combined with rice planting after the start of the monsoon (which starts much earlier in Bangladesh), enabled much wetter soil conditions to be maintained throughout the crop cycle, and ponding during the early stage to assist weed control. The result would be better weed control and less drying of the root zone soil below saturation, including in the raised beds.

Changes in soil properties in the permanent beds over time are seemingly important. In our trials in Punjab, performance of transplanted rice on fresh beds with full furrow irrigation was usually comparable with PTR on both soils. All sowing and furrow cleaning/reshaping operations on permanent beds used a four-wheel tractor with standard tractor tyres (Figure 17), whereas most or all operations in Bangladesh and Nepal were by hand or used a small two-wheel tractor. It is likely that the wide tyres used on the four-wheel tractors in Punjab caused compaction with adverse impacts on the soil properties in the zone where the rice was transplanted (on the shoulders of the beds) in search of a more favourable (wetter) hydrologic regime. Detailed studies on the changes in soil properties on the permanent beds may identify the cause of the poorer performance of transplanted rice on permanent beds, even when rice was only the second crop. In most studies of the physical and other properties of permanent beds, the measurements are only made in the centre of the beds (e.g. Jat et al. 2008; Yadvinder-Singh et al. 2008b). The issue of attempting to change systems without considering all aspects is highlighted in Figure 17. Future work investigating the design and management of mechanised permanent bed RW systems in the IGP would be aided by comparisons of crop performance and compaction of beds using tractors with standard and narrow tyres. Other aspects of permanent beds that need further research to improve performance include development of varieties suited to beds under transplanted and direct-seeded conditions, control of weeds and prevention of iron deficiency in direct-seeded rice.

Performance of rice on beds was sensitive to water management, especially to depth of water in the furrows when irrigated at the same frequency as PTR (i.e. 2 days after the floodwater had dissipated from the flats/furrows). Yields of transplanted rice on fresh beds were only similar to yields of PTR when the furrows were filled close to the top at each irrigation. Whether this was a direct effect of soil water availability or an indirect effect on other factors such as redox and nutrient availability is not known.

While the performance of rice on beds was suboptimal in this environment, the performance of other summer and winter crops sensitive to waterlogging tends to be comparable, or superior where waterlogging occurs (Ram et al. 2005; Jat 2006).

Figure 17. Tractor wheels pressing on location where rice is transplanted (rows of rice stubble) on sides of beds

Conclusions

The results of this work show that, with current technology, permanent bed RW systems in Punjab, India, are not able to maintain rice yield, and are consequently not financially attractive in comparison with PTR followed by wheat sown with the ‘zero-till’ drill (Dhaliwal et al. 2008). They also show that, on these free-draining coarse-textured soils, permanent bed systems require more precise management than CTW to ensure good establishment and early vegetative growth because of the faster drying of the beds. In contrast, experience in Bangladesh and Nepal shows superior performance of both crops on permanent bed RW systems. The reasons for the different responses between the eastern and western IGP need further examination to help develop design criteria and management practices for more productive permanent bed RW systems in Punjab.

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Permanent beds for rice–wheat systems in Punjab, India. 2: Water balance and soil water dynamics

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Abstract

Components of the water balance and soil water dynamics of a rice–wheat (RW) cropping system were compared for conventional tillage on the flat, and in fresh and permanent beds, over 4 years in Punjab, India. Detailed studies were undertaken in replicated small plots on sandy loam and loam soils, and in large blocks (farmer field size) on the loam. There were two water management treatments for puddled transplanted rice on the flat (PTR)—continuous flooding (PTR-CF) and frequent alternate wetting and drying (PTR-2d, irrigated 2 days 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).

Irrigation applications to PTR-CF were in the range 3,300–4,300 mm in the small plots and 2,200–2,300 mm in the large blocks. 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 intermittent flooding. However, underbund seepage was also a major component of the water balance in the large farmer-field blocks, accounting for 60% of the irrigation input in PTR-CF. Total deep drainage (in-field and underbund seepage) in the large block with PTR-CF was 2,120 mm (90% of the irrigation input), and was roughly halved in PTR-2d. Thus, even with recommended water management for PTR, deep drainage (~1,000 mm) was very high in the farmer's field, raising the question of the suitability for rice culture of such free-draining soils with deep watertables.

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.

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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 depth of water at each irrigation was much higher than with a half-furrow; 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, the 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 those 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 CPE-rain for both beds and flats, meaning that the beds were irrigated more frequently after CRI.

Deep drainage during the wheat season was very small (negligible to less than 100 mm) in comparison with that from rice (up to ~2,000 mm) in both flat and bed layouts. 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 water balance studies in small rice plots unless adequate measures have been undertaken to prevent disproportionately high seepage losses, especially from continuously flooded rice. 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 permanent raised beds, further detailed investigations are needed in farmer-field-sized blocks for a range of soil types, watertable conditions and irrigation management.

Introduction

Permanent raised beds have been proposed as a means of increasing the productivity, profitability and sustainability of rice–wheat (RW) systems in the Indo-Gangetic Plain (IGP), principally through improved soil structure and drainage for wheat, direct drilling of both crops and water saving (Hobbs et al. 2002; Connor et al. 2003). There have been many reports of irrigation water savings through growing rice and wheat on beds in small plots and farmers' fields in the IGP. The published irrigation water savings for wheat on beds range from 0% to 54%, and generally seem to be larger in farmers' fields (Singh et al. 2002; Kahlown et al. 2006) than in small plots (Sharma et al. 2002; Aggarwal and Goswami 2003; Sharma et al. 2004; Choudhury et al. 2006; Bhushan et al. 2007; Jat et al. 2008; Jehangir et al. 2007; Lauren et al. 2008). Irrigation water savings for rice on beds in comparison with puddled transplanted rice (PTR) on the flat are in the range 9–58% (Sharma et al. 2002; Singh et al. 2002; Aggarwal and Goswami 2003; Balasubramanian et al. 2003; Singh et al. 2005; Choudhury et al. 2006; Bhushan et al. 2007; Jat et al. 2008; Jehangir et al. 2007; Lauren et al. 2008), with the largest savings associated with comparisons of beds and continuously flooded puddled transplanted rice (PTR-CF) (Sharma et al. 2002; Choudhury et al. 2006). However, many comparisons of rice on beds and flats do not report the water management of the control (usually PTR), especially farmer-field trials. It is unclear whether intermittent ponding of PTR would give the same water savings as intermittently irrigated beds, or whether the beds confer further advantages in terms of water savings.

Many studies of water management for PTR in the IGP show that shifting from continuous ponding to frequent intermittent ponding results in irrigation water savings of around 50%, with only a small effect on yield (see reviews by Gupta et al. 2002; Humphreys et al. 2005). Thus, intermittent ponding (irrigating 2–3 days after the floodwater has dissipated) is the recommended practice for PTR in the north-western IGP. However, few studies have compared rice on beds and flats with intermittent ponding. In a replicated small plot experiment, Choudhury et al. (2006) found a similar reduction in irrigation water application to rice on beds and direct-seeded rice on the flat with the same irrigation management in comparison with PTR-CF.

In contrast with rice, many (or perhaps most) comparisons of wheat on beds and flats have used the same irrigation timing for both layouts, resulting in lower applications to the beds because of the volumetric limitation of the furrows and/or the more rapid progress of irrigation water across the field. Few studies have attempted to determine whether the performance of conventionally tilled wheat on the flat (CTW) can be maintained with a similar (reduced) application rate as on the beds.

Most comparisons of RW on beds and flats have probably been for newly formed or 'fresh' beds, but this information is often lacking. Connor et al. (2003) hypothesised that the lack of puddling and development of macropores on permanent beds would increase infiltration and affect irrigation amount. Consistent with this, Sharma et al. (2002) found that infiltration rate in beds (20 mm/day) was double that in the puddled treatment.

There are few detailed studies of the fate of water in rice and wheat grown on beds, fresh or permanent, other than irrigation amount. While any technology that reduces irrigation amount is beneficial, a more important question is the effect of the technology on water depletion by evapotranspiration (ET), especially in the north-western IGP where current rates of depletion of water by RW systems are unsustainable. Choudhury et al. (2006) calculated significantly lower ET for rice on beds than direct-seeded rice with similar irrigation management.

The objective of the work presented in this paper was to compare components of the water balance for beds and conventional tillage for a RW cropping system in Punjab, India. Kukal et al. (2008) reported crop performance of rice and wheat grown on fresh and permanent beds over 4 years (8 crops) in small plots and large farmer-field blocks on two soil types. This paper presents a detailed analysis of components of the water balance and soil water dynamics in those experiments.

Methods

Replicated small plot and unreplicated large block field experiments were conducted at two locations in Punjab, India, from 2002 to 2006. The sites, treatments and management are described in Kukal et al. (2008) and in more detail by Yadvinder-Singh et al. (2007), and are briefly summarised here for convenience, together with details of the water and soil water monitoring.

Replicated small plot experiments

Replicated experiments were established on sandy loam and loam soils to compare four flat and bed treatments for a RW sequence over 4 years (8 crops) (Table 1; Figs 1a,b). The width of the beds (mid-furrow to mid-furrow) was 67 cm, with 30 cm wide flat tops and 15 cm furrow depth. Plot size was 10.7 × 12 m on the loam and 6.7 × 12 m on the sandy loam, with earth bunds around each plot. The depth to the groundwater was over 10 m at each site.

Table 1. Treatments[a] in the small plot replicated experiments on two soils

Layout	Wheat	Rice
Flat	CTW	PTR-2d
Fresh bed/flat	WFB	PTR-CF[b]
Permanent bed	DDWB	TRB-2d
Permanent bed	DDWB	DSRB-2d[c]

[a] CTW = conventional tillage wheat; WFB = wheat drilled on fresh beds; DDWB = direct-drilled wheat on permanent beds; PTR = puddled transplanted rice; TRB = transplanted rice on permanent bed; DSRB = direct-seeded rice on permanent bed; CF = continuously flooded; 2d = irrigated 2 days after the floodwater / furrow water had dissipated

[b] Converted to fresh beds for rice (TRB-2d) for the fourth (last) rice crop

[c] TRB-2d for the fourth (last) rice crop

Prior to wheat sowing, all treatments received a pre-sowing irrigation, followed by a common irrigation around the time of crown root initiation (applied on the same day in all treatments). Subsequent irrigation scheduling for both flats and beds was based on net cumulative pan evaporation (CPE-rain), using IW/(CPE-rain) of 0.9 to 1.0 (Prihar et al. 1974), where IW is the amount of irrigation water (except for an error in scheduling leading to overirrigation at both sites in late 2002–03—see later).

All rice treatments were irrigated prior to cultivation and puddling or seeding/planting, and then daily for the first 2–3 weeks after transplanting/sowing (except when there was significant rain). Thereafter, irrigations were applied 2 days after the floodwater had dissipated from the flat plots and furrows. The furrows in transplanted rice on beds (TRB-2d) and direct-seeded rice on beds (DSRB-2d) were filled close to the top of the beds at each irrigation except in 2005. Puddled transplanted rice on the flat (PTR-2d), TRB-2d and DSRB-2d were almost always irrigated on the same day. There was also a continuously flooded puddled transplanted treatment (PTR-CF) in the first 3 years that was topped up to a depth of 50–80 mm each day except after significant rain. Transplanting was always completed within a day of pre-puddling irrigation and puddling.

Farmer field experiments

Fresh and permanent beds were compared with conventional tillage on the loam soil in large, unreplicated blocks running the full length (~60 m) of a farmer's field (Figures 1c,d; Table 2). Permanent beds were constructed in block 1, starting with wheat in 2003–04, and compared with conventionally tilled flat layouts and fresh beds for wheat or rice in the adjacent block 2. Beds were also constructed in block 3, starting with rice in 2005. Dimensions of the beds were as for the small plots. Measurement of irrigation water application, as affected by layout and irrigation management, commenced in 2005. The same flow-meter was used for measuring irrigation applications to all large blocks and small plots.

Irrigation treatments

Three irrigation schedules were compared, as follows, for the 2005–06 wheat on permanent beds (2nd crop) in block 3, which was sown with the Happy Seeder (Sidhu et al. 2008) with rice residues retained:
- IW/(CPE-rain) = 0.9
- IW/(CPE-rain) = 1.2
- soil moisture potential (SMP) = –35 kPa at 40 cm depth in the beds.

In blocks 1 and 2 irrigation of 2005–06 wheat on fresh and permanent beds was scheduled using

IW/(CPE-rain) = 1.2

while irrigation of conventionally tilled wheat (CTW) was scheduled using the recommended practice (IW/(CPE-rain) = 0.9) because of previous observations of more rapid drying of the beds.

The same three irrigation treatments were compared for rice on permanent beds in block 1 in 2005, and for rice on permanent and fresh beds in blocks 1 and 2b in 2006 (Table 3):
- Full-2d: irrigation with a full-furrow depth of water 2 days after the furrow water had dissipated
- Half-2d: irrigation with a half-furrow depth of water 2 days after the water had dissipated
- Half-SMP: irrigation with a half-furrow depth of water when soil matric potential at 20 cm depth in the beds increased to –20 kPa.

Components of the water balance

Irrigation

All small plots and large blocks were irrigated, one at a time, with groundwater via a piped irrigation system. Irrigation volume was measured with a Woltman® helical turbine flowmeter. Total irrigation water (IW) reported for each crop includes pre-tillage and/or pre-sowing irrigations unless stated otherwise. At each irrigation the same amount of water was applied to all four replicates of respective treatments; therefore, there is no statistical analysis of irrigation amounts.

Soil water depletion (small plots only)

The soil was sampled at sowing (after pre-irrigation) and harvest of the first three wheat crops, and prior to pre-irrigation and at harvest of the first three rice crops, by augering to 180 cm. Harvest (and soil sampling) of wheat were done as soon as grain moisture had decreased to a few per cent, which occurred 2–4 weeks after the last irrigation (except in 2004–05 when there was only one post-sowing irrigation due to significant, well-distributed rain). Volumetric soil water content (VWC) was determined from gravimetric water content and bulk density. Bulk density was determined throughout the profile from undisturbed cores collected from the walls of soil pits in the buffer areas at each site.

Table 2. Treatments in the farmer-field-sized (~60 m) blocks

Block	Width (m)	Treatment	2005[a,b]	2005–06[a,b]	2006[a,b]
1	16	Permanent beds	TRB (4)	DDWB (5)	TRB (6)
2a	15	Flat	PTR-CF	WFB	PTR-CF
2a	11	Flat	PTR-CF	CTW	PTR-CF
2b	8.5	Flat	PTR-farmer	CTW	PTR-2d
2b	20	Flat	PTR-farmer	CTW	TRFB (1)
3a	10	Fresh beds for rice	TRFB (1)	DDWB (2)	TRFB (1)
3b	10	Permanent beds	TRFB (1)	DDWB (2)	TRB (3)

[a] CTW = conventionally tilled wheat; DDWB = direct-drilled wheat on permanent beds; WFB = wheat drilled on fresh beds; PTR = puddled transplanted rice; TRB = transplanted rice on permanent beds; TRFB = transplanted rice on fresh beds; CF = continuously flooded; 2d = irrigated 2 days after the floodwater / furrow water had dissipated; farmer = continuously flooded for 40 days after transplanting, then weekly

[b] Age of beds (number of consecutive crop) in parentheses

Figure 1a. First post-sowing irrigation of conventionally tilled wheat (CTW) in small plots on loam in November 2002

Figure 1b. First post-sowing irrigation of wheat on fresh beds (WB) in small plots on loam in November 2002

Figure 1c. Puddled transplanted rice with continuous flooding (PTR-CF) in a large block on loam soil in 2004

Figure 1d. Transplanting of rice on permanent beds (TRB) in a large block on loam soil in 2004

Figure 1e. S.S. Kukal with PVC cylinders used for measuring infiltration in puddled transplanted rice with continuous flooding (PTR-CF) in a small plot on loam soil in 2004

Field capacity was determined in two bare small plots in the buffer areas by ponding water for about 1 week and then collecting (by 75 mm auger) soil samples to a depth of 180 cm after ponding ceased. The plots were covered with polythene sheets to prevent soil evaporation. The samples were collected at depth increments of 15 cm for the top two layers, and at increments of 30 cm from 30 cm to 180 cm. Sampling was continued until the soil water content became relatively constant (field capacity). This took 1–2 days for the upper layers, and 2–4 days for the deeper layers. Soil water content was also determined at 1,500 kPa on augered samples using pressure plate apparatus. Plant available soil water capacity (PAWC) was calculated from the difference between field capacity and soil water content at 1,500 kPa.

Neutron access tubes were installed in four replicates of selected treatments, prior to rice 2005, for determination of VWC throughout the profile to 180 cm. Dry down of the soil profile after rice on the sandy loam was monitored by frequent readings during the 39 days between the last irrigation for rice in PTR-CF and pre-irrigation for wheat. Less frequent monitoring was also done on the loam during the dry down after rice 2005, and during the period between grain filling of wheat and pre-irrigation for rice in 2006 on both soils. The neutron probe was calibrated in the sandy loam topsoil over a range of 10 values of VWC from 0.06 to 0.45, giving the relationship VWC = 0.3519C–0.1204 ($R^2 = 0.89$), where C is the ratio of the actual count to the standard count in the hydrocarbon lined sheath supplied with the instrument (CPN 2007).

Rainfall and evapotranspiration

Rainfall was measured using a rain gauge within each experimental field at both sites. Daily maximum and minimum temperatures, sunshine hours and Class A pan evaporation were collected from the meteorological station on the Punjab Agricultural University (PAU) farm at Ludhiana, about 1.5 km from the sandy loam site and about 20 km from the loam site. Evapotranspiration during the period from wheat sowing or pre-irrigation for rice to physiological maturity was estimated using the CSM-CERES Rice and CSM-CERES Wheat models (Hoogenboom et al. 2004) following calibration and determination of genetic coefficients for each variety (J. Timsina and D. Smith, unpubl. data).

Infiltration during rice

Infiltration was measured every 1–4 days throughout the season from transplanting to the time of the last irrigation of the first three rice crops with PTR-CF in the small plots on both soils, and in PTR-CF in the farmer's field on loam in 2005. PVC cylinders (20 cm in diameter and 40 cm high) were installed into the hardpan to a depth of 25 cm in all four replicates in the small plots (Figure 1e), and at three locations in the farmer's field. The cylinders were covered with close-fitting caps with a small hole in the side to maintain atmospheric pressure. They were topped up to plot water depth whenever the plots

Table 3. Irrigation water applications to transplanted rice on beds and flats in the farmer-field blocks

Block	Layout	2005[a]			2006[a]			
		Irrigation treatment	No. of irrigations	Amount (mm)		Irrigation treatment	No. of irrigations	Amount (mm)
1	TRB	Full-2d Half-2d Half-SMP	43 41 36	2,360 1,650 1,310	TRB (6)	Full-2d Half-2d Half-SMP	45 44 38	2,360 1,480 1,310
2a	PTR-CF	CF	83	2,310	PTR-CF	CF	90	2,190
2b	PTR-farmer	CF for 40 days then weekly	56	1,750	PTR-2d	2d	38	1,378
2b					TRFB (1)	Full-2d Half-2d Half-SMP	43 42 33	1,770 1,349 1,084
3a	TRFB (1)	Half-SMP	34	1,030	TRFB (1)	Full-2d	45	2,020
3b					TRB (3)	Full-2d	47	2,220

[a] PTR = puddled transplanted rice; TRB = transplanted rice on permanent beds; TRFB = transplanted rice on fresh beds; CF = continuously flooded; 2d = irrigated 2 days after the floodwater/furrow water had dissipated; SMP = soil matric potential; age of beds (number of consecutive crops) in parentheses

were irrigated, and infiltration was calculated from the decline in water depth between irrigations using scales (rulers) installed in the cylinders or a hook gauge. In 2003 infiltration was measured in the same way in the furrows of an additional DSRB treatment in the replicated experiments, which was irrigated daily to try to maintain ponding in the furrows.

Deep drainage and seepage

Net deep drainage (DD, mm) beyond the root zone (180 cm) of the first three wheat crops was estimated as DD = I+R-ET–ΔSWC, where ΔSWC is the soil water content (SWC, 0–180 cm) at harvest minus SWC at sowing. As the soil was sampled at sowing after pre-irrigation, the amount of pre-sowing irrigation is not included in the calculation. The calculation assumes that lateral flow and underbund losses (seepage) from the small plots were negligible. The assumption of negligible seepage from each plot during the wheat season is probably reasonable given the concurrent irrigation of all plots and buffers on the same day, the deep watertable and the high hydraulic conductivity of the soil. The hydraulic conductivity of the most limiting layer (a hardpan at about 20 cm depth) during the wheat season was 25 mm/hour at 1 kPa tension on the sandy loam and 3 mm/hour at 1 kPa tension on the loam (Humphreys et al. 2004).

Deep drainage of PTR-CF during the rice phase (transplanting to harvest) was estimated from infiltration. At the time of transplanting, the soil profile was already wet to depth (see later); therefore, in-field deep drainage beyond the RW system root zone (180 cm) during this period would be similar to total infiltration over the same period. It was not possible to estimate deep drainage during the rice season using the water balance method used for wheat due to disproportionately large seepage (see later) from PTR-CF in the small plots. Seepage (S, mm) during the ponded period of PTR-CF was estimated from S = I+R–ET–Inf+200, where Inf is infiltration measured in the PVC cylinders. This calculation assumes 200 mm of infiltration from the pre-cultivation and pre-puddling irrigations, roughly the amount of water required to refill the profile to depth.

Soil matric potential was also logged, using granular matric sensors (Watermark®), in the small plots from late 2003 to early 2006 to identify drainage gradients and fluxes. The sensors were installed at depths of 120, 160, 200 and 240 cm in flat and permanent bed plots in two replicates on the sandy loam and one replicate on the loam, and logged every 2 hours using GBugs®. Holes were augered to the desired depth, the sensors were embedded in loam slurry and the holes were backfilled with loam and bentonite plugs. The soil tension data are incomplete because of loss of data (and no data in 2002–03) due to theft of loggers, vandalism and technical problems. However, there are sufficient data to demonstrate some important findings.

Results and discussion

Plant available soil water capacity

Total PAWC in the 0–180 cm profile was 291 mm on the sandy loam and 389 mm on the loam. PAWC of the sandy loam was slightly higher than that determined by others in similar trials. It was 52 mm and 16 mm higher than PAWC determined by Gajri et al. (1992, 1993) for two sandy loam soils at PAU, but those soils had lower clay content (6–10% and 10–14%, respectively, in the top 120 cm) compared with our soil (14–17% in the top 120 cm). PAWC in our sandy loam was also 34 mm higher than in the top 180 cm of the sandy loam soil used by Singh et al. (2005).

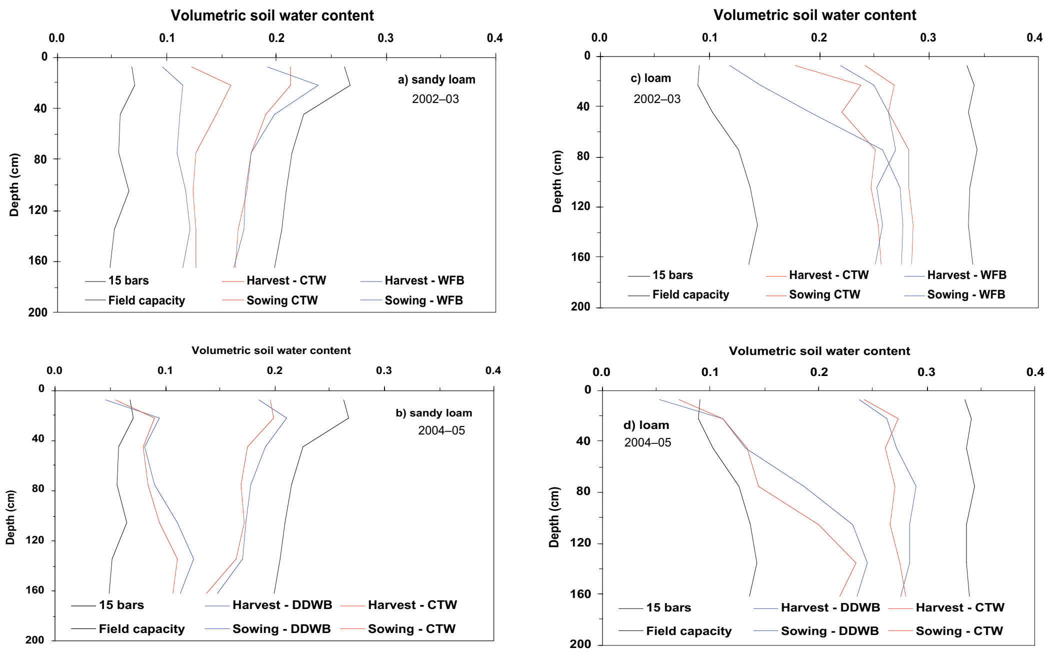
Components of the water balance during the wheat season

Water requirement and irrigation of wheat

At the time of wheat sowing, soil water content was always below field capacity throughout the profile (Figures 2a–d), despite irrigation a few days prior to sowing. Simulated ET (sowing to harvest) was in the range 313–353 mm from 2002–03 to 2005–06 (J. Timsina, unpubl. data), which is similar to the values estimated by Ahmad et al. (2004) in Punjab, Pakistan, using the Soil Water Atmosphere Plant (SWAP) model (<http://www.wiz.uni-kassel.de/model_db/mdb/swap.html>) and those calculated from periodic determination of soil water depletion throughout the season near Delhi by Choudhury et al. (2006). However, using the CROPMAN model (<http://cropman.brc.tamus.edu/>), Chahal et al. (2007) estimated slightly higher values of ET for wheat sown on 11 November at PAU (range 369–472 mm over the 23 years 1982–2004).

The number of post-sowing irrigations of wheat in each season ranged from one (CTW on both soils in 2004–05) to four–five (WB on sandy loam and loam, respectively, in 2002–03). As the irrigation amounts on the beds were usually less than on the flats (because of the volume limitation of the furrows), use of the same irrigation scheduling rule for beds and flats meant that the beds were usually irrigated slightly more frequently. Total water input (post-sowing irrigation + rain) to wheat on both beds and flats in the small plots was much higher in 2002–03 than in the following 3 years on both soils (Figures 3a,b). On the sandy loam total input was 353 mm and 383 mm on the flats and beds in 2002–03, respectively, compared with 212–263 mm in all other years. On the loam total input was 407 mm and 428 mm on the beds and flats in 2002–03, compared with 216–295 mm in the other years. In 2002–03 total water input exceeded simulated ET on both flats and beds due to unusually high rainfall in February (in excess of 90 mm in a single event at both sites) and subsequent overirrigation (too soon after the rain). In all other years total post-sowing water input was less than ET (by 43–149 mm), as expected given that all plots had been irrigated prior to sowing. Also, the goals of the irrigation scheduling were to force the crop to use the residual soil water after rice, and to avoid late irrigation of the wheat to force the crop to use the plant available water in the soil profile prior to harvest. There was no consistent trend for higher or lower irrigation amount on beds versus flats, in contrast with the findings of many other studies (see 'General discussion'). The relative amount of irrigation water applied to the beds and flat plots was largely influenced by the incidence of rain in relation to irrigation—the treatments were often irrigated on different dates because of the different irrigation amounts applied to flats and furrows while using the same ratio of IW/(CPE-rain) for both.

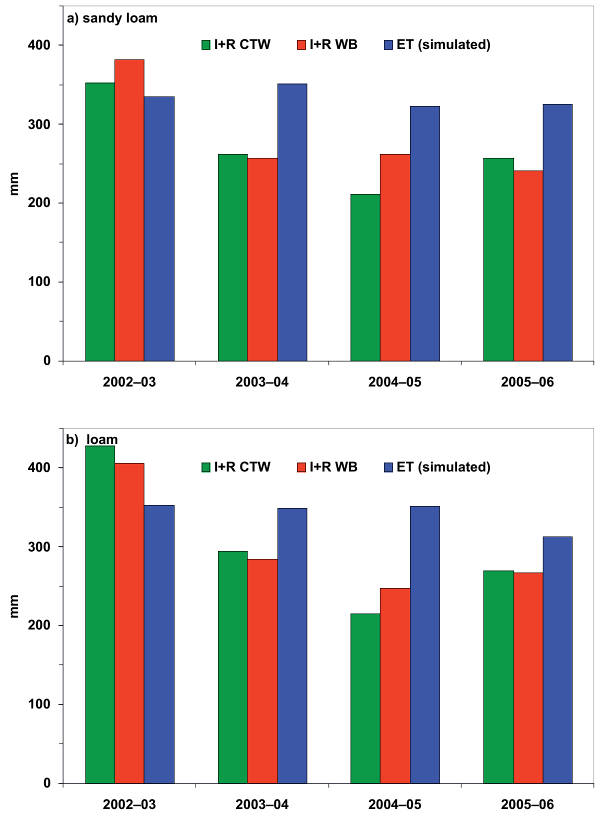
As with the small plots, total irrigation application in 2005–06 in the large blocks (1 and 2) was similar for fresh beds, permanent beds and CTW (284–293 mm including pre-sowing irrigation). Total irrigation in the large blocks was almost identical to that in the small plots at the same site in the same season (279–286 mm), suggesting that the small plots were reasonably representative of the large blocks in terms of irrigation amount.



Figures 2a-d. Soil water content in conventionally tilled wheat (CTW), fresh beds (WFB) and permanent beds (DDWB) at sowing and harvest of wheat on sandy loam in: a) 2002–03 and b) 2004–05; and on loam in: c) 2002–03 and d) 2004–05

Soil water depletion during wheat

At the time of wheat harvest the profile had dried to the depth of sampling (180 cm) on both soils each year, except on the loam in 2002–03 where drying was only to about 60 cm (Figures 2a–d). The extent of drying to depth was greater on the sandy loam than the loam and, somewhat surprisingly, there was even drying to depth in the overirrigated crops on the sandy loam in 2002–03. While there was evidence of roots to 140–160 cm on both beds and flats on both soils at heading in 2002–03 and 2003–04 (no sampling in later years), root length density was very low (<0.3 cm/cm^3) below about 50 cm (Humphreys et al. 2004; Yadvinder-Singh et al. 2008), suggesting that the drying at depth was due to upflow and/or deep drainage rather than extraction by roots. Soil water depletion generally tended to be greater in the topsoil of the beds than the flats, but less in the beds than flats at depth. The magnitude of soil water depletion between sowing and harvest ranged from 87 mm (2002–03) to 141 mm (2004–05) in CTW on the sandy loam, and from 54 mm (on beds in 2002–03) to 177 mm in CTW in 2004–05 on the loam. Prihar et al. (1976, 1978b) also showed significant drying to 180 cm between sowing and harvest for a range of irrigation schedules based on growth stages or IW/(CPE-rain) on a sandy loam overlying a loam subsoil. Prihar et al. (1978a) found that yield was maintained for soil water depletion up to 110 mm on a loamy sand over a sandy loam, and up to 170 mm on a sandy loam overlying a clay loam. This suggests that our crop on the sandy loam in 2004–05 may have suffered from soil water stress during grain filling, when soil water depletion increased to 141 mm.



Figures 3a,b. Input water (I+R, irrigation plus rain) of wheat established with conventional tillage (CTW) or on beds (WB) and ET (simulated using CSM-CERES Wheat) in small plots on a) sandy loam and b) loam soil

The soil tension data show gradual drying at depth (120–240 cm) during the second, third and fourth wheat seasons (no soil tension data for 2002–03) on both soils in both flat and bed plots (Figures 4a–f), which is consistent with the observations from soil sampling at sowing and harvest (Figures 2a–d). During the latter part of the season the 'upper' subsoil layers (120–160 cm) became drier than the deeper layers (200–240 cm), favouring upflow. The fact that soil tension in the wetter, deeper layers continued to increase between the last irrigation of rice and the early part of the wheat season (i.e. before significant wheat root development) suggests that deep drainage (unsaturated flow) and/or upflow continued during the fallow period between rice and wheat, and during the wheat season. The soil tension data during the wheat season also show occasional downward spikes or, sometimes, slowing of the rate of increase in tension, more so in the upper subsoil depths (120–160 cm). This coincided with irrigation or heavy rainfall, suggesting that there were deep drainage fluxes in response to some (but not all) irrigations and rains during the wheat season. For example, in both CTW and wheat on permanent beds (WB) on the sandy loam (Figures 4a,b), there was a sharp fall in soil tension at all depths at the time of the pre-sowing irrigation on 6–7 November 2003. However, soil tension thereafter continued to increase, more so in the upper layers, to the end of the wheat season. There was no evidence of deep drainage in response to irrigation or rain during the 2004–05 and 2005–06 wheat seasons on the sandy loam (but note that there were no data at the time of pre-irrigation for wheat in 2004–05). In contrast, on the loam there is evidence of several deep drainage events (during both years for which data are available, i.e. 2003–04 and 2004–05), coinciding with both pre- and post-sowing irrigations and major rains, in both flats and beds (Figures 4c,d). It is interesting to note that there was a large response to pre-sowing irrigation in the beds on the loam on 5 November 2004, but not in the flats. This probably reflects the fact that the soil profile in the beds was much wetter than in the flats at the time of pre-sowing irrigation because the last irrigation of DSRB was on 15 October 2004, 5 weeks after the last irrigation of PTR-2d, due to the very late maturity of the DSRB.

Water balance of wheat

The water balance calculations (sowing to harvest) show significant deep drainage (beyond 180 cm) on both beds and flats on both soils in 2002–03 (105–174 mm) (Figure 5a), a result of very high rainfall in a short period of time in February 2003 and subsequent overirrigation. Drainage was higher on the beds than flats on the sandy loam, where the beds received 30 mm more irrigation; but less on the beds than the flats on the loam, where the beds received 20 mm less irrigation. In contrast with 2002–03, the calculations suggest no net deep drainage between sowing and harvest on the sandy loam on either the beds or flats in 2003–04 (Figure 5b), which is consistent with the soil tension observations. Note that there was deep drainage associated with the pre-sowing irrigation in 2003–04 which should be attributed to wheat but which is not included in the 'sowing to harvest' water balance calculation. The calculations also suggest a small amount of deep drainage (flats 30 mm, beds 70 mm) during the season on the sandy loam in 2004–05 (Figure 5c) and, on the loam, 36–87 mm of deep drainage of in 2003–04 and 2004–05, again consistent with the soil tension observations.

Soil drying between the last irrigation of wheat and pre-irrigation for rice

The neutron probe data show drying of the sandy loam profile in the top 50 cm between the last irrigation of wheat and pre-irrigation for rice in 2006 (Figure 6) due to both crop water use prior to maturity and soil evaporation. The considerable drying of the surface layers after harvest is a result of the very high evaporative demand during the period between wheat harvest in early April and pre-irrigation for rice in early June (CPE in April and May 2006 was 510 mm) and the absence of rain. The relatively constant soil water content below 80 cm suggests no drainage or upflow losses from the deeper subsoil during this period.

Components of the water balance during rice

PTR

The soil tension data show rapid wetting of the soil profile to at least 2.4 m (the maximum depth of measurement) at the times of irrigation for puddling and sowing of the permanent beds each year on both soils (Figures 4a–f). The data also suggest continuous deep drainage beyond 2 m during the rice season, as evidenced by close examination of the responses of the sensors at all depths to each irrigation in PTR-2d and TRB-2d in 2004 on the sandy loam (Figures 4e,f). The stepwise shift to lower minimum tension at 120 cm on 6 August 2004 coincided with irrigation

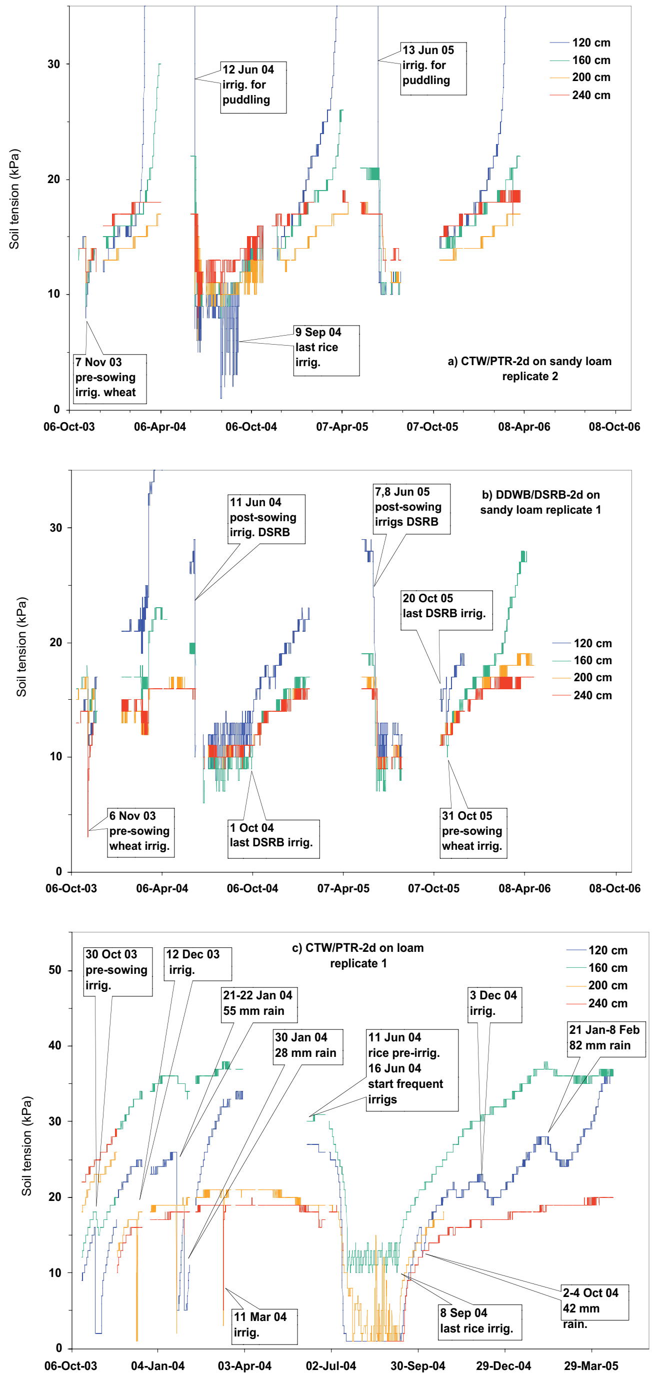


Figure 4a-c. Soil tension at depth in conventionally tilled flat plots (CTW/PTR-2d) and permanent beds with direct-seeded wheat and rice (DDWB/DSRB-2d) on: a,b) sandy loam 2003–06; c) loam 2003–05

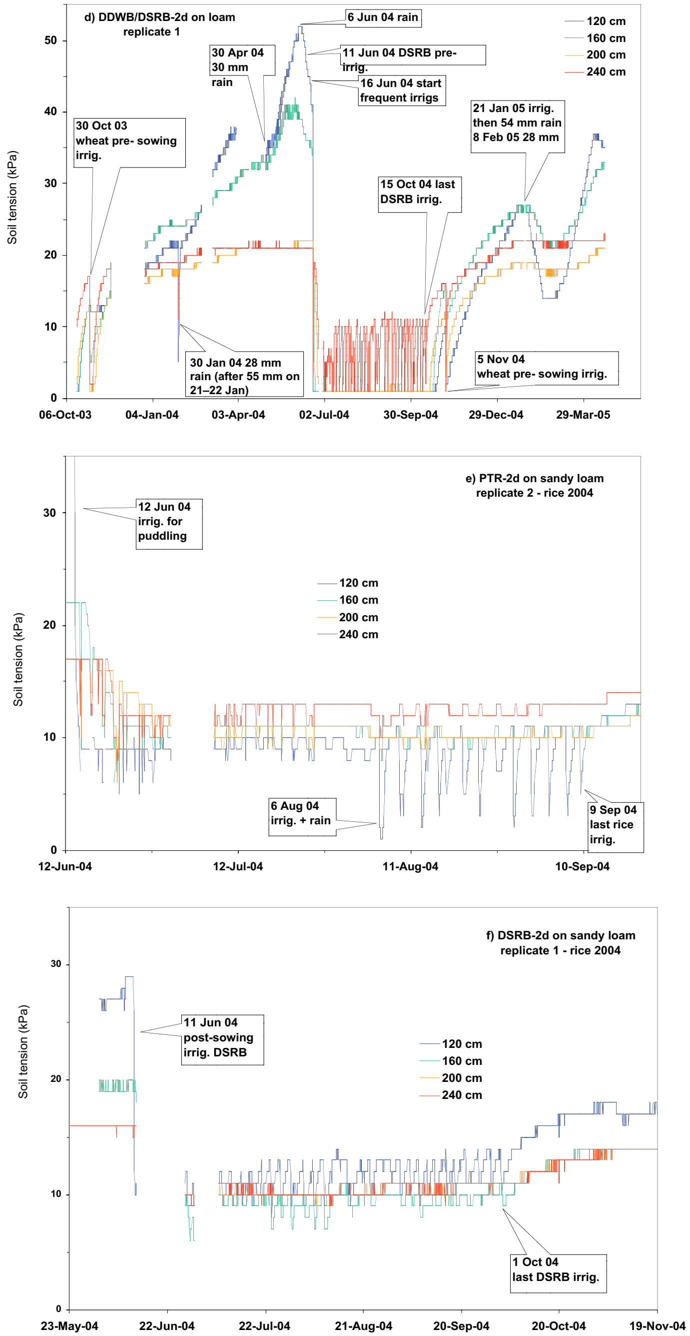
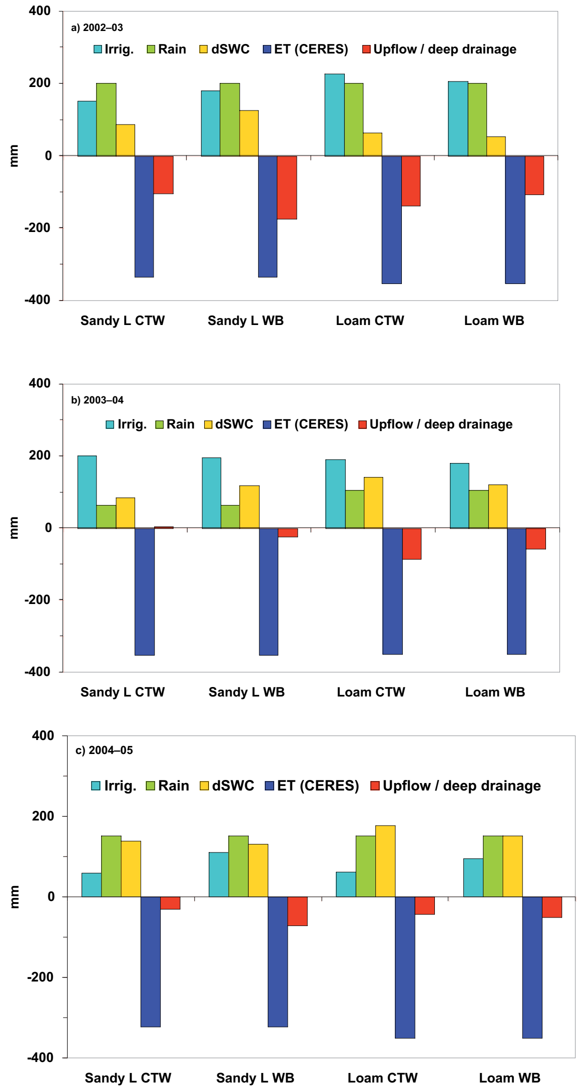


Figure 4d-f. Soil tension at depth in conventionally tilled flat plots (CTW/PTR-2d) and permanent beds with direct-seeded wheat and rice (DDWB/DSRB-2d) on: d) loam 2003–05; e,f) a zoom view for 2004 rice on sandy loam followed by rain on the same day, followed by a further 136 mm of rain over the next 3 weeks, often falling within 24 hours after irrigation.

Infiltration rate in PTR-CF was relatively constant throughout the season, in the range 4–6 mm/day on both soils in the replicated experiments and large block over the 3 years (Figure 7). The duration of ponding (transplanting to time of last irrigation) was approximately 90 days for PR115 and 105 days for PR118, giving total infiltration of around 450–550 mm. This almost matches the total rainfall in 2003 and 2005 but exceeds rainfall by 100–200 mm in the drier 2004 season. Choudhury et al. (2006) observed similar infiltration rates (5–7 mm/day) in PTR-CF on loam and sandy loam soils near Delhi.



Figures 5a-c. Components of the water balance for conventionally tilled wheat (CTW) and wheat on beds (WB) in: a) 2002–03; b) 2003–04; and c) 2004–05

On the sandy loam, ponded infiltration rate in the furrows of daily-irrigated DSRB (12.7 mm/day) was triple that in PTR-CF (4.3 mm/day) in 2003, suggesting that puddling reduced infiltration rate by about two-thirds. The effect of puddling on the loam was much smaller—infiltration of 5.2 mm/day in PTR-CF compared with 6.6 mm/day in the furrows of daily-irrigated DSRB. On a silty loam Sharma et al. (2002) found that infiltration rate in the non-puddled beds (20 mm/day) was almost double that in PTR-CF (10 mm/day); infiltration rate in the furrows was not determined.

Simulated ET of PR115 ranged from 460 mm to 510 mm in 2003 and 2004, about 150 mm lower than ET of the longer duration PR118, which ranged from 610 mm to 650 mm in 2005 (D. Smith, unpublished data). The values for PR115 were similar to those for a variety with similar duration in Punjab, Pakistan,

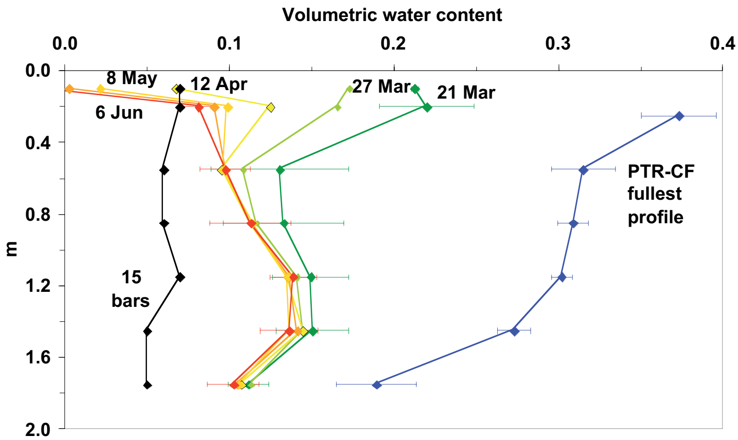


Figure 6. Soil water content between wheat harvest and pre-irrigation for rice in 2006 on: a) sandy loam and b) loam soils (data are means of four replicates; horizontal bars are standard deviations, shown only for some profiles for simplicity). PTR-CF is puddled transplanted rice with continuous flooding

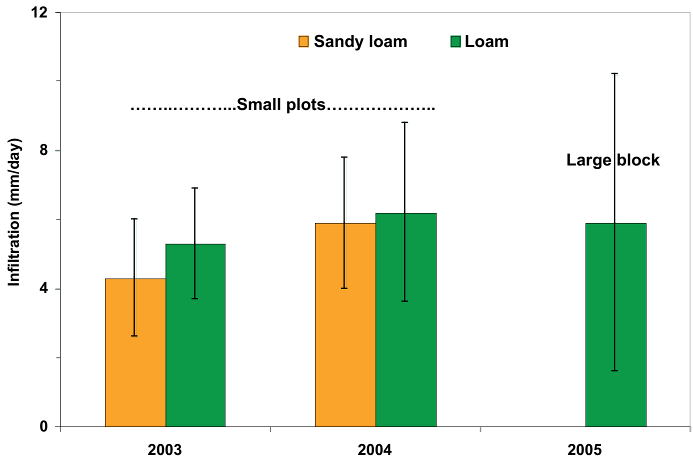


Figure 7. Infiltration rate in puddled transplanted rice with continuous flooding (PTR-CF). Data are means (±std. dev.) of numerous readings throughout the season from PVC microplots in four replicates (small plots) or three locations (large block)

estimated using the SWAP model (Ahmad et al. 2004). Our values of ET for PR118 were also in the range of values (480–683 mm) estimated by Chahal et al. (2007) using 23 years of weather data at PAU and the CROPMAN model. Using another variety with similar duration to PR118, Choudhury et al. (2006) estimated considerably higher values of ET (781 mm and 899 mm) than our estimates using CSM-CERES Rice. Their values were calculated from the water balance and are probably inflated by the assumption of zero seepage from the small plots. Even with plastic lining in the bunds to 10 cm below the soil surface, there is likely to be significant underbund seepage (Tuong et al. 1994).

There was a consistent trend for slightly lower ET in PTR-2d than PTR-CF but the differences were negligible (a few mm). The similar ET is to be expected given that the topsoil of PTR-2d was always between saturation and field capacity, and there was similar biomass production in both PTR-CF and PTR-2d (Prashar et al. 2004; Yadvinder-Singh et al. 2007). Using the ORYZA model, Bouman et al. (2006) also found only small reductions in ET (25 mm) in changing from PTR-CF to 3 days of dry

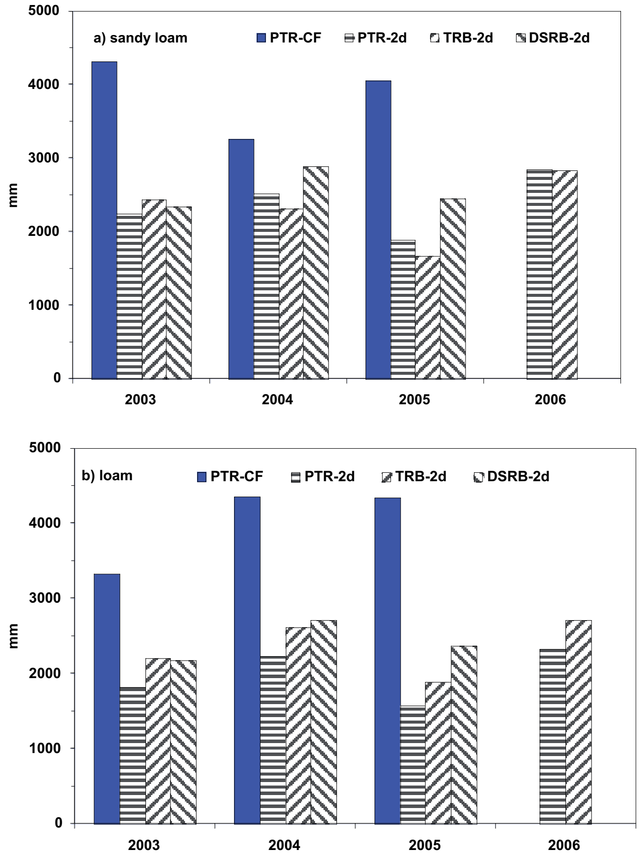
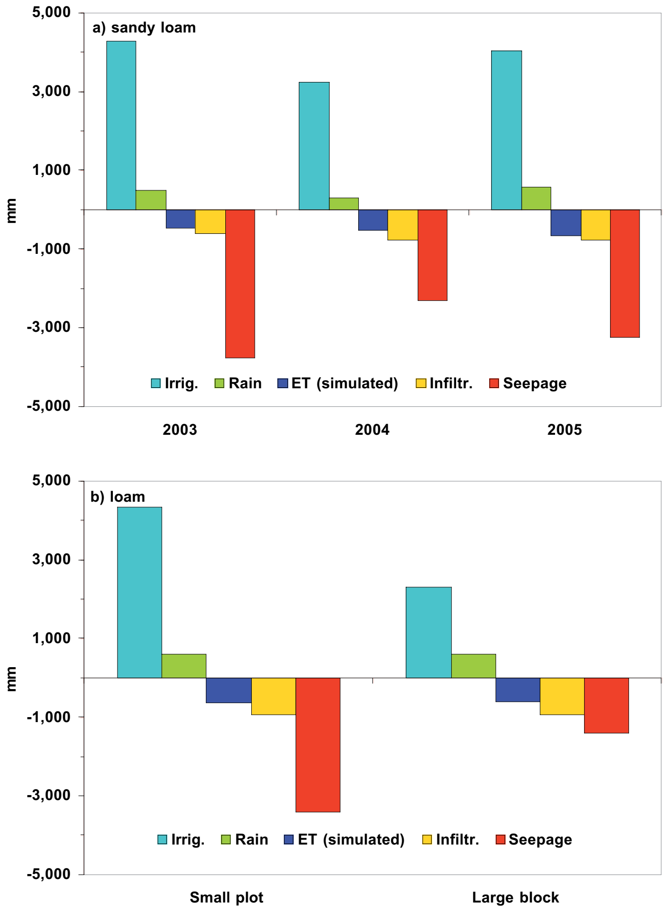


Figure 8a,b. Total irrigation amount for rice on small plots on: a) sandy loam and b) loam soils as affected by layout/planting method and irrigation management. PTR-CF = puddled transplanted rice with continuous flooding, PTR-2d = puddled transplanted rice irrigated 2 days after the floodwater has dissipated, TRB = transplanted rice on permanent beds irrigated 2 days after the furrow water has dissipated, DSRB = direct-seeded rice on permanent beds irrigated 2 days after the furrow water has dissipated soil between irrigations in a shallow watertable situation (30 cm) in northern China.

Total irrigation application to PTR-CF in the small plots ranged from 3,300 mm to 4,300 mm on both soils (Figures 8a,b). Thus, irrigation applications in the small plots were about six times the magnitude of ET, rain or total infiltration, which were all of similar order of magnitude (Figures 9a,b). This suggests that underbund seepage (vertical and/or lateral) was the dominant component of the water balance in the small plots, ranging from 2,300 mm to 3,780 mm or 71–87% of the amount of irrigation.

The high irrigation amounts in PTR-CF in our small plots are similar to irrigation amounts in PTR-CF in many other small plot studies in the north-western IGP under similar climatic conditions (e.g. Sandhu et al. 1980; Sharma 1989; Singh et al. 1996; Sharma et al. 2002; Chahal et al. 2007; Bhushan et al. 2007). However, irrigation and total water input to PTR-CF near Delhi were only about 1,350 mm and 1,600 mm, respectively, in small plots with plastic lining in the bunds to 10 cm below the soil surface (Choudhury et al. 2006), suggesting that the lining greatly reduced seepage losses.



Figures 9a,b. Components of the water balance in puddled transplanted rice with continuous flooding (PTR-CF): a) in small plots on sandy loam over 3 years; b) in small plots compared with large block on loam in 2005. ET estimated using CSM-CERES Rice

There was a large reduction in irrigation amount in PTR-2d compared with PTR-CF in the small plots on both soils, usually by around 50% (Figures 8a,b), which is consistent with the findings of many other studies in the IGP (e.g. Table 6 in Gupta et al. 2003; Humphreys et al. 2005). Infiltration in PTR-2d is likely to have been less than in PTR-CF due to the reduced period of ponding but, even if infiltration were halved, the difference would have been small relative to the size of the largest components of the water balance. Assuming similar infiltration in PTR-CF and PTR-2d, seepage in PTR-2d is conservatively estimated to have ranged from 1,100 mm to 1,700 mm. Thus, seepage was much less in PTR-2d than in PTR-CF (reduced by ~50%) but still substantial and by far the largest loss of water from the small plots.

Components of the water balance in PTR-CF in the small plots and large block were compared on the loam in 2005 (Figure 9b). Irrigation in the large block was 2,310 mm, 53% of that in the small plots, while seepage in the large block was 1,380 mm, 60% of the irrigation amount. Total deep drainage (infiltration plus seepage) in the large block was 2,120 mm. The results support the suggestion that seepage in the small plots, and therefore irrigation application to PTR-CF, were unrepresentative of the situation in the large blocks or farmers' fields. This is not surprising given the much larger perimeter:area ratio of the small plots (0.35 m/m^2) compared with that of the 0.39 acre large blocks (0.12 m/m^2). In comparison, the perimeter:area ratio of a typical Punjab farmer's rice irrigation block (0.5 acre or ~60x30 m) is 0.10 m/m^2, similar to that of our large blocks. In 2006 PTR-2d reduced the irrigation amount in the large blocks by 810 mm or 37% compared with PTR-CF. As differences in ET between PTR-CF and PTR-2d were negligible, this suggests that total deep drainage losses (seepage and in-field deep drainage) were more than halved by switching to PTR-2d.

Irrigation application to rice on beds vs flats

Small plots. Irrigation amount on the puddled transplanted flats and transplanted beds with the same irrigation scheduling (i.e. PTR-2d, TRB-2d) was similar on the sandy loam each year (within ±10%) (Figures 8a,b). However, on the loam there was a consistent trend for higher irrigation amount in TRB-2d than PTR-2d, by 16–21%. As the flat and bed plots had similar water management, it is likely that underbund and lateral seepage were similar, or possibly higher in PTR-2d as it remained ponded for longer than TRB-2d. On both soils the water in the furrows of the permanent beds disappeared within 2–3 hours, compared with 12–18 hours for the floodwater to disappear from PTR-2d. Irrigation amount in DSRB-2d tended to be higher than in TRB-2d due to the delayed maturity and therefore longer irrigation period of the direct-seeded rice (by 20–25 days for PR115, and by more in 2005 with the longer duration PR118). Choudhury et al. (2006) also found a 17–27 day longer duration for DSRB than PTR near Delhi using a variety with similar duration to PR118.

There are few other studies comparing beds and PTR with the same water management in small plots. The results from our small plots suggested similar or higher irrigation amount with TRB-2d compared with PTR-2d. In contrast, Jat et al. (2008) found a 15% reduction in irrigation amount for DSRB and PTR, when both were irrigated according to soil water tension = 30 kPa at 15 cm depth on a similar sandy loam soil to that at PAU. In other studies, either PTR-CF is compared with alternate wetting and drying in the furrows or the water management for PTR is not known. Small-plot studies that compare rice on beds with PTR-CF show irrigation savings of 45–58% on beds (Sharma et al. 2002; Choudhury et al. 2006), which is consistent with our findings.

Farmer-field-sized blocks. Irrigation amount in PTR-CF in the large block was similar in both years—2,310 mm in 2005 and 2,190 mm in 2006 (Table 3). As in the small plots, frequent alternate wetting and drying decreased irrigation amount compared with PTR-CF in both years. In 2005 the farmer's water management decreased irrigation amount by 24% (to 1,750 mm), while in 2006 PTR-2d decreased irrigation amount by 37% (to 1,380 mm), compared with PTR-CF. In comparison, in the small plots on the same soil, PTR-2d decreased irrigation amount by much greater amounts (51–64%). The reduction was least in the lowest rainfall year (2004), and rainfall was similarly low in 2006. Thus, the reduction in irrigation amount in going from PTR-CF to PTR-2d in the small plots was ~1.5 times that in the large block, consistent with the disproportionately high seepage losses in PTR-CF in the small plots.

Irrigation amount in our large blocks with PTR-2d and PTR-farmer was comparable to that of large (6–10 ha) rice farms in Punjab, Pakistan, where farm average irrigation amount over 3 years was in the range 1,100–1,510 mm (Jehangir et al. 2007). The lower values in Pakistan occurred on farms where transplanting was delayed until after the monsoon had started, thus lowering crop water use requirement.

The depth of water in the furrows had a large effect on irrigation amount in both fresh and permanent beds (Table 3). In fresh beds reducing the depth of water in the furrows from full to half at each irrigation reduced irrigation amount by about 25%. In permanent beds the reduction was greater (about 33%), possibly as a result of bypass flow due to the development of cracks and biopores (worm channels, rat holes) on the permanent beds. There is considerable earthworm activity on the permanent beds during the third rice crop (sixth crop) shown in Figure 10. Consistent with this, irrigation amount on permanent beds with a full-furrow depth of water was about 600 mm (20% higher) than on fresh beds.

Irrigation amount in the permanent beds (TRB-2d) with a full-furrow depth of water at each irrigation (block 1 in 2005, blocks 1 and 3b in 2006; Table 3), was similar to or higher than irrigation amount in PTR-CF. Furthermore, with a full-furrow depth, irrigation amount of TRB-2d was 61% and 71% higher than PTR-2d. We suspect that these findings are due to the development of macropores in the non-puddled permanent beds. Reducing the depth of water in the furrows to half at each irrigation reduced irrigation amount by about one-third, to amounts similar to that in PTR-2d; however, this also reduced yield on the permanent beds by about 20% (Kukal et al. 2008).

Soil drying between the last irrigation of rice and pre-irrigation for wheat

The fact that soil water content at the time of wheat sowing was always much less than field capacity (Figures 2a–d) was curious given the expectation of considerable residual soil water after rice, and also that the plots were irrigated just a few days prior to sowing wheat. The neutron probe data show considerable drying of the profile to depth between the last irrigation of rice in 2005 and the pre-sowing irrigation for wheat 39 days later on the sandy loam (Figure 11a). A similar effect was observed on the loam although no data are available for the period shortly prior to the pre-sowing irrigation for wheat, 35 days after the last rice irrigation (Figure 11b). The data are consistent with the increase in soil tension at depth after irrigation of each rice crop ceased (Figures 4a–f). The total water loss from the sandy loam profile between the last irrigation of rice and pre-irrigation for wheat was calculated to be 187 mm. During this period there was no rain, CPE was 136 mm and the rice was harvested 18 days after ponding ceased. ET is likely to have been

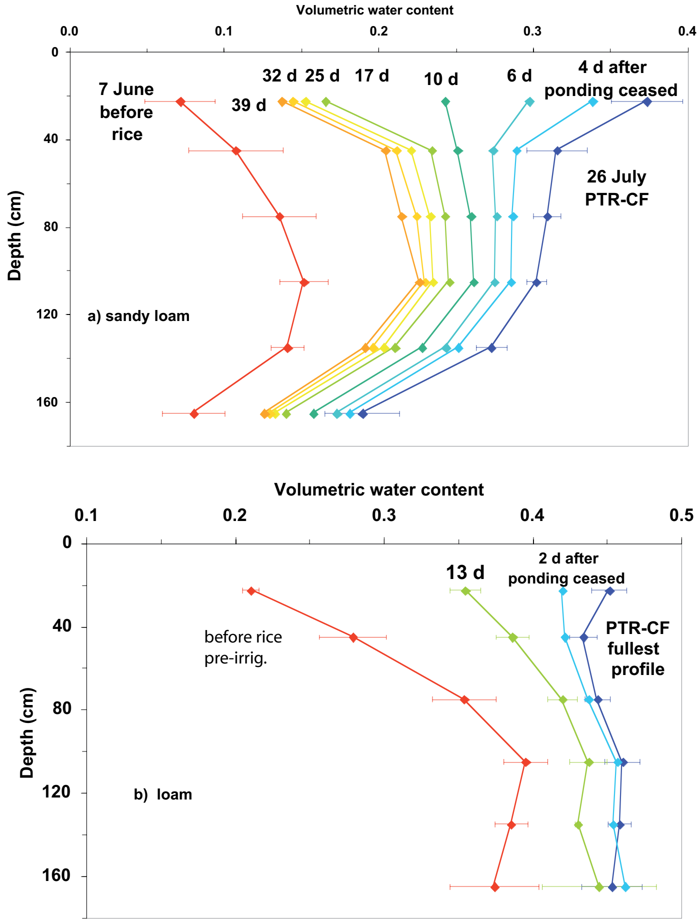
Figure 10. Earthworm castings on permanent beds (sixth crop) on loam soil in small plots during rice 2005

considerably less than CPE given that the field was bare for 21 days and that the topsoil was relatively dry for most of that period. The results therefore suggest that there was significant deep drainage (unsaturated flow) beyond 180 cm during the period between the last irrigation of rice and wheat sowing. The amount of pre-sowing irrigation for wheat was 70–80 mm, well below the amount needed to refill the profile to 180 cm. This is consistent with the observations that the neutron probe data show no wetting of the profile beyond 0.5 m 1 day after the pre-sowing irrigation of wheat on the loam in late 2005 (Figure 12), and that the soil profile was always well below field capacity at the time of wheat sowing (Figures 2a–d).

General discussion

Determining components of the water balance in small plots

The similar total irrigation amounts and crop performance for wheat in the small plots and farmer-field



Figures 11a,b. Dry down of the soil profile between the last irrigation of rice 2005 and pre-irrigation for wheat on: a) sandy loam and b) loam (data are means of four replicates; horizontal bars are standard deviations, shown only for the wettest and driest profiles for simplicity). PTR-CF = puddled transplanted rice with continuous flooding; d = day blocks on the loam suggest that the small plots can be considered to be realistic representations of the average across typical farmers' fields. However, small plots, whether beds or flats, can be irrigated in a few minutes, whereas it usually takes about 2 hours to irrigate conventionally tilled wheat blocks. In Punjab these are typically one-sixth of an acre (667 m^2) irrigation blocks formed by constructing bunds within a 1-acre field after sowing wheat. Thus, Punjabi farmers who adopt this practice already have relatively efficient irrigation management provided the land is reasonably well levelled. The longer irrigation time in farmers' fields increases the opportunity for deep drainage losses. Therefore, small plots would not represent the likely heterogeneity in water distribution and losses in farmers' fields, especially where the irrigation blocks are larger, for example in the very large wheat fields/irrigation blocks (several hectares) of the large landholders in Punjab, Pakistan.

By far the largest components of the water balance during the rice season were irrigation and seepage, in both the small plots and large blocks. However, seepage in the small plots with PTR-CF was disproportionately high in comparison with the large blocks which were more representative of farmers' rice blocks. Tuong et al. (1994) showed the importance of underbund seepage (which drained to the groundwater) in small plots despite plastic lining to 60 cm depth in the centre of the bunds to prevent lateral seepage. The high amount of underbund seepage was attributed to the very high hydraulic conductivity of the bunds. Underbund seepage is also likely to be responsible for the 10–80-fold difference between seepage plus percolation and percolation alone in the studies of Painuli et al. (1988) and Wopereis et al. (1992). Tuong et al. (1994) also pointed out that underbund losses are likely to be more pronounced in small plots because of the higher perimeter:area ratio.

The results suggest that under the free-draining soil and deep watertable conditions of much of north-western India, small plot determination of irrigation water requirement for rice, as affected by water management, is unlikely to be representative of the situation in farmers' fields unless adequate measures are taken to reduce seepage losses to realistic amounts. In the absence of adequate seepage control measures, small plots are likely to overestimate the savings in irrigation water in changing from PTR-CF to alternate wetting and drying, whether on flats or beds. Therefore, our discussions below on the effect of soil and water management on rice irrigation amount are confined to results from large blocks and farmers' fields. Whether lining the bunds with plastic or other measures can achieve realistic seepage losses in small plots has not been demonstrated for the highly permeable soils and deep watertable conditions of Punjab. However, the results of Choudhury et al. (2006) suggest that inserting plastic sheets in the bunds reduced irrigation amounts of PTR-CF to values similar to those in farmers' fields. The propor-

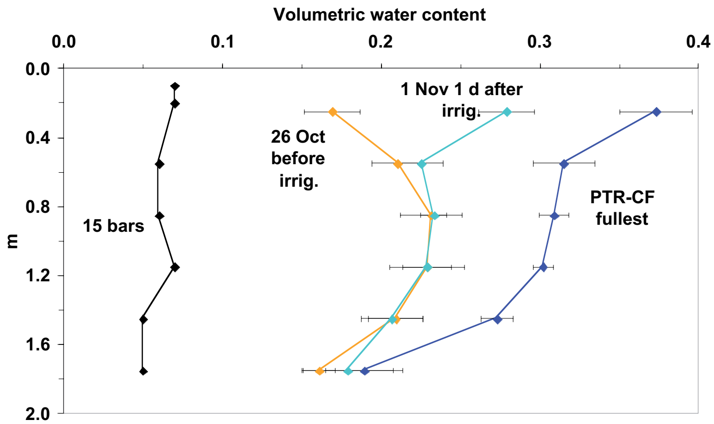


Figure 12. Soil water content before and after pre-sowing irrigation wheat in November 2005 on sandy loam (data are means of four replicates; horizontal bars are standard deviations). PTR-CF = puddled transplanted rice with continuous flooding

tion of seepage from small plots is likely to be influenced by several factors including depth to the watertable, soil permeability and water management outside the plots. Because of seepage, results of determination of infiltration in rice by monitoring the change in water depth in small plots (rather than in infiltration cylinders sealed into the hardpan) are also likely to be overestimated (Tuong et al. 1994).

Effect of soil and irrigation management on rice irrigation amount in large blocks

Irrigation amount in the large blocks was reduced by ~800 mm (37%) in PTR-2d in comparison with PTR-CF, suggesting that deep drainage and seepage were roughly halved through avoiding continuous ponding. Irrigation amount was similar in PTR-2d and permanent and fresh beds with the same irrigation scheduling and a half-furrow depth of water at each irrigation. The results suggest that the saving in irrigation amount had more to do with the method of irrigation than the presence of beds, which is consistent with the findings of Choudhury et al. (2006).

In apparent contrast with our findings, there are several reports of significantly reduced irrigation times (which equate to irrigation water savings) of around 40% in farmer-field comparisons of rice on beds (probably fresh beds) and PTR in India (Balasubramanian et al. 2003; Gupta et al. 2003). Jehangir et al. (2007) also reported average measured irrigation water savings of 15% and 30% for DSRB and TRB, respectively, in nine farmers' fields in Pakistan. Unfortunately there is no information on the farmers' water management in their puddled fields or beds in any of these reports. It is therefore unclear whether any (or how much) of the saving in irrigation water was due to changed irrigation management and how much to the beds per se. Our results suggest, at best, similar irrigation amounts on beds and puddled flats with the same irrigation scheduling/frequency, and a rice yield penalty on permanent beds (Kukal et al. 2008).

Water depth in the furrows had a large effect on irrigation amount in the large blocks, more so in the permanent beds than the fresh beds, probably due to macropore development (e.g. cracks, worm and root channels) and bypass (preferential) flow in the permanent beds. Changing from a full-furrow depth to a half-furrow depth on the permanent beds reduced irrigation amount by 880 mm or 37% compared with a reduction of 421 mm or 24% on the fresh beds. However, reducing furrow depth gave a yield penalty of 10–25% on both the fresh and permanent beds (Kukal et al. 2008).

Our findings of irrigation amount on permanent beds in farmers' fields are preliminary due to limited replication over space and time, and further investigations are needed for a range of soil types, watertable conditions and irrigation management. Our results suggest that growing rice on permanent or fresh beds does not save irrigation water in comparison with the recommended practice of PTR-2d in deep watertable conditions on sandy loam and loam soils in Punjab, and that beds may even use considerably more irrigation water depending on the depth of water applied to the furrows and the age of the beds. This may be due to infiltration in the non-puddled soil being considerably higher than in the puddled soil, and the development of macropores in the permanent beds.

Our results also highlight the importance of providing sufficient contextual detail in reports on comparisons of soil and water management for RW systems. For example, details of the water management (scheduling rules and depth), depth to the watertable, age of beds, plot size and measures to reduce seepage are needed to enable interpretation and extrapolation of the results. This sort of information is normally lacking from reports of irrigation amount on beds and flats in RW systems. Humphreys et al. (2007) provide further examples of the contextual information and measurements needed to undertake rigorous analysis of components of the water balance for RW systems.

Deep drainage and seepage in rice and wheat

It is reasonable to presume that the infiltration rate of 4–6 mm/day in the PTR-CF plots and large blocks is a good approximation of the deep drainage rate between transplanting and the time of the last irrigation, given that the profile was already wetted to depth during the pre-puddling irrigations (Figures 4a–d). This suggests in-field deep drainage (beyond 180 cm) of around 500 mm during this 90–100-day period in addition to seepage losses. Seepage in the large PTR-CF block was also substantial (1,384 mm) despite the fact that this block was surrounded by frequently irrigated, often flooded, rice fields. It is likely that the seepage was both under the bunds and adjacent to the bunds inside the field, and was due to the difficulty of thorough puddling close to the bunds and the fact that the sediment adjacent to the bunds was used to 'plaster' the bunds to seal them, thus destroying the clay 'skin' at the soil surface adjacent to the bund. The clay skin is the most restricting layer to infiltration in these soils (Kukal and Sidhu 2004), and bund plastering is a routine practice. Both the in-field deep drainage and underbund seepage are not losses in this system as they drain to the groundwater which is used for irrigation. Therefore, total deep drainage in PTR-CF in the large blocks was in excess of 2,000 mm. This loss was reduced by almost half by changing to PTR-2d. Regardless of irrigation management, the deep drainage losses were very high, raising the question of the appropriateness of growing rice in this environment.

Deep drainage did not cease when irrigation of the rice ceased. The soil tension data and volumetric soil water profiles between the last irrigation of rice and pre-irrigation for wheat show further drainage during this period (of the order of 100 mm), with an exponential decrease in drainage rate with time after the last irrigation.

Water continued to drain slowly past the bottom of the root zone during the first part of the wheat season, with occasional deep drainage spikes from some irrigations or significant rain, more so at times when the root zone was already wet due to prior irrigation or rain. Both the soil water balance and soil tension data suggest that there was often some deep drainage beyond the root zone (180 cm) in wheat associated with the pre-sowing irrigation (when there was still some residual soil water after rice) on both soils. The data also suggested that in some situations (e.g. in 2003–04 and 2005–06 on the sandy loam) there may be no deep drainage from wheat. Overall, the amount of drainage during the wheat season was small compared with rice (–24 mm to <87 mm except in 2002–03 when there was over 90 mm of rain in a single event, followed by overirrigation). During the period between wheat harvest and the first irrigation for rice, there was no evidence of deep drainage; rather, there was net drying of the soil profile in the upper layers due to evaporation.

Effect of soil management on wheat irrigation and total water use

In our experiments there was no consistent trend for higher or lower water input for beds or flats on either soil in either the small plots or the large blocks. The lack of a clear trend in our studies is expected because we based irrigations on IW/(CPE-rain) and used the same ratio for beds and flats. Therefore, on average, a similar amount of water was applied to beds and flats. Our results are in contrast with many findings in the literature in both small plots and farmers' fields (Singh et al. 2002; Aggarwal and Goswami 2003; Balasubramanian et al. 2003; Sharma et al. 2004; Choudhury et al. 2006; Kahlown et al. 2006; Bhushan et al. 2007; Jat et al. 2008; Jehangir et al. 2007; Lauren et al. 2008). In general, the reported irrigation water savings for wheat on beds seem to be larger in farmers' fields (45–54% in Haryana, Singh et al. 2002; 34% mean of 71 fields in Pakistan, Kahlown et al. 2006) than in small plot studies (0–33%). However, Jehangir et al. (2007) found average irrigation water savings of 14–20% in nine farmers' fields in Pakistan. A possible explanation for larger savings in farmers' fields is the longer irrigation time, especially where levelling is poor or flow rates are low, leading to greater opportunity for deep drainage losses. In many of the small plot studies the beds and flats were always irrigated on the same day, with less water applied to the beds because it takes less water to fill the furrows than to flood the flat plots. None of those studies compare what would have happened if the same irrigation amount applied to the beds had also been applied to CTW. In the studies in farmers' fields, irrigation management is not known. In practical terms the lowest application rate that can be applied and provide full coverage of a 'flat' field will depend on how well the field has been levelled and on the flow rate. Laser levelling in Punjab, Pakistan, resulted in average wheat irrigation water savings of 21% in comparison with non-lasered fields (Kahlown et al. 2006). In Punjab, India, irrigation block size is relatively small (e.g. 0.25 acres) and lower application rates similar to those applied to beds may be feasible given good levelling.

Any savings in irrigation amount with beds are likely to be due to reduced deep drainage to the groundwater. Where groundwater can be used for irrigation, this is not a water saving but it is a highly beneficial saving of both energy and cost due to reduced pumping (Ahmad et al. 2007).

More comprehensive experiments are needed in farmers' fields to rigorously test the hypothesis of lower irrigation requirement on beds, as well as studies to determine the optimum irrigation scheduling for wheat on beds. Such studies should include determination of soil water depletion in the root zone between sowing (or pre-irrigation) and harvest, evidence of whether or not there is significant deep drainage beyond the root zone, and estimates of total crop water use (ET) in addition to irrigation and rainfall. It is only by doing a complete water balance that conclusions can be drawn about the magnitude and types of water savings on beds in comparison with flats.

Water depletion as ET

Whether beds actually save water (i.e. reduce ET) in RW systems has been little studied. Beds may actually increase non-beneficial soil evaporation because of increased surface area and reduced shading due to uneven row spacing, especially earlier during the crop growth cycle (Humphreys et al. 2004; Choudhury et al. 2006; Kukal et al. 2008). Choudhury et al. (2006) determined ET of wheat on beds from periodic measures of soil water depletion. They found ~15% reduction in ET on the beds; however, crop growth and leaf area index (LAI) (and yield) on the beds were significantly lower than on the flats with regular 20-cm row spacing, and some or all of the reduction in ET would have been due to the reduced LAI.

Conclusions

Our studies show that seepage losses from continuously flooded rice in unlined small plots on free-draining soils with deep watertables can be disproportionately large in comparison with those in farmers' fields. This leads to overestimation of the potential saving in irrigation water by changing to intermittent flooding. Therefore, results of water balance studies for rice in small plots should be interpreted with caution. Nonetheless, seepage was also the major component of the water balance in the large blocks on loam soil. Total deep drainage (in-field and via seepage) from rice in the large block was 2,120 mm (91% of the irrigation input) in PTR-CF. Switching from PTR-CF to frequent alternate wetting and drying (PTR-2d) in the large block reduced irrigation amount by over one-third (~800 mm). A similar reduction was achieved with transplanted rice on fresh or permanent beds with the same irrigation scheduling as PTR-2d, with half-filled furrows. The results suggest that the reduction in irrigation amount in switching to rice on beds had more to do with the change in irrigation management rather than the beds per se. Depth of water in the furrows had a large effect on rice irrigation amount on both fresh and permanent beds. With a full furrow, irrigation amount of TRB-2d exceeded that of PTR-2d, probably because of higher permeability of soil in the unpuddled furrows and greater macropore development on the permanent beds.

Total irrigation application to wheat was not affected by layout, due to the fact that the same irrigation scheduling rule (based on the ratio of irrigation amount to cumulative pan evaporation) was used for both beds and flats. Deep drainage from wheat was relatively small (sometimes negligible and usually less than 100 mm) in comparison with rice (up to ~2,000 mm) in both flat and bed layouts.

Our findings on irrigation amount on permanent beds in farmers' fields in Punjab are preliminary and further investigations are needed for a range of soil types, watertable conditions and irrigation management. The findings also highlight the importance of providing sufficient contextual detail in reports on comparisons of soil and water management for RW systems to enable interpretation and extrapolation of the results.

Acknowledgments

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Yield and N use efficiency of permanent bed rice–wheat systems in north-western India: effect of N fertilisation, mulching and crop establishment method

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Abstract

Rice–wheat (RW) is the dominant cropping system in north-western India and is of immense importance for national food security. However, the sustainability of the RW system is threatened by water shortage and nutrient mining. Permanent bed RW systems with crop residue retention have been proposed as a means of reducing irrigation water use, improving soil properties and reducing the cost of crop establishment. A field experiment was conducted over 4 years in Punjab, India, 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 four N application rates (0, 80, 120, 160 kg N/ha).

Rice grain yield increased significantly as N rate increased up to 160 kg N/ha irrespective of method of rice establishment. Puddled transplanted rice (PTR) was always superior to all other establishment methods in terms of biomass, yield and NUE. 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, but 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 but 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 14% for TRB and 17% for DSRB. The majority (65–83%) of the crop N uptake 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 conventionally 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 (DDW) on the flat. 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 (27–38%) and soil (45–59%) were much higher than in rice. Total fertiliser N losses were

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much lower in wheat (mean 14–21%) compared with rice (mean 38–60%). After eight 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 permanent raised beds should focus on selection of rice and wheat cultivars that are better suited to beds; soil health issues such as nematodes and iron deficiency; weed control; N, water and residue management; and machinery development and practices.

Introduction

Rice and wheat are the two main staple food crops grown in annual rotation on about 14 million hectares (Mha) in the Indo-Gangetic Plain (IGP) of South Asia (Timsina and Connor 2001). With the dominance of the rice–wheat (RW) system, the area under crops with lower water requirements has decreased drastically, resulting in overexploitation of groundwater resources in many parts of the IGP (Humphreys et al. 2005). The worsening situation can only be reverted if water is managed more efficiently and judiciously. In many parts of the IGP farmers burn crop residues, particularly rice straw, because the residues left after combine harvesting interfere with tillage and seeding operations for the next crop. Concern about environmental pollution and nutrient losses from burning has motivated the study of alternative tillage and straw management practices. Recently, Sidhu et al. (2007) reported that yields of wheat sown into rice residues using the 'Happy Seeder' were always comparable to or higher than yields with conventional sowing. The mulch also reduced soil evaporation. Rahman et al. (2005) also obtained higher wheat yields with rice straw mulching compared with no mulch under limited water supply conditions. Liu et al. (2003) reported that wheat straw mulching decreased or maintained rice yields in China.

Soils in the IGP are generally low in organic matter, and N fertilisers have contributed substantially to increasing crop yields. Fertiliser N recovery in both rice and wheat is, however, very low and a substantial amount of applied N is lost from the soil–plant system (Yadvinder-Singh et al. 2007). Inefficient N use contributes to greater use of energy resources, increased production costs and pollution of groundwater by nitrates (Bijay-Singh and Yadvinder-Singh 2004).

One of the proposed innovations to improve the productivity of the RW system and reduce water requirement is the use of permanent raised beds (Connor et al. 2003; Hobbs and Gupta 2003). Traditional land preparation for both wheat and rice consists of five to seven cultivations followed by levelling with a heavy wooden plank, resulting in high energy use which may also delay wheat sowing. The use of a permanent raised-bed system would reduce production costs for tillage, allow more timely sowing and reduce irrigation water requirement. Limon-Ortega et al. (2000) reported that a combination of permanent beds and straw mulch produced higher yields of maize and wheat than other practices in high-yielding environments in the Yaqui Valley in Mexico.

Traditionally, rice is transplanted into puddled soil and farmers try to maintain ponded water on the surface throughout the cropping season. Rice requires more water than other crops because of the continuous seepage and percolation flows induced by the ponding of water, and relatively high evaporation rates (Tuong et al. 2005). In recent years direct seeding (dry or wet) has been promoted as a replacement for transplanting to address the problems of labour scarcity and high water demand. The water saving feature of direct seeding is largely attributed to the change in conventional land preparation practices for transplanted rice (Cabangon et al. 2002; Tuong et al. 2000). Ali et al. (2005) reported that crop establishment method did not influence rice yield and nitrogen use efficiency (NUE), but direct-seeded rice required less water and therefore had higher water use efficiency than transplanted rice. Dry seeding, either on beds or on flat surfaces, may require a different N management strategy than transplanted rice because of the changed water dynamics and establishment method and their interactions with N dynamics.

In high-residue zero-till farming systems, efficient N fertiliser management remains a challenge because of slower N mineralisation (Philips et al. 1980), greater N immobilisation (Rice and Smith 1984), and higher denitrification and ammonia volatilisation losses (Yadvinder-Singh and Ladha 2004). A change from traditional rice and wheat cultivation to permanent beds and straw mulching is likely to exert large influences on N availability and N cycling. Straw retention can lead to temporary nutrient deficiency due to microbial immobilisation (Yadvinder-Singh et al. 2005). In China, Fan et al. (2005) showed that wheat straw mulching under non-flooded conditions decreased rice yield by 16% compared with traditional flooding with lower N inputs, but yields were comparable to those under traditional flooding cultivation at higher N inputs (>150 kg N/ha).

The objectives of the study presented here were: (i) to study the response of rice and wheat to different N levels, (ii) to study the effect of straw mulch on yield and N use efficiency of rice and wheat on permanent beds and (iii) to evaluate methods of rice establishment (direct seeded, transplanted) in a permanent bed RW system.

Materials and methods

Site details

The experiment was conducted for 4 years from rice 2002 to wheat 2005–06 at the research station of Punjab Agricultural University at Ludhiana (30°56'N, 75°52'E, 247 m above sea level) in north-western India. The climate of the region is subtropical and semi-arid. Average annual rainfall is about 700 mm, of which about 80% falls from June to September and about 100 mm during the wheat season (November–April). The mean daily minimum and maximum temperatures during the rice season (July–October) are 18 °C and 35 °C, respectively, compared with 6.7 °C and 22.6 °C during the wheat season. The soil (0–15 cm) of the experimental field was a sandy loam and contained 4.9 g/kg organic C, 0.04% total N, 6.2 mg P/kg (Olsen P) and 45 mg/kg NH_4OAc-exchangeable K.

Experimental design and treatments

The experiment comprised two crops in annual rotation—rice as a summer crop and wheat as a winter crop, and was designed as a randomised complete block with three replicates, commencing with rice in 2002. The main plots consisted of six layout or crop establishment straw treatments:

1. **PTR/CTW**—puddled transplanted rice with all straw removed followed by conventionally tilled wheat with all straw removed
2. **DSRF/DDW**—dry-seeded rice on cultivated flats with all straw removed followed by direct-drilled (‘zero-till’) wheat with all straw removed
3. **TRB/WB**—transplanted rice on permanent beds with all straw removed followed by direct-drilled wheat on permanent beds with all straw removed
4. **TRB/WB+M**—transplanted rice on permanent beds with wheat straw (5 t/ha) as surface mulch followed by direct-drilled wheat on permanent beds with rice straw (6 t/ha) as mulch
5. **DSRB/WB**—direct/dry-seeded rice on permanent beds with all straw removed followed by direct-drilled wheat on permanent beds with all straw removed
6. **DSRB/WB+M**—transplanted rice on permanent beds with wheat straw (5 t/ha) as surface mulch followed by direct-drilled wheat on permanent beds with rice straw (6 t/ha) as mulch.

Subplot treatments for both rice and wheat consisted of four N fertiliser rates (0, 80, 120 and 160 kg N/ha) applied as urea in a split plot design. Subplot size was 2.68 × 10 m (i.e. four beds per subplot).

Wheat and rice straw harvested from the actual plot were cut into 25–30-cm-long pieces (similar to the length after sowing with the Combo Happy Seeder) and used for mulching. The raised beds were prepared mechanically by a bed planter, and were 37 cm wide separated by furrows 30 cm wide and 25 cm deep.

Microplots (1.2 × 0.8 m for flat and 1.5 × 0.67 m for beds) were installed for ^{15}N studies in the 120 kg N/ha subplots (Figure 1). ^{15}N labelled urea (~5 at.% ^{15}N) was applied at 120 kg N/ha at the same time and method as the surrounding subplot. Soil and plant sampling in the microplots was done at physiological maturity.

Crop management

After removal of the wheat straw at harvest in mid April, the fields were fallowed until pre-irrigation for rice in early June. Transplanting of rice (cultivar PR 116 in 2002 to 2004 and PR 118 in 2005) on flats and beds took place about 7–10 days after direct seeding. For dry seeding, the seeds (50 kg/ha) were soaked overnight in water then partially air-dried in the shade. The DSRF was sown in 20-cm-wide rows, after conventional tillage, by hand placement of seed in a furrow made using a hand plough. DSRB was sown by hand in a similar manner with a row spacing of about 25 cm, but the beds were not cultivated prior to sowing. TRB was established by manually transplanting 30–35-day-old rice seedlings in two rows spaced at 25 cm with 10 cm between the plants

(30 hills/m^2) on the beds, compared with a spacing of 20 cm x 15 cm (33.3 hills/m^2) in PTR. In the second and subsequent years the beds were reshaped after pre-irrigation, prior to sowing, with minimal disturbance of the beds. A small tine was used to create a loosened soil slot to facilitate transplanting in TRB.

All treatments received 13 kg P/ha, 25 kg K/ha and 15 kg Zn/ha (as single superphosphate, muriate of potash and $ZnSO_4$) broadcast prior to sowing and bed formation/renovation or pre-puddling irrigation. In transplanted rice half of the N as urea was broadcast prior to the pre-puddling irrigation or bed preparation in the first year, and prior to bed reshaping in subsequent years, and the remainder was topdressed 21 and 42 days after transplanting. In DSRB one-quarter of the N was applied before sowing / bed preparation / reshaping and the remainder was applied in three splits 21, 42 and 63 days after sowing (DAS). During rice 2004 soil solarisation of the plots was done to control nematodes by applying a heavy irrigation on 14 May, then covering the plots with a plastic sheet from 15 May until 5 June. Weeds were controlled in PTR using butachlor (a.i. 1,500 mL/ha) 2 days after transplanting. Sofit (pretilachlor + safener, a.i. 470 mL/ha) was applied to DSRB 5–6 DAS. Weed infestation on the permanent beds was very severe every year, especially in DSRB, and several hand weedings were required. Iron deficiency was observed in DSRF/DSRB and two to four sprayings of 1% ferrous sulfate were applied at weekly intervals after emergence. The crop was irrigated daily for the first 2 weeks after planting to assist weed control. It was further irrigated 2 days after the free water had disappeared from the surface of the flat plots or furrows and topped up to about 10 cm depth on the flats and in the furrows. Irrigation water was sourced from a canal or tube-well depending on the availability of canal water. Rice straw was removed from all plots before sowing wheat.

After rice harvest each year, wheat was sown during 10–18 November following conventional tillage on the flats after PTR (CTW) and by direct drilling on all the beds and flats after DSRF. The field was irrigated 5–7 days prior to cultivation or sowing. In the flat plots the land was cultivated four times (with a disc plough then tine harrow), followed by planking. The flat plots were sown with a tractor-driven combine seed drill (CTW) or zero-till drill (DDW) with 20-cm row spacing, while the beds were sown with a bed planter at 20-cm row spacing. The beds were reshaped each year after the pre-sowing irrigation using the bed planter, with little soil disturbance in the beds. Wheat (variety PBW 343) was sown (100 kg seed/ha on flats and 75 kg seed/ha on beds) in rows 20 cm apart at a depth of about 5–6 cm. Two rows of wheat were planted on top of each bed with 20 cm between the rows. After seeding, a light plank was dragged over the flat plots to cover the seed.

All treatments received 26 kg P/ha and 50 kg K/ha (as single superphosphate and muriate of potash)

Figure 1. Microplot for nitrogen balance study in transplanted rice on beds with mulch (June 2003)

broadcast prior to bed formation/renovation or the last tillage on the flats. Nitrogen as urea was applied in two equal splits—the first half at sowing along with the P and K, and the other half as topdressing on the bed surface between the rows, broadcast in the flat plots prior to the first irrigation after sowing. When rainfall was insufficient, all plots were irrigated on the same days around the critical growth stages for wheat—at crown root initiation (2–3 weeks after sowing), maximum tillering (7–8 weeks after sowing), flowering (13–14 weeks after sowing) and soft dough (17–18 weeks after sowing). The total number of post-sowing irrigations in wheat varied from three to four across years. Weeds were well controlled by spraying sulfosulfuron (a.i. 32.5 g/ha) within 1 week after the first post-sowing irrigation.

Crop growth, yield and N uptake

Dry matter yield of rice and wheat was determined by cutting two adjacent rows of 1-m length at the soil surface around 45 DAS and at anthesis. Grain and straw yields were determined by manually harvesting an area of 13.4 m^2 in the middle of each subplot at maturity. Grain yield of rice is presented at 140 g/kg water content, while wheat grain yield and straw yield of both crops are on a dry weight basis. Plant and grain samples were analysed for total N by a micro-Kjeldahl method (Bremner and Mulvaney 1982).

Soil analyses

After three and four cycles of the RW rotation, soil organic C, Olsen P and exchangeable K were determined from the surface layer (0–15 cm depth) using standard methods (Sparks et al. 1996).

Soil temperature

Soil temperature at 5 cm depth was measured in beds with and without straw mulch during the initial 20–30 DAS of both rice and wheat. Measurements were made using a mercury-in-glass thermometer installed in each plot at 9 am (‘minimum’ soil temperature) and 3 pm (‘maximum’ soil temperature).

Nematode infestation in rice

Rice plant roots from one hill in each plot were excavated with a hand shovel from 0–25 cm depth at 4 weeks after planting. Roots were washed in water and any roots infested with root knot nematodes were observed with the naked eye. Roots infested with root knot nematode were given a score from 0 (no roots infested) to 10 (all roots infested).

Soil and plant sampling and analysis of microplots

At crop maturity all the rice and wheat plants were harvested from each microplot, dried in a hot-air oven at 65 °C for 3 days, and grain and straw yield were determined. Soil samples were collected to 75 cm depth at increments of 0–15, 15–30, 30–45 and 45–75 cm using a 5-cm-diameter auger. Each sample was a composite from three locations between the two crop rows within a microplot. The soil samples were mixed thoroughly, air-dried, crushed to pass through a 2-mm sieve and stored in sealed plastic jars. Soil and plant samples were sent to the International Atomic Energy Agency (IAEA) for ^{15}N and total N analysis to calculate the N recovery in the soil, grain and straw.

Data analysis

All data were subjected to statistical analysis using IRRISTAT version 5.0 and the means were tested by the least significant difference (LSD) at 5% level of significance. Data for nematode infestation in rice, ^{15}N analysis of soil, and plant samples and soil fertility parameters were analysed using Duncan’s Multiple Range Test.

Results and discussion

This paper summarises the results of 4 years of detailed experiments, presenting selected results to illustrate the main findings.

Soil temperature

Soil temperature in the beds planted to rice in 2005 fluctuated from about 27 °C to 37 °C during the first 3 weeks after sowing/transplanting. Minimum soil temperature was consistently about 1.0 °C higher with mulching compared with no mulching, while maximum temperature was about 1.0 °C lower with mulching (Figure 2a). These differences persisted until 26 days after planting and then gradually declined with time. The decline was probably due to the fact that the mulch gradually moved from the tops of the beds into the furrows as a result of irrigation and manual weeding and growth of the plant canopy.

Similar observations of the effect of mulch on soil temperature were found in rice during the other 3 years (data not shown).

During wheat 2005–06 soil temperature in the beds initially fluctuated between about 14 °C and 24 °C, but both maximum and minimum temperature declined with time. As with rice, maximum soil temperature was consistently lower (on average by 1.5 °C) under mulch compared with no mulch during the initial 30 DAS, while minimum soil temperature was about 1 °C higher under mulch (Figure 2b).

The results in both rice and wheat are consistent with the fact that mulch suppresses maximum soil temperature by shielding the soil surface from solar radiation, and increases minimum soil temperature by suppressing heat loss from the soil when the air temperature is cooler than the soil temperature. Sidhu et al. (2007) found that daily mean temperature during the first week after sowing of wheat was about 2 °C lower under mulch than without mulch, and suggested that mulching in the environment of Punjab, India, may retard germination and emergence of

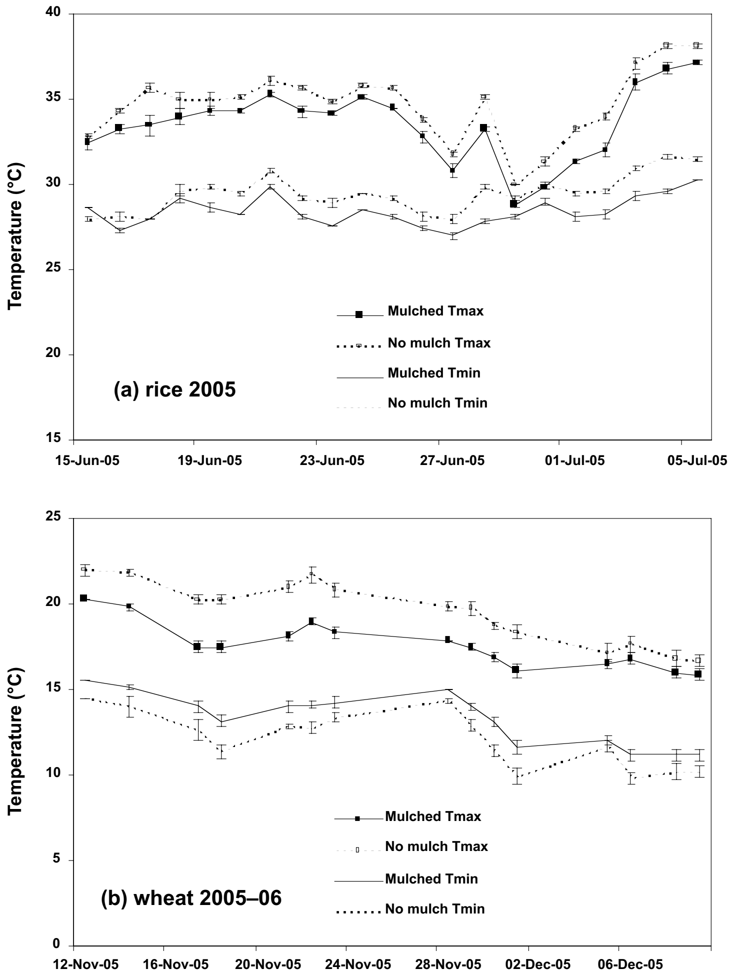

Figure 2. Maximum and minimum soil temperatures as influenced by straw mulch in: (a) rice (2005) and (b) wheat (2005–06) on permanent beds (vertical bars are standard error)

wheat due to suppression of soil temperature, but that the effect is likely to be small. The effect of mulching on temperature for rice establishment is likely to be very small because at the time of sowing the prevailing soil temperature in Punjab is within the optimum range (around 30 °C; Roberts 1962; Vorob'ev 1974).

Biomass accumulation

Rice

Biomass in PTR was greater than in all other treatments within the same N rate on all sampling dates in all four seasons. The differences were usually significant. For example, at anthesis in 2003, biomass with 120 kg N/ha was 8.7 t/ha for PTR compared with 5.8–7.1 t/ha for TRB and 1.0–6.4 t/ha for DSRB (Table 1). Transplanting was always superior to direct seeding on both beds and flats (Figure 3). In 2003 and 2005 early growth was reduced by mulching in both DSRB and TRB but the effect was much greater with DSRB. The effect on biomass was still apparent at anthesis in 2003.

Nematode infestation in rice

Nematode infestation was detected in all treatments in 2003 and was higher with mulching and with direct seeding, compounding in the mulched DSRB (Table 2). Thus, the cause of poor growth in the presence of mulch appears to be at least partly associated with increased nematode infestation as a result of mulching. Nitrogen rate did not affect root nematode infestation. On a sandy loam at Delhi, Singh et al. (2002) reported large root knot nematode populations in rice on both beds (DSRB) and flats (DSRF), which led to root galling that was twice as

Table 1. Effect of method of crop establishment, wheat straw mulch and N rate on dry matter yield (g/m^2) of rice at anthesis during 2003

Treatment (rice/wheat)	Fertiliser N rate (kg/ha)			
	0	80	120	160
PTR/CTW	409	761	870	912
DSRF/DDW	274	513	487	627
TRB/WB	390	617	711	889
TRB/WB+M	275	450	582	801
DSRB/WB	356	543	641	764
DSRB/WB+M	75	98	104	129
LSD 0.05 (Main × N rate interaction)	93.8			

Note: Date of sampling for transplanted rice—3 September 2003, and for dry-seeded rice—24 September 2003

Figure 3. Transplanted rice on permanent beds (TRB, foreground) and direct-seeded rice on beds (DSRB, background), both treatments with wheat straw mulch, in July 2005

severe as in continuously flooded PTR. Why mulching and direct seeding were more conducive for nematode infestation is unclear. In 2002 and 2004 there was no effect of mulching on biomass at any sampling time (data not shown). It appears that the nematode problem developed in 2003 but was reasonably well controlled by soil solarisation prior to rice establishment in 2004. However, no solarisation or fumigation was applied prior to establishment of rice in 2005.

Wheat

Dry matter production at 58 DAS (maximum tillering stage) in 2003–04 was similar under the different methods of crop establishment, except in wheat sown after TRB in the absence of N fertiliser (Table 3). The rate of dry matter accumulation between 58 and 93 DAS was very fast, and dry matter yield at 93 DAS was about 10–11 times that at 58 DAS. By the time of anthesis, biomass accumulation in CTW was significantly higher than on the beds in both the 0 and 120 kg N/ha treatments each year (e.g. 2003–04 wheat in Table 3). There was no significant residual effect of method of rice establishment on the beds on biomass at anthesis or maturity.

Grain yield

Rice

Method of crop establishment had a marked influence on grain yield of rice in all seasons (Table 4). In all 4 years higher yields were obtained on flats than on beds, with PTR significantly outyielding all other treatments within each N rate. In 3 of the 4 years there was usually a significant response to increasing N rate up to 160 kg N/ha in all treatments. This suggests that the recommended rate (120 kg N/ha) may be too low for maximising rice yield. Mean yield of PTR at 160 kg N/ha over the 4 years was 7.01 t/ha. At the same rate the mean yield of DSRB was 37–52% lower than that of PTR and 14–37% lower than that of TRB. The mean yield of DSRF was 36%

Table 2. Effect of method of rice establishment, wheat straw mulch and N application on nematode infection in rice 2003

Crop establishment (rice/wheat)	Nitrogen rate (kg/ha)				Mean
	0	80	120	160	
PTR/CTW	0.6	0.9	0.6	0.5	0.7
DSRF/DDW	2.9	3.6	2.9	1.7	2.8
TRB/WB	0.5	0.9	0.6	0.9	0.7
TRB/WB+ M	3.9	2.1	2.6	2.4	2.8
DSRB/WB	2.7	1.7	2.4	4.2	2.8
DSRB/WB+ M	6.1	4.7	4.5	3.1	4.6
Mean	2.8	2.3	2.3	2.1	
LSD (0.05)	Main: 1.45; N rate: NS; Interaction: NS				

Note: 0 = no roots infected, 10 = all roots infected

Table 3. Effect of method of rice establishment, rice straw mulch and N application on dry matter (g/m^2) of wheat 2003–04 at 58 and 93 days after sowing

Treatment (rice/wheat)	58 DAS		93 DAS	
	Nitrogen rate (kg/ha)			
	0	120	0	120
PTR/CTW	24.4	46.7	278	528
DSRF/DDW	24.5	42.1	305	547
TRB/WB	34.2	43.1	205	401
TRB/WB+M	32.0	43.1	215	427
DSRB/WB	20.8	39.6	202	428
DSRB/WB+M	23.8	43.6	227	470
LSD 0.05 (main treatment × N rate)	6.9		41.6	

DAS = days after sowing

lower than that of PTR. In contrast, Kundu et al. (1993) and Kim et al. (2001) reported similar yields of DSRF and PTR. Qureshi et al. (2006) and Cabangon et al. (2002) reported lower yields of DSRF compared to PTR, in Pakistan and Malaysia respectively, but irrigation water productivity of direct-seeded rice was 21% more than with PTR. They concluded that more effort is needed to develop techniques to control infestation of weeds to increase rice yields under dry seeding.

Application of wheat straw mulch in DSRB caused significant reduction in grain yield compared with no mulching in all years except 2004, presumably as a result of the pre-planting soil solarisation in 2004. The size of the yield reduction in DSRB generally increased with N rate. There was no effect of mulching on grain yield of TRB in any year.

The lower yield of direct-seeded rice on flats and permanent beds compared with PTR and TRB, respectively, was probably due to severe iron deficiency, nematode infestation and weed growth. Possible reasons for the yield differences between TRB and PTR include differences in plant spacing, water availability, the soil physical environment and nutrient availability as a result of differences in redox potential. Choudhury et al. (2007) reported that loss in yield of direct-seeded rice on both flats and beds in comparison with flooded transplanted rice was not caused by differences in water regime. They found similar yields of direct-seeded rice on beds and flats with a similar spacing under non-flooded conditions on a loam soil.

Yield of DSRB declined relative to PTR over the 4 years in the absence of mulch but not in the presence of mulch (Figure 4). Kukal et al. (2008) also found that yield of both DSRB and TRB declined as the beds aged. However, in the present study the relative yields of TRB were fairly constant during the first 3 years, followed by a sharp decline in the fourth year in both the mulched and unmulched treatments, which coincided with changing variety. It

Table 4. Effect of crop establishment, straw mulch and N application on grain yield (t/ha) of rice during 4 years

Crop establishment treatment		N rate (kg/ha)	2002	2003	2004	2005	Mean
Rice	Wheat						
PTR	CTW	0	3.73	3.68	3.03	3.46	3.48
		80	6.03	5.48	5.34	4.98	5.46
		120	7.07	6.36	6.26	5.91	6.40
		160	7.57	6.63	7.05	6.79	7.01
DSRF	DDW	0	2.83	2.72	1.27	1.19	2.00
		80	4.10	3.67	2.39	2.21	3.09
		120	5.20	5.04	3.13	2.46	3.96
		160	5.60	5.50	3.63	3.27	4.50
TRB	WB	0	3.00	3.17	2.82	2.16	2.79
		80	3.87	4.14	4.03	2.94	3.75
		120	4.70	4.86	4.69	3.36	4.40
		160	5.70	5.78	5.32	3.67	5.12
TRB+M	WB+M	0	2.40	2.84	2.98	2.16	2.60
		80	4.20	4.10	3.95	2.98	3.81
		120	5.40	4.66	4.77	3.32	4.54
		160	6.07	5.86	5.53	3.87	5.33
DSRB	WB	0	2.87	1.09	1.61	1.12	1.67
		80	3.83	2.70	2.77	1.91	2.80
		120	4.97	3.47	3.51	2.36	3.58
		160	5.50	4.80	4.06	3.27	4.41
DSRB+M	WB+M	0	1.77	0.67	1.54	0.79	1.19
		80	2.80	1.00	2.79	1.21	1.95
		120	3.77	1.76	3.42	1.66	2.65
		160	4.63	2.65	4.17	2.02	3.37
LSD (0.05) Tmt × N rate			0.37	0.56	0. 56	0.79	–

is not known whether the decline in the fourth year is due to PR118 being less suited to beds or a combination of factors. In another experiment on a loam soil in the same year PR118 yielded well on fresh beds (Kukal et al. 2008). Grain yield of DSRB in the fourth year was 41–52% of that in the third year, while the decrease in yield of PTR from year 3 to year 4 was much smaller (about 10%). Singh et al. (2005) also reported a yield gap between rice on beds and PTR that increased with time over 3 years, and with a larger yield gap for DSRB than TRB. Jat et al. (2008) showed a yield gap of 24% for DSRB compared with PTR in the eighth rice crop on permanent beds. It is important to select varieties for beds capable of filling the furrow gap quickly to maximise radiation interception, and which are efficient users of soil P and Fe under the more aerobic conditions that occur on beds.

Wheat

Yields of wheat were less affected by layout than yields of rice but were highly responsive to N rate (Table 5, Figure 5). Wheat grain yield during 2002–03 was lower on beds than on flats, probably due to poor crop establishment as a result of improper depth of sowing of seed on beds. In other years similar yields were obtained on flats and permanent beds at the same N rate, which is consistent with the findings of others (Hobbs and Gupta 2004; Kukal et al. 2005; Ram et al. 2005). Wheat grain yield increased significantly with N rate up to 120 kg N/ha irrespective of establishment method. Nitrogen application at 120 kg N/ha produced about 105–185% higher wheat yield compared to the no N control. This demonstrates the importance of the recommended N rate of 120–kg N/ha for CTW wheat in this region (Yadvinder-Singh and Bijay-Singh 2001). The yields were, however, higher at 160 kg N/ha than 120 kg N/ha in 2 out of 4 years, suggesting that a higher N rate is desirable to maximise yields in all years. Nitrogen application at 160 kg N/ha produced about 5–14% higher mean wheat yield compared to the recommended rate of 120 kg N/ha. There was a trend for lower yield with mulching at low N rates in the first, second and fourth wheat crops, with significant differences in the first 2 years when yields were low due to unusually low radiation prior to heading. The mean reduction in wheat yield with mulching was about 27% in the no N control treatment.

In the same region Gangwar et al. (2006) reported lower yields of zero-till wheat than conventionally tilled wheat due to lower soil moisture, lack of seed cover, seed damage by birds and soil compactness. They reported highest wheat yields with reduced tillage and rice straw incorporation followed by burning and removal of straw prior to sowing. In contrast, Azam et al. (1990) observed that straw incorporation significantly reduced grain yield and ^{15}N uptake by wheat. Grain yield of wheat on permanent beds in our study showed no decreasing trend relative to conventional tillage over the 4 years (Figure 6). Grain yield of wheat was lowest during 2004–05,

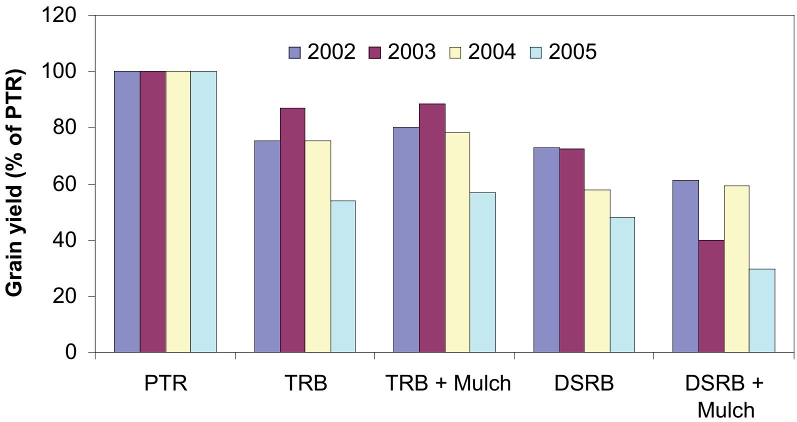

Figure 4. Relative rice yields over 4 years at 120 kg N/ha. PTR = puddled transplanted rice, TRB = transplanted rice on permanent beds, DSRB = direct-seeded rice on permanent beds

perhaps due to soil water deficit as a result of too long a delay prior to irrigation(s). The data suggest that wheat can be produced on permanent beds in a RW rotation without any loss in wheat yield, but that rice yield is reduced with current technology.

Fertiliser N recovery

Apparent N recovery

Mean recovery efficiency (RE) of applied N (calculated from the difference in N uptake between the fertilised and control treatments as a percentage of the amount applied) was significantly higher (50.3%) in PTR than in all other treatments (31.7–40.4%) (Table 6). Recovery efficiency was similar in transplanted and direct-seeded rice on both flats and beds. Application of straw mulch significantly reduced RE compared with no mulch. The low RE on permanent beds suggests the need to develop better methods for N application to rice on beds.

Recovery efficiency of wheat was higher than for rice and ranged from 55.2% in WB after TRB to 67.5% in CTW after PTR (Table 6). These data suggest higher losses of applied N in rice than in wheat. Recovery efficiency was significantly higher in CTW than in wheat on permanent beds. In contrast with rice, application of rice straw mulch caused a significant increase in RE in wheat on permanent beds.

Table 5. Effect of crop establishment, straw mulch and N application on grain yield (t/ha) of wheat during 4 years

Crop establishment treatment		N rate (kg/ha)	2002–03	2003–04	2004–05	2005–06	Mean
Rice	Wheat						
PTR	CTW	0	1.88	2.14	1.58	2.05	1.91
		80	3.66	3.65	3.17	4.53	3.75
		120	4.65	4.16	3.90	4.87	4.40
		160	4.46	4.96	4.11	4.98	4.63
DSRF	DDW	0	1.74	2.21	1.17	1.51	1.66
		80	3.83	3.72	2.87	4.24	3.67
		120	4.58	4.30	3.51	4.67	4.27
		160	4.56	4.91	3.75	4.78	4.50
TRB	WB	0	1.89	2.06	1.62	2.02	1.90
		80	3.34	3.53	3.12	4.16	3.54
		120	3.65	4.05	3.42	4.57	3.92
		160	3.82	4.64	3.59	4.75	4.20
TRB+M	WB+M	0	1.03	1.55	1.42	1.51	1.38
		80	3.05	3.26	3.08	4.16	3.39
		120	3.61	3.79	3.59	4.64	3.91
		160	4.06	4.76	3.84	5.11	4.44
DSRB	WB	0	1.64	2.51	1.34	1.96	1.86
		80	3.32	3.46	3.19	3.96	3.48
		120	3.58	3.97	3.44	4.48	3.87
		160	3.78	4.67	3.52	4.77	4.19
DSRB+M	WB+M	0	1.01	1.63	1.20	1.64	1.37
		80	2.66	3.43	3.23	4.22	3.39
		120	3.39	4.04	3.58	4.58	3.90
		160	3.94	4.78	3.59	4.87	4.30
Mean		0	1.53	2.02	1.39	1.78	1.68
		80	3.31	3.51	3.11	4.21	3.54
		120	3.91	4.05	3.57	4.64	4.04
		160	4.10	4.79	3.73	4.88	4.38
LSD (0.05)							
Tmt			–	–	–	–	
N rate			–	–	0.21	0.30	
Tmt × N rate			0.42	0.52	–	–	

^{15}N recovery and balance in rice

The proportion of N uptake derived from fertiliser (%Ndff) in the straw and grain was generally similar, in the range 15–34% in 2003, 14–35% in 2004 and 19–35% in 2005 (Table 7). The values were much higher in PTR and DSRF than on the permanent beds, and with a consistent trend for lower %Ndff in TRB than DSRB. The majority of the N uptake (65–88%) by rice was derived from the soil despite application of fertiliser at 120 kg N/ha. Recoveries in rice straw on the beds were similar to those in the grain, but recovery in the straw in PTR was lower than in the grain (but still higher than on the beds). The total crop recovery of fertiliser N in the rice crop during 3 years was in the range 7.9–20.7% (mean 14%) on the beds compared with 26.3–35.8% (mean 30%) in PTR.

Figure 5. Wheat on permanent beds with mulch in February 2006; left to right four beds each of 80, 0, 120, 160 kg N/ha

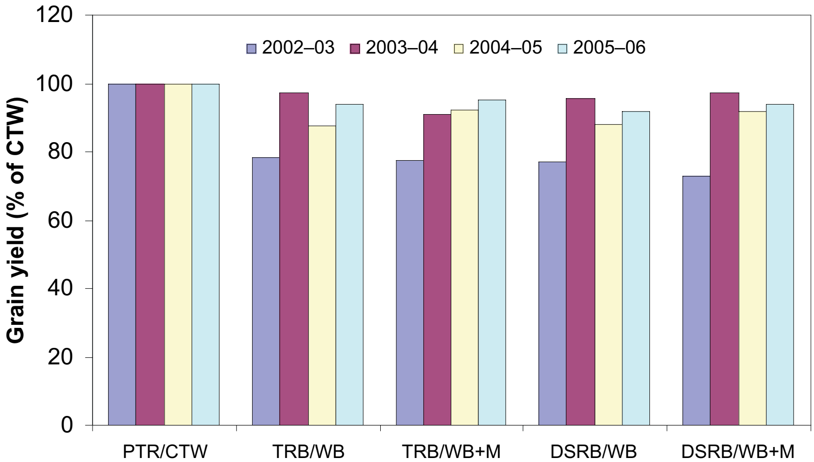

Figure 6. Relative wheat yields over 4 years at 120 kg N/ha. PTR = puddled transplanted rice, CTW = conventionally tilled wheat, TRB = transplanted rice on permanent beds, WB = direct-drilled wheat on permanent beds, +M = mulched, DSRB = direct-seeded rice on permanent beds

Plant recovery in DSRB was significantly reduced by mulching. Total unaccounted-for N was least in PTR (38%, 3-year mean) and much higher in TRB and DSRB (45–69% with a mean of 57%). On a similar soil type Katyal et al. (1985) reported similar rice plant recoveries (~27%) of urea N by PTR but higher losses (48%) compared with our experiments.

Table 6. Effect of method of crop establishment, wheat straw mulch and N application on mean apparent recovery efficiency (%) of fertiliser N by rice and wheat (at 120 kg N/ha) (mean for 3 years)

Rice	Wheat	Rice[A]	Wheat[A]
PTR	CTW	50.3 a	67.5 a
DSRF	DDW	40.4 b	63.9 ab
BTR	WB	37.8 c	55.2 c
BTR+M	WB+M	31.7 d	61.2 b
DSRB	WB	35.5 c	56.8 c
DSRB+M	WB+M	29.9 d	62.1 b

[A] Values followed by the same letter within a column are not significantly different ($P \leq 0.05$)

^{15}N recovery and balance in wheat

Mean plant %Ndff was much higher in wheat than rice and ranged from 38% to 49% in the grain and 30% to 47% in the straw (Table 8). The %Ndffs in wheat during the 3 years ranged from 51% to 70% compared with 65% to 85% in rice. The total recovery of ^{15}N in the wheat crop ranged from 27% to 38% compared with 8% to 36% in the rice. A large proportion of the applied N (47.6–51.2%, 3-year mean) was recovered in the soil (0– 75 cm). A major proportion (about 80%) of the ^{15}N recovered in the soil was in the top 0–30 cm. Recovery in the soil after wheat was much higher and less variable than after rice (17–30%); 7–28% of applied N could not be accounted for in the wheat, and losses from the respective rice treatments were about three times those from wheat. There was a trend for lower losses of N applied to wheat on the beds than on the flats but the differences were small and there was no consistent effect of mulching. Other researchers from different climates have reported values of ^{15}N-labelled fertiliser recovery in the crop ranging from 18% to 68% for wheat (Lopez

Table 7. Effect of planting methods and straw management on ^{15}N recovery in plant and soil (0–75 cm) at 120 kg N/ha in rice

Crop establishment		^{15}N derived from fertiliser (%)		^{15}N derived from soil (%)		Total plant ^{15}N recovery (%)[A]	^{15}N recovery from soil (%)[A]	^{15}N losses (%)[A]
Rice	Wheat	Grain	Straw	Grain	Straw			
		A. Rice 2003						
PTR	CTW	34.2	28.5	65.8	71.5	35.8 a	27.2 b	37.0 c
DSRF	DDW	31.8	30.9	68.2	69.1	27.8 b	24.3 c	47.9 b
TRB	WB	22.8	18.2	77.2	81.8	20.7 c	32.7 a	46.6 b
TRB+M	WB+M	14.6	16.3	85.4	83.7	17.9 c	32.2 a	49.9 b
DSRB	WB	27.1	25.0	72.9	75.0	19.7 c	29.5 ab	50.8 b
DSRB+M	WB+M	27.4	17.8	72.6	82.2	13.3 d	24.1 c	62.6 a
		B. Rice 2004						
PTR	CTW	35.1	33.5	67.2	66.5	27.6 a	38.4 a	34.0 d
DSRF	DDW	32.9	31.0	67.1	69.0	25.8 a	35.1 a	39.9 c
TRB	WB	14.7	13.9	86.5	88.0	9.3 d	21.2 c	69.5 a
TRB+M	WB+M	18.8	15.0	81.2	87.0	12.7 cd	23.8 c	63.5 a
DSRB	WB	20.2	25.4	79.8	74.6	20.3 b	34.4 ab	45.3 b
DSRB+M	WB+M	21.9	22.0	78.2	78.0	16.8 c	33.8 b	49.4 b
		C. Rice 2005						
PTR	CTW	21.6	35.1	67.4	64.9	26.3 a	31.9 b	41.8 c
DSRF	DDW	22.6	28.3	77.4	71.7	18.0 b	36.4 a	45.6 c
TRB	WB	21.0	19.8	79.0	80.2	12.7 c	30.1 b	57.2 b
TRB+M	WB+M	20.8	18.9	79.2	81.1	10.2 c	27.1 b	62.7 b
DSRB	WB	23.4	23.9	76.6	76.1	11.1 c	28.4 b	60.5 b
DSRB+M	WB+M	24.2	21.0	75.8	79.0	7.8 d	23.5 c	68.7 a

[A] Values followed by the same letter within a column are not significantly different ($P \leq 0.05$)

et al. 1992; Zapata and Hera 1995; Bijay-Singh et al. 2001). The recovery of N from fertiliser in a crop is also influenced by plant requirements and climatic and soil characteristics. Azam et al. (1990) reported that total fertiliser N recovery was similar (31.4% vs. 30.8%) with and without straw retention. Seligman et al. (1986) reported that, despite the high C:N ratio of the organic residues, some N in the added straw was mineralised and taken up by the wheat plants.

Effect of crop establishment method and mulching on soil properties

After the eighth crop, soil organic C, total N and available K were significantly higher in mulched than non-mulched beds (Table 9), which is consistent with the findings of Talukder et al. (2008). Total N and available K were also significantly higher on non-mulched beds than in PTR (also non-mulched);

Table 8. Effect of planting methods and straw management on ^{15}N recovery in plant and soil (0–75 cm) at 120 kg N/ha in wheat

Crop establishment		^{15}N derived from fertiliser (%)		^{15}N derived from soil (%)		Total plant ^{15}N recovery (%)[A]	^{15}N recovery from soil (%)[A]	^{15}N losses (%)[A]
Rice	Wheat	Grain	Straw	Grain	Straw			
	A. Wheat 2002–03							
PTR	CTW	49.1	38.2	50.9	61.8	38.3 a	51.4 a	10.3 c
DSRF	DDW	45.6	29.8	54.4	70.2	35.9 a	51.8 a	12.3 c
TRB	WB	46.2	41.6	53.8	58.4	31.1 b	45.4 b	23.5 ab
TRB+M	WB+M	41.5	37.8	58.5	62.2	27.5 c	46.8 b	25.7 a
DSRB	WB	42.4	38.4	57.6	61.6	26.5 c	45.8 b	27.7 a
DSRB+M	WB+M	43.1	38.1	56.9	61.9	27.0 c	50.7 a	22.3 b
	B. Wheat 2003–04							
PTR	CTW	43.6	45.3	56.4	54.7	35.4 a	51.5 a	13.1 c
DSRF	DDW	43.3	37.6	56.7	62.4	34.0 a	52.2 a	13.8 c
TRB	WB	42.4	43.8	57.6	56.2	35.9 a	46.7 b	17.4 b
TRB+M	WB+M	41.2	39.3	58.8	60.7	30.9 b	47.4 b	21.7 a
DSRB	WB	42.3	40.9	57.7	59.1	32.7 b	46.4 b	20.9 a
DSRB+M	WB+M	43.5	43.8	56.5	56.2	33.0 ab	44.2 b	22.8 a
	C. Wheat 2004–05							
PTR	CTW	37.7	46.5	62.3	53.5	33.7 a	49.2 b	17.1 a
DSRF	DDW	39.1	45.6	60.9	54.4	33.7 a	48.2 b	18.1 a
TRB	WB	41.9	40.7	58.1	59.3	37.9 a	50.6 b	11.5 b
TRB+M	WB+M	40.1	41.7	59.9	58.3	35.7 a	48.8 b	15.5 ab
DSRB	WB	41.1	40.3	58.9	59.7	36.1 a	56.6 a	7.3 c
DSRB+M	WB+M	39.7	44.0	60.3	56.0	33.8 a	58.7 a	7.5 c

[A] Values followed by the same letter within a column are not significantly different ($P \leq 0.05$)

Table 9. Effect of method of crop establishment and mulching on soil fertility (0–15 cm) after wheat 2005–06

Crop establishment treatment		Organic C (g/kg)[A]	Total N (%)[A]	Available K (mg/kg)[A]
Rice	Wheat			
PTR	CTW	5.4 b	0.041 c	34.4 c
DSRF	DDW	5.0 c	0.042 c	39.6 b
TRB	WB	4.9 c	0.045 b	41.9 b
TRB+M	WB+M	5.7 a	0.048 a	51.0 a
DSRB	WB	5.4 b	0.044 b	41.4 b
DSRB+M	WB+M	6.0 a	0.048 a	52.6 a

[A] Values followed by the same letter within a column are not significantly different ($P \leq 0.05$)

however, it is not known if this was a residual effect of the fact that the beds were formed from topsoil, which is inherently more fertile. Organic C was significantly lower in DSRF than PTR (both non-mulched), while available K was significantly higher with DSRF. Yadvinder-Singh et al. (2004) also observed that straw retention (incorporation) increased soil organic C in comparison with burning or removal, which is consistent with other results from RW systems (Yadvinder-Singh et al. 2005; Talukder et al. 2008).

Conclusions

Permanent raised beds systems for RW in the Indo-Gangetic Plain of India seem to have limited potential, particularly due to the lower yields of both transplanted and direct-seeded rice on beds, with current practice.

Grain yield of direct-seeded rice on raised beds declined as the beds aged. This effect has also been observed with transplanted rice on beds in other studies (Singh et al. 2005; Kukal et al. 2008) but not in this study. Straw mulch showed no beneficial effect on yield of rice and wheat on the permanent beds, and consistently an adverse effect for direct-seeded rice on beds. The main reasons for low yields of direct-seeded rice were due to severe iron deficiency, infestation of root knot nematodes, excessive weed growth and low N recovery. We also speculate that adverse changes in soil physical properties, which could restrict the rice root growth, occurred on the beds. Wheat yields were generally similar on permanent beds and flat layouts. Response of rice and wheat to N fertiliser was not influenced by method of crop establishment. Recovery of fertiliser N in the rice crop was also lower for transplanted as well as direct-seeded rice on beds compared with puddled transplanted rice. Further research on permanent raised beds for RW 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; N; water and residue management; machinery development and practices; and long-term effects.

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A financial analysis of permanent raised beds for rice–wheat and alternative cropping systems in Punjab, India

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Abstract

Overexploitation of natural resources to grow high-yielding varieties of both rice and wheat has lead to serious problems of environmental and economic sustainability of the rice–wheat (RW) cropping system in Punjab, India. Further, the poorly drained ‘flat’ field layout used for the RW system offers limited scope for growing higher value or lower water use crops such as vegetables, maize and soybean as they are sensitive to waterlogging. Recent research suggests that there may be considerable benefits in changing from flat layouts with conventional tillage to permanent raised beds (PRB) for RW and alternative cropping systems in Punjab. The potential benefits include lower irrigation water use, reduced tillage costs, and improved soil structure and drainage as a result of the bed–furrow layout. The aim of the present study was to determine the benefits and costs of adoption of PRB for RW, maize–wheat (MW) and soybean–wheat (SW) cropping systems in Punjab, India. The tillage × layout treatments (referred to as ‘layouts’ for simplicity) compared were: I. conventional tillage (flat) for both crops; II. zero tillage (flat) for both crops for MW and SW, but for wheat only in RW (with conventional tillage for rice); III. conventional tillage for the summer crop (rice, maize, soybean) followed by wheat on fresh beds; IV. fresh beds for the summer crop followed by wheat direct drilled on the beds; and V. PRB—all crops direct drilled except rice, which was transplanted on the beds.

PRB 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. PRB also 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). 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 a lower irrigation requirement of rice on the beds.

RW was slightly more profitable than MW for respective layouts and 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 a much lower irrigation requirement than for 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.

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Introduction

Punjab state, with only 1.5% of the geographical area of the country, contributed 55.4% of wheat and 37.1% of rice to the central Government of India (GOI) pool in 2004–05 (GOP 2006a). The introduction of high-yielding varieties of wheat in the late 1960s followed by high-yielding varieties of rice in the early 1970s and the expansion of irrigation led to a rapid increase in the area under cultivation of these two crops in Punjab, India (Table 1).

To further increase the area and production of these crops, both the central and state governments provided incentives including free electricity to agriculture for pumping groundwater, subsidised surface (canal) water, fertilisers and fuel, loans and procurement of rice and wheat with a guaranteed minimum price. Consequently, the rice–wheat (RW) rotation now predominates in the large irrigated areas of Punjab. No other crop or cropping system is as profitable and reliable as RW. Rice occupies 60% of the total land area in summer, with less than 5% under maize, while 80% of the land area is under wheat in winter (GOP 2006b). Rice growing has even expanded from traditional rice soils to coarse-textured, permeable soils more suitable for maize and groundnut production.

Although continuous double cropping of rice and wheat has led to a significant increase in farmer income, high use of chemicals and overexploitation of natural resources to achieve high yields have also led to serious problems of environmental and economic sustainability of rice farms (Singh 2002). Now, in most of the rice growing regions of Punjab, watertables are declining rapidly (Table 2), greatly increasing pumping costs due to the need to change from centrifugal to submersible pumps. The proportion of submersible pumps in the RW belt of Punjab almost doubled from 2003–04 (17%) to 2005–06 (33%) (Dept of Agriculture, Punjab). This involves additional expenditure of up to 100,000 Rs (~A$3,000) per conversion (Singh et al. 2008).

Table 2. Trends in decline in depth of the watertable (% of area in each depth range) in central zone of Punjab from 1973 to 2002

Year	Depth of watertable		
	< 5 m	5–10 m	>10 m
1973	39	58	3
1990	9	66	25
2000	6	41	53
2002	2	22	76

Source: Hira et al. (2004)

In recent years the cost–price squeeze of agricultural commodities and the very limited scope for further expansion of the rice area have had a serious impact on the economic viability of rice farms in Punjab. Further, rice-based cropping systems are grown on flat layouts that offer limited scope for growing alternative, waterlogging-sensitive crops such as maize and soybean. Furrow-irrigated raised beds greatly improve surface drainage, and may increase crop flexibility due to the ability to grow more waterlogging-sensitive species.

The ACIAR project 'Permanent raised beds for irrigated rice–wheat and alternative cropping systems in north-west India and south-east Australia' aimed to evaluate the performance of RW and alternative cropping systems on raised beds in comparison with conventional layouts in terms of crop performance, water use and financial feasibility for farmers. The results of the financial analysis are pre-

Table 1. Trends in area ('000 ha) of different crops in Punjab from 1960–61 to 2004–05

Crops	Year					
	1960–61	1970–71	1980–81	1990–91	2000–01	2004–05
Rice	227	390	1,183	2,015	2,611	2,647
Wheat	1,400	2,299	2,812	3,273	3,408	3,482
Maize	327	555	382	188	165	154
Cotton	446	397	648	701	474	509
Pulses	903	414	341	149	61	40
Oil seeds	185	295	248	113	87	91
Sugarcane	133	128	71	101	121	86
Total	3,621	4,478	5,685	6,540	6,927	7,009

Source: GOP (2006a)

sented here. The objectives of the financial analysis were:

- to identify field layouts currently being used or tested for irrigated RW and alternative cropping systems in Punjab
- to estimate potential financial benefits of adoption of PRB over alternative layouts
- to determine the costs involved in the adoption of PRB
- to compare the benefits and costs of adoption of PRB by farmers.

Methodology

The financial analysis involved a partial budgeting approach in which the additional and foregone annual costs and benefits of the options were compared. The analysis sought to ascertain, using financial values for all relevant inputs and outputs, the attractiveness of the options from the perspective of a farmer. '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 PRB technology were determined was 30 years. A discount rate of 7% p.a. 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% rate normally used for economic assessments in India to take into account 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.

Estimation of farm-level benefits

The study used gross margin (GM) and crop sequence gross margin analysis to estimate the on-farm financial benefits and costs of adoption of PRB.

Gross margin analysis

Gross margin is the gross return from a crop (yield times price) less the variable costs of production including tillage, seed, fertilisers, irrigation, chemicals, fuel, harvesting, levies etc. The costs of some inputs or operations such as irrigation, fertiliser and machinery operations vary with field design and tillage practices. Also, increases in yield and/or price lead to increases in the costs of some variable inputs and operations such as harvesting and transport to markets. Therefore, the variable costs and returns of individual crops and crop rotations were calculated separately for each treatment.

Crop sequence GM analysis

The life of the 'permanent' beds was assumed to be 5 years for the RW rotation and 10 years for the MW and SW rotations, based on experimental observations of a decline in rice yield on permanent beds over time in this environment (Kukal et al. 2005, 2008). In contrast, there is no evidence of a decline in yields of non-rice crops over time on permanent beds, although there are few reports of studies longer than a couple of years, with the exception of wheat in rice-based systems (Ram et al. 2005; Ram 2006; Jat et al. 2008; Lauren et al. 2008; Talukder et al. 2008). A crop sequence GM analysis was undertaken to capture variations over time and to measure the NPV of each cropping system on each layout. The NPV of the GM of a cropping system was calculated as the sum of the discounted annual GM from the crops in the rotation, using equation 1:

$$\text{NPV} = \sum_{t=1}^{n} GM_t/(1 + \text{rate})^t \qquad \text{equation (1)}$$

where *rate* is the discount rate (7%) and GM_1, GM_2, …, GM_t are the GMs for years 1 to n (n=30 in this study).

Data and assumptions used in the analysis

The data on cultural practices, nature and amount of inputs and yields of each crop in each layout and cropping system were based on the experimental findings of the ACIAR project and other reports (Ram et al. 2005; Kukal et al. 2005, 2008; Humphreys et al. 2007, 2008), PAU recommended practices (Anon. 2006a, 2006b) and advice from extension and research staff on actual farmer practice.

The key data and assumptions used in the GM analysis and estimation of the financial value of the potential benefits of adoption of PRB are given below. The variable costs of production for each input, and the total variable cost, are provided for rice, maize, soybean and wheat grown with conventional tillage in Appendixes 1–6.

Input and output prices

Output prices of rice and wheat used in the analysis were the GOI announced procurement prices for 2005–06 (Table 3). The government guarantees to purchase all rice and wheat at the procurement price. The prices of maize and soybean used in the analysis were the support prices announced by the GOI during 2005–06. The price support system involves the government entering the market if the market price falls below the support price and restoring prices to the announced value. The prices of the by-products of wheat, maize and soybean and the costs of inputs were the market prices in 2005–06 (Appendix 1).

Machinery costs

There is a general lack of information on the cost of using a farmer's own machinery for cultural operations. Due to overcapitalisation in Punjab agriculture, tractors and other machinery are used at only 35% of capacity. Farmers who own machinery and have surplus capacity can work as part-time machinery contractors and hire out machinery at very competitive rates. Therefore, the study has used the 'custom hiring' charges for tractors and other machinery to estimate the machinery costs for production of crops (Appendix 2). These costs include the cost of diesel and labour to operate the machinery.

Field preparation for growing wheat using conventional practice typically involves two cultivations with discs, two cultivations with tine harrows and one planking (Gajri et al. 2002). The first discing requires more energy and time and costs 750 Rs/ha, and subsequent cultivations cost 500 Rs/ha. Conventional cultivation for maize typically involves one discing, two harrowings and two plankings, whereas conventional cultivation for soybean involves one discing, one harrowing and two plankings. Conventional cultivation for rice involves two discings and two cultivations, followed by puddling (two cultivations with cultivators and one planking in flooded soil).

Permanent beds are formed after two discings and two harrowings prior to the first crop. Wheat is direct drilled on the beds after removal of the rice, maize or soybean residues, and there is no reshaping of the permanent beds. For subsequent maize and soybean crops on PRB, reshaping and sowing are done in the same operation, so no additional cost is involved in reshaping. In the case of rice, reshaping is done as a separate operation before transplanting; therefore, the costs of reshaping and transplanting are included separately. No land preparation cost is involved in zero-till wheat on beds or flats, just the sowing cost.

Cost of hiring casual labour

Farmers in Punjab can easily hire casual labour from the open market at 10 Rs/hour or 80 Rs/day. In the analysis the same wage rate was used for estimating the value of both family and hired labour.

Cost of pumping groundwater

Electricity is the main source of power for pumping groundwater to irrigate all crops grown in the RW areas of Punjab, and is supplied free to farmers. In the case of conventional puddled transplanted rice, some irrigations are also done by diesel-

Table 3. Procurement price for wheat and rice and minimum support price for soybean and maize in India

Crop year	Procurement price (Rs/t)		Minimum support price (Rs/t)	
	Paddy	Wheat	Maize	Soybean (yellow)
2000–01	5,400	6,100	4,450	8,650
2001–02	5,600	6,200	4,850	8,850
2002–03	5,600+200[a]	6,200+100[a]	4,850+50[a]	8,850+100[a]
2003–04	5,800	6,300	5,050	9,300
2004–05	5,900	6,400	5,250	10,000
2005–06	6,000	6,500	5,400	10,100

[a] One-time special drought relief given over minimum support price
Source: CACP, Ministry of Agriculture, Government of India

powered pumps because of the high irrigation water requirement and the fact that availability of electricity is limited during the peak rice growing period (June–July). Due to lack of information on the amount of diesel-powered pumping for irrigation of rice, the analysis assumed that electricity was used for all irrigations for all crops including rice. The operating cost of pumping groundwater was estimated to be 7.34 Rs/ha for each irrigation of 7.5 cm depth, based on the costs of depreciation and annual maintenance of a typical centrifugal electric pump used in RW farming systems in Punjab.

Cost of marketing of grain

Marketing costs paid by the farmer for transportation of grain from the farm to the local market yard, unloading and cleaning were also included in the GM analysis (Table 4).

Table 4. Marketing costs paid by farmers in Punjab during 2004–05

Operation/crops	Charges (Rs/t)		
	Maize	Soybean	Wheat and paddy
Transportation	30.0	30.0	30.0
cleaning and sieving of grains	11.2	21.6	20.6
Unloading of grains	11.2	10.8	12.5

Sources: 1. Pers. comm., Dr M.S. Sidhu, Professor of Marketing, PAU, Ludhiana, 2005
2. Mandi Board Punjab, Chandigarh

Interest on crop loans

Due to continuous double cropping of high-yielding varieties of rice and wheat in Punjab, farmers rely heavily on chemical fertilisers, insecticides and pesticides to achieve high yields. Most farmers do not have sufficient cash to meet the large costs of these chemicals and take out short-term loans ('crop loans') from both commercial and state cooperative banks at a nominal 9% p.a. interest rate for both winter and summer crops. The loan has to be repaid (both principle and interest) at the end of the cropping season. Therefore, in the GM budgets, the study included the interest paid by farmers for 6 months on the total variable cost of production of each crop.

Enterprise budget

The total cash variable expenses for each operation for rice, maize, soybean and wheat with conventional tillage are listed in Appendixes 3–6. These show that machinery ('mechanical labour', combine harvesting) and human labour are the major costs, followed by chemical fertilisers and biocides.

Cropping rotations and field layouts considered in the analysis

The analysis was conducted for three cropping systems:

- rice–wheat (RW)
- maize–wheat (MW)
- soybean–wheat (SW)

grown using five different layout/tillage treatments.

Layout/tillage treatment

The benefits and costs of adoption of PRB were compared with four other layout/tillage treatments. The tillage × layouts treatments (referred to as 'layouts' for simplicity) compared were:

I. conventional tillage (flat) for both crops
II. zero tillage (flat) for both crops for MW and SW, but for wheat only in RW (with conventional tillage for rice)
III. conventional tillage for the summer crop followed by wheat on fresh beds
IV. fresh beds for each summer crop and wheat direct drilled on the beds after harvest of the summer crop
V. permanent raised beds (direct drilled for all crops except rice, which was transplanted on the beds).

I. Conventional tillage on the flat

RW—puddled transplanted rice followed by stubble burning, conventional tillage prior to wheat sowing, and wheat straw removed after grain harvest. Virtually all rice in Punjab is grown using this method, and about 90% of wheat.

MW, SW—conventional tillage prior to each crop, with all stubbles removed.

II. Zero tillage on the flat

RW—puddled transplanted rice followed by stubble burning and direct drilling of wheat using the zero-till drill, and wheat straw removed after harvest. Adoption of wheat sown with the zero-till drill after burning the rice residues is increasing rapidly in Punjab, with about 10% of the wheat after rice sown with the zero-till drill in 2006 (Department of Agriculture, Punjab)

MW, SW—'zero tillage' (direct seeding) of maize or soybean followed by stubble removal and direct-drilled wheat, i.e. zero tillage for wheat followed by stubble removal.

III. Wheat on fresh beds, conventional tillage (flat layout) for summer crops (rice, maize, soybean)

Summer crop stubbles are removed prior to cultivation and sowing of wheat on fresh beds formed at the same time as sowing. The beds are knocked down by discing after wheat harvest and straw removal to prepare a flat layout for puddled transplanted rice or maize/soybeans. The same number of discings is carried out for conventional tillage for the next crop following bed or flat layouts, so there is no additional cost of dismantling**.**

IV. Fresh beds for rice, maize and soybean in summer followed by wheat direct drilled on the beds in winter

The soil is cultivated and fresh beds formed which are transplanted with rice or sown with maize or soybean. After harvest, rice stubbles are burnt, maize and soybean stubbles are removed and wheat is direct drilled on the beds. After wheat harvest, wheat straw is removed and the beds are knocked down by discing, then reformed for the next summer crop. Again there is no additional cost of dismantling the beds**.**

V. PRB for all crops

PRB are constructed to grow rice, maize or soybeans in summer and wheat in winter. Rice is transplanted on the beds and all other crops are direct seeded on the beds using the bed planter. All crop stubbles are removed (rice straw is burnt). The life of the PRB is 5 years for RW and 10 years for MW and SW. The beds are reshaped before planting the summer crop each year. It is assumed that there is no additional cost of harvesting with combines on the beds.

Benefits of PRB

The study has estimated the potential financial benefits and costs/losses from adoption of PRB over the other layouts. Although there are also some significant economic, social and environmental benefits from the adoption of PRB in RW and alternative cropping systems, these are beyond the scope of this analysis.

Potential financial benefits to farmers

The potential financial benefits of adoption of the alternative layouts vary across the different designs. Financial benefits could accrue from:

- yield increases
- irrigation water savings
- labour savings (both family and hired labour)
- machinery cost savings due to reduced tillage

On the other hand, additional costs or losses associated with the adoption of alternative layouts could accrue from:

- seed saving (lower seed rate for wheat on beds)
- yield declines
- additional rodent control costs where the soil is not cultivated.

Estimation of the value of potential financial benefits/costs to farmers

Grain and straw yield

The research results generally showed similar yields of wheat, maize and soybean, respectively, for all layouts within the same crop sequence (Kukal et al. 2005, 2008; Ram et al. 2005; Ram 2006). The analysis assumes no effect of layout on yield of these three crops. Yields of maize and wheat in the MW system were assumed to be 4.5 and 5.6 t/ha, respectively (Table 5). Yields of soybean and wheat were assumed to be 1.5 and 5.6 t/ha, respectively, with wheat yield increasing to 5.9 t/ha from year 3 onwards and providing additional income of 2,240 Rs/ha (Table 6), based on the findings of Ram (2006).

In the case of transplanted rice on PRB in Punjab, Kukal et al. (2008) and Yadvinder-Singh et al. (2008) found that yield of transplanted rice on PRB relative to that of puddled transplanted rice declined as the beds aged. Based on their results, the financial analysis assumed the same yield of rice on fresh beds and on puddled soil in the first year, and then yield declines on PRB of 10%, 15%, 20% and 25% in years 2–5, respectively (Table 7). The value of the yield loss varied from 4,100 Rs/ha in year 2 to 10,300 Rs/ha in year 5 of growing rice on PRB. Yield of conventionally tilled rice was assumed to be 7 t/ha, while yield of wheat was assumed to be 5.2 t/ha (Table 7). Yield of wheat in the RW system was lower than yield of wheat in the other systems, based on experimental findings (Boparai et al. 1992; Ram 2006; Kukal et al. 2008).

The GM analysis includes the value of the maize residues (400 Rs/t) and wheat residues (1,500 Rs/t) as income (i.e. used for cattle feed). The yield of residues is assumed to be 2.3 times the grain yield (i.e. 10.4 t/ha) for maize and equal to the grain yield for wheat. Harvesting the wheat straw involves an additional cost of 2,000 Rs/ha. The harvesting cost of maize residues is included in the harvesting cost of maize (human labour), whereas for wheat the grain and straw are harvested mechanically in two separate operations.

The by-product of soybean, which is 1.5 times the grain yield, is valued at 400 Rs/t and is used to feed cattle. Because more than 90% of the rice straw produced in Punjab is burnt in the field, no income from the straw is included in the GM analysis.

Irrigation water saving in maize, soybean and wheat

In the case of wheat, maize and soybean sown on a flat layout with conventional tillage, farmers typically apply one pre-sowing irrigation of about 10 cm, followed by four post-sowing irrigations (7.5 cm each) for wheat and three for maize and soybean. For each crop we assumed the same irrigation frequency for all layouts in the analysis. Planting non-rice crops on beds typically saves 20% of irrigation water compared to the conventional flat layout (Ram et al. 2005; Humphreys et al. 2007). There are also several reports of irrigation water saving with direct drilling of these crops on the flat into non-cultivated soil, with most of the saving occurring with the first irrigation (Humphreys et al. 2007). We assumed an irri-

Table 5. Grain yield, irrigation water use and GM of crops in the MW rotation

MW		Maize				Wheat			MW
Tillage (layout)		Yield (t/ha)	Irrigation (cm)	GM (Rs/ha)	Tillage (layout)	Yield (t/ha)	Irrigation (cm)	GM (Rs/ha)	GM (Rs/ha/yr)
I.	Conventional (flat)	4.5	32.5	20,356	Conventional (flat)	5.6	40	30,156	50,512
II.	Zero till	4.5	30.5	22,529	Zero (flat)	5.6	38	32,254	54,783
III.	Conventional (flat)	4.5	32.5	20,356	Fresh beds	5.6	32	30,459	50,814
IV.	Fresh beds	4.5	26	20,766	Same beds	5.6	32	32,875	53,642
V.	PRB	4.5	26	22,517	PRB	5.6	32	32,917	55,434
Increase in GM of PRB over:									
I.	Conventional (flat)			2,161	Conventional (flat)			2,761	4,922
II.	Zero till			–12	Zero (flat)			663	651
III.	Conventional (flat)			2,161	Fresh beds			2,458	4,620
IV.	Fresh beds			1,750	Same beds			42	1,792

Note: The GM of MW on PRB does not include the initial cost of preparing the beds (included in years 1, 11, 21 only).

Table 6. Grain yield, irrigation water use and GM of crops in the SW rotation

SW		Soybean			Wheat				SW
Tillage (layout)		Yield (t/ha)	Irrigation (cm)	GM (Rs/ha)	Tillage (layout)	Yield[a] (t/ha)	Irrigation (cm)	GM (Rs/ha)	GM (Rs/ha/yr)
I.	Conventional (flat)	1.5	32.5	3,485	Conventional (flat)	5.9	40	30,288	33,773
II.	Zero till	1.5	30.5	5,413	Zero (flat)	5.9	38	32,366	37,779
III.	Conventional (flat)	1.5	32.5	3,485	Fresh beds	5.9	32	30,632	34,118
IV.	Fresh beds	1.5	26	3,481	Same beds	5.9	32	33,049	36,530
V.	PRB	1.5	26	5,388	PRB	5.9	32	33,055	38,444
Increase in GM of PRB over:									
I.	Conventional (flat)			1,903	Conventional (flat)			2,768	4,670
II.	Zero till			–25	Zero (flat)			689	664
III.	Conventional (flat)			1,903	Fresh beds			2,423	4,326
IV.	Fresh beds			1,907	Same beds			6	1,913

[a] 5.6 t/ha in 1st and 2nd year only. The GM of SW on PRB does not include the initial cost of preparing the beds (included in years 1, 11, 21 only).

gation water saving of 20% on the PRB compared with conventional tillage, and a saving of 20% in the pre-sowing irrigation only for direct-seeded crops on the flat. The total irrigation water saving for MW and SW on PRB was therefore 15 cm compared with conventional tillage, and 4 cm for double zero tillage compared with conventional tillage (Tables 5, 6).

Irrigation water saving in rice

Several reports suggest irrigation water savings of around 30% for rice on beds compared with conventional practice (see summary in Humphreys et al. 2007). Humphreys et al. (2008) found that continuously flooded puddled transplanted rice in farmer-field sized blocks required about 200 cm of irrigation water, compared with about 140 cm on raised beds (furrow half filled at each irrigation), a net saving of 60 cm (30%). In the analysis the total number of irrigations to both the puddled transplanted rice and the beds was the same (30) but the amount of water per irrigation was reduced from an average of 6.67 to 4.67 cm on PRB.

Manual labour

Irrigation. In Punjab a typical farmer hires casual labour for operations such as field preparation, sowing, irrigation, fertiliser application, spraying, weeding and harvesting. Permanent raised beds reduce the amount of labour required for land preparation and irrigation in comparison with conventional layouts. The value of the labour saved is measured though the reduction in time required for these operations. Rice is typically grown in blocks of 2,000 m^2 (5 blocks/ha) separated by earthen bunds, whereas wheat, maize or soybean blocks are typically around 660 m^2 (15 blocks/ha). Irrigation water is directed to each block by making a cut in the bund, which is closed at the end of irrigation. It therefore takes more time to manage irrigation of wheat, maize and soybean compared to rice.

The analysis assumed that it takes 15 person-hours to apply one irrigation (7.5 cm) to 1 ha of wheat, maize or soybean sown on a flat layout with conventional tillage, and 12 person-hours to apply one irrigation to 1 ha of PRB. For rice it is assumed that it takes 2.5 person-hours to apply one irrigation (6.7 cm) to 1 ha of puddled transplanted rice. Although rice on beds leads to 30% irrigation water saving, it is assumed that the labourer has to spend almost the same amount of time to supervise the irrigation as for puddled transplanted rice.

Thus, the total human labour savings for irrigation of PRB compared with conventional tillage were 18.5, 36.5 and 38.0 hours/ha, equating to 185, 365 and 380 Rs/ha for RW, MW and SW, respectively.

Transplanting. Transplanting rice on beds needs 25% or 16 hours of additional labour compared to that required for transplanting rice in a puddled flat layout (pers. comm. Yadvinder-Singh and S.S. Kukal).

Machinery operation savings

Direct drilling on PRB reduces the number of machinery operations. The cost of machinery is based on contract rates which include the fuel and human labour requirements as well as the cost of the machines.

Table 7. Grain yield, irrigation water use and GM of crops in the RW rotation

RW	Rice				Wheat				RW
Tillage (layout)		Yield (t/ha)	Irrigation (cm)	GM (Rs/ha)	Tillage (layout)	Yield (t/ha)	Irrigation (cm)	GM (Rs/ha)	GM (Rs/ha/yr)
I.	Conventional (flat)	7.0	200	25,247	Conventional (flat)	5.2	40	30,377	55,624
II.	Conventional (flat)	7.0	200	25,247	Zero (flat)	5.2	38	33,383	58,629
III.	Conventional (flat)	7.0	200	25,247	Fresh beds	5.2	32	30,728	55,975
IV.	Fresh beds	7.0[a]	140	25,105	Same beds	5.2	32	33,680	58,785
V.	PRB	7.0[a]	140	28,044	PRB	5.2	32	33,680	61724
Increase in GM of PRB over:									
I.	Conventional (flat)			2,797	Conventional (flat)			3,303	6,100
II.	Conventional (flat)			2,797	Zero (flat)			298	3,094
III.	Conventional (flat)			2,797	Fresh beds			2,952	5,749
IV.	Fresh beds			2,939	Same beds			0	2,939

[a] Yield in first year only—yield declines by 10% in the 2nd year and an additional 5% each year from 3rd to 5th year. The GMs of RW on PRB do not include the initial cost of preparing the beds (included in years 1, 6, 11….26 only).

Seed savings

Previous research has shown that the seed rate of wheat on beds can be reduced by 25% in comparison with the recommended rate for conventionally tilled wheat on the flat (100 kg/ha) (Dhillon et al. 2002). This is a saving of 25 kg/ha or 300 Rs/ha. There is no saving of maize and soybean seed while sowing on beds using the same plant population density for both layouts.

Saving of operating costs of tube-wells

The reduction in operating costs of tube-well pumps from reduced irrigation time on PRB over conventional tillage was 166 Rs/ha in RW and 35 Rs/ha in both MW and SW. Due to the free supply of electricity to the agriculture sector, the value to the farmer of saved electricity was zero.

Gross margin analysis

The crop GMs in Tables 5–7 do not include the initial cost of preparing the beds. However, in the benefit–cost analysis (see below) these costs were included in the first crop and then after every 5 years in the RW system and after every 10 years in the MW and SW systems, over 30 years.

MW rotation

The GM of the MW sequence was greatest on PRB (55,434 Rs/ha), followed by double zero tillage (54,783 Rs/ha) (Table 5). The GM of MW with PRB was 4,922 Rs/ha (10%) higher than the GM when both crops were grown with conventional tillage, and 4,620 Rs/ha higher than when maize was grown with conventional tillage followed by wheat on fresh beds. The financial benefits of PRB over conventional tillage were due to reduced tillage, labour, irrigation and wheat seed costs.

SW rotation

The GM of the SW sequence was also highest with PRB (38,444 Rs/ha) and double zero tillage (37,779 Rs/ha) (Table 6). The lowest GM (33,773 Rs/ha) occurred when both soybean and wheat were sown with conventional tillage. There was a 13% increase in GM for SW on PRB (4,670 Rs/ha) over conventional tillage. As for MW, the increase in GM on PRB was due to reduced tillage, labour, wheat seed and irrigation costs.

RW rotation

The GM for rice on PRB in Table 7 is based on the yield of the first year of rice on beds, i.e. 7.0 t/ha. The impact of the decline in yield of rice on PRB from 0% in year 1 to 25% in year 5 is considered in the benefit–cost analysis below.

Benefit–cost analysis

Financial value of benefits over 30 years

The profitability of RW on PRB was similar to the profitability of conventional tillage for both crops, and of rice on fresh beds followed by direct-drilled wheat on the beds (Table 8). Growing RW on PRB was about 5% less profitable than growing puddled transplanted rice followed by zero-till wheat or wheat on fresh beds.

The main reason for the poor performance of RW on PRB compared to other layouts was the progressive reduction in yield of rice from the second year to the fifth year, which was more costly than the value of reductions in tillage, labour, wheat seed and irrigation costs.

In contrast with the RW system, MW and SW grown on PRB were more profitable than on all other layouts (Table 8). The NPV of benefits of PRB increased by about 10% over conventional tillage for both crops, and for conventional tillage of the summer crop followed by wheat on fresh beds. However, the NPV of benefits of PRB over double zero tillage were small (around 1%) for both MW and SW.

Sensitivity analysis

Sensitivity analysis was used to show the effects on NPV of changes in the relative yield of rice, maize, soybean and wheat on PRB compared to the other layouts (Tables 9, 10). In the case of maize and soybean, widespread adoption of these crops would mean growing them on fields with a long history of rice culture. In this case it is likely that beds would confer a considerable advantage in terms of improved soil properties of the root zone, especially less waterlogging on the raised beds than on flats due to the formation of a hardpan as a result of puddling for rice. Some studies also show higher yields of wheat on PRB compared with conventional tillage (Jat et al. 2008; Lauren et al. 2008; Talukder et al. 2008). In Bangladesh and Nepal higher yields of transplanted rice on PRB than puddled rice have also been achieved (Lauren et al. 2008; Talukder et al.

2008). The yield levels of rice, maize, soybean and wheat used in the sensitivity analysis were**:**

- same and 10% lower yield of rice on PRB compared to conventional tillage
- 10% increase in yield of maize, soybean and wheat on PRB compared to conventional tillage.

The results show that if the yield loss of rice on PRB relative to conventional tillage could be restricted to 10% during years 2 to 5, there would be small financial benefits of up to 5% over layouts with puddled transplanted rice followed by conventionally tilled wheat or fresh beds (Table 9). The NPV of RW on PRB would be slightly less than the NPV of rice grown on fresh beds followed by wheat on the same beds and zero-till wheat after puddled transplanted rice. If rice yields could be maintained on PRB, the benefits of PRB over the other layouts would increase to 4–9%. The effect of a 10% increase in yield of wheat grown on PRB is similar to the effect of restricting the rice yield loss to 10%, i.e. an increase in NPV of PRB of about 4% compared to conventional tillage for both crops, and to fresh beds after puddled transplanted rice.

A 10% increase in the yield of maize, soybean or wheat on PRB relative to conventional tillage leads to a substantial increase (5–17%) in the NPV of the benefits compared with all other layouts in MW and SW systems (Table 10).

General discussion

RW grown on PRB was slightly more profitable than with conventional tillage, but the difference was small and at the cost of significantly decreased rice

Table 8. NPV of benefits from growing different crops on PRB

Tillage/layout	NPV of GM of crops grown on PRB and other layouts (‘000, Rs/ha)		
	Rice–wheat	Maize–wheat	Soybean–wheat
I.	690	627	443
II.	728	680	493
III.	695	631	447
IV.	730	666	477
V.	692	685	499
Benefits from PRB over:			
I.	1.3 (0.2)	58.5 (8.5)	56.2 (11.6)
II.	–36.0 (–5.2)	5.5 (0.8)	6.5 (1.3)
III.	–3.1 (–0.4)	54.7 (8.0)	51.9 (10.4)
IV.	–38.0 (–5.5)	19.6 (2.9)	22.0 (4.4)

Note: Figures in parentheses are the percentage benefits from PRB over different field layouts.

Table 9. Effect of relative rice and wheat yield on NPV of benefits of PRB compared with other layouts for RW

Tillage/layout	NPV of benefits from PRB over other selected layouts (’000, Rs/ha)			
	Default (25% rice yield decline by year 5 on PRB; no change in wheat yield)	10% rice yield loss in years 2–5 on PRB	No rice yield loss on PRB	10% higher yield of wheat on PRB
I.	1.3	29.0	68.1	32.3
II.	–36.0	–8.3	30.6	–5.1
III.	–3.1	24.6	63.7	27.9
IV.	–38.0	–10.3	28.9	–6.7
Benefits (%) from PRB over:				
I.	0.2	4.0	9.0	4.5
II.	–5.2	–1.2	4.1	–0.7
III.	–0.4	3.4	8.4	3.9
IV.	–5.5	–1.4	3.8	–1.0

production, which reached 25% in year 5. This may be an important consideration in terms of food security. However, growing rice on beds also reduced irrigation amount and therefore consumption of electricity for pumping groundwater. While the financial benefit of reduced pumping to the farmer is small because electricity is provided free for agriculture, the reduced consumption of electricity would be beneficial to society. The Punjab State Electricity Board tries to ensure a fairly reliable power supply for irrigation at the cost of other users of electricity, including business and industry. Unreliable supply of electricity to industry leads to increased production costs, and loss of employment, productivity and export earnings to the state (*The Tribune*, Chandigarh, 28 August 2006). It also adversely affects the prospects of attracting investments for setting up big power-based industries in Punjab. In addition, the community has to bear major impacts on its quality of life.

If the rice yield decline could be reduced to 10%, there would be significant financial benefits of PRB over the other layouts except for zero-till wheat after puddled transplanted rice and rice on fresh beds followed by wheat on the same beds. If rice yields on PRB could be maintained, then it would be the most profitable option. Reasons for the poor performance of rice on PRB in Punjab need to be identified and overcome. In the eastern Indo-Gangetic Plain yields of transplanted rice on PRB were higher than with conventional tillage (Lauren et al. 2008; Talukder et al. 2008).

In contrast with RW, the NPV of the financial benefits of MW and SW on PRB in comparison with layouts other than double zero tillage were substantial, with comparable yields and reduced irrigation, machinery, labour and wheat seed costs.

The NPV of the GM of RW with conventional tillage was about 10% higher than for MW with conventional tillage due to the much higher price of rice, which more than offset the higher variable costs of growing rice compared with maize (Appendixes 3, 4). The higher profitability of RW was consistent with the fact that Punjab farmers choose to grow rice rather than maize. The NPV of the GM of SW was considerably lower than for the other two systems, largely due to the much lower yield of soybean than maize or rice and the much lower price of soybean than rice. Expansion of production of maize or soybean would not be financially viable for farmers unless policies and markets were developed to support maize, as currently occurs for rice and wheat. However, replacing rice with maize or soybean would have significant economic and social benefits due to the much lower use of electricity for pumping groundwater because of the much lower irrigation water requirement of maize and soybean (about 15% of that for rice using conventional tillage for both systems).

A 10% increase in yield of maize, soybean or wheat on beds would make the MW and SW rotations much more financially attractive, provided markets and marketing infrastructure were available. Such a yield increase is likely if these systems expand to lands with a long history of rice culture due to reduced waterlogging on the beds.

Table 10. Effect of relative maize, soybean or wheat yield on NPV of benefits of PRB compared with other layouts for MW and SW

Field layout	NPV of benefits from PRB over other selected layouts ('000, Rs/ha)					
	MW	SW	Maize–wheat		Soybean–wheat	
	Default	Default	10% higher yield of maize	10% higher yield of wheat	10% higher yield of soybean	10% higher yield of wheat
I.	58.5	56.2	97.9	89.5	75.9	90.3
II.	5.5	6.5	44.9	36.5	26.2	40.6
III.	54.7	51.9	94.2	89.7	71.6	86.0
IV.	19.6	22.0	59.1	50.7	41.7	56.1
Benefits (%) from PRB over:						
I.	8.5	11.6	13.5	12.5	14.5	16.8
II.	0.8	1.3	6.2	5.1	5.0	7.6
III.	8.0	10.4	13.0	12.0	13.7	16.0
IV.	2.9	4.0	8.2	7.1	8.0	10.4

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Appendix 1. Input costs and market prices of products, 2005–06

Item	Price	Item	Price
Seed		*Main product and by-product*	
Paddy	100 Rs/8 kg	Paddy fine	60,000 Rs/t
Maize	145 Rs/8 kg	Paddy straw	0 Rs/t
Moong	36.3 Rs/kg	Maize grain	5,400 Rs/t
Soybean	625 Rs/25 kg	Maize stalks	750 Rs/t
Wheat	12 Rs/kg	Moong	15,200 Rs/t
Manures and fertilisers		By-product Moong	450 Rs/t
Urea 46%	4,780 Rs/t	Wheat	6,400 Rs/t
DAP (18:46)	9,350 Rs/t	Wheat straws	1,500 Rs/t
MOP	4,450 Rs/t	Soybean	10,000 Rs/t
SSP	3,113 Rs/t	Soybean product	450 Rs/t
Zinc sulphate	16,500 Rs/t	*Miscellaneous*	
Ferrous sulphate	7,000 Rs/t	Manual labour	10 Rs/ha
Agro-chemicals		Electricity for irrigation	0 Rs/hour
Atrazin	150 Rs/500 g	Pump maintenance:	
Baviston	225 Rs/500 g	centrifugal	18.35 Rs/irrigation/ha
Blitox	110 Rs/500 g	submersible	45 Rs/irrigation/ha
Rhizobium culture	10 Rs/packet (for 1 acre)		
Ekalux	310 Rs/L		
Nuvan	300 Rs/L		
Thiodaan	250 Rs/L		
Chlorpyriphos	175 Rs/L		
Atrataf	300 Rs/kg		
Stomp (litre)	430 Rs/L		
Leader (litre)	725 Rs/13 g		
Tilt	980 Rs/L		
Butachlor	180 Rs/L		
Thiodaan	250 Rs/L		
Sevin	360 Rs/kg		
Monocrotophos	240 Rs/L		
Karathane	1700 Rs/L		
Rogan 30 EC	225 Rs/L		
Zineb	220 Rs/kg		
Basalin	530 Rs/L		
Captan	360 Rs/kg		

Appendix 2. Custom hiring charges for crop production operations in Punjab

Operation	Charge
Discing first time	750 Rs/ha
Discing second time	500 Rs/ha
Cultivation with tine harrows	500 Rs/ha
Planking	250 Rs/ha
Puddling/ha	1,250 Rs/ha
Misc. operations, e.g. transportation	200 Rs/hour
Combine harvesting	1,125 Rs/ha
Straw making	400 Rs/trolley load
Manual labour	10 Rs/hour
Bund making	125 Rs/ha
Sowing on flat	500 Rs/ha
Sowing on beds	750 Rs/ha
Hoeing / mechanical weeding	250 Rs/ha
Stubble shaver including human labour	525 Rs/ha
Burning of paddy straw	37.5 Rs/ha
Bed making for rice and wheat	2,750 Rs/ha
Bed making for soybean and wheat	1,750 Rs/ha
Bed making for maize and wheat	2,250 Rs/ha

Sources: Department of Agriculture, Punjab; Department of Farm Power and Machinery, PAU, Ludhiana; and progressive farmers of the state

Appendix 3. Rice variable production costs in RW rotation with conventional tillage

	Item	Cost (Rs/ha)
1	Seed	250
2	Seed treatment	0
3	Manure and fertilisers:	
	urea	896
	superphosphate	
	DAP	1,753
	MOP	223
	zinc sulphate	1,031
	ferrous sulphate (foliar sprays)	35
4	Plant protection (pesticides/fungicides/insecticides):	
	Monocrotophos 2 sprays	672
	Tilt 3 sprays	1,470
5	Herbicides:	
	Butachlor	540
6	Irrigations	490
7	Human labour	2,753
8	Tractor operations (tillage, sowing)	4,000
9	Harvesting by combine on contract basis	1,125
10	Marketing:	231.7
	unloading and cleaning/sieving (2)	210.0
	transportation	
11	Interest on operating capital @ 9% for 6 months	706
	Total cash variable expenses	16,385

Appendix 4. Maize variable production costs in MW rotation with conventional tillage

	Item	Cost (Rs/ha)
1	Seed	363
2	Seed treatment (Bavistan)	27
3	Manure and fertilisers: urea superphosphate DAP MOP	 1315 1167 223
4	Plant protection (pesticides/fungicides/insecticides: Thiodaan Sevin	63 90
5	Herbicides: Atrataf	375
6	Irrigations	99.5
7	Labour	4,105
8	Tractor operations (tillage, sowing)	3,375
9	Harvesting by combine on contract basis	0
10	Marketing: unloading and cleaning/sieving (2) transportation	 101 135
11	Interest on operating capital @ 9% for 6 months	514
	Total cash variable expenses	11,820

Appendix 5. Soybean variable production costs in SW rotation with conventional tillage

	Item	Cost (Rs/ha)
1	Seed	1,563
2	Seed treatment (Captan)	68
3	Manure and fertilisers: urea superphosphate	 335 1167
4	Plant protection (pesticides/fungicides/insecticides): Ekalux Nuvan Thiodaan Chlorpyriphos	 388 150 313 438
5	Herbicides: Stomp	 645
6	Irrigations	79.5
7	Human labour	3,375
8	Tractor operations (tillage, sowing)	3,375
9	Harvesting by combine on contract basis	0
10	Marketing: unloading and cleaning/sieving (2) transportation	 48.50 45
11	Interest on operating capital @ 9% for 6 months	540
	Total cash variable expenses	12,527

Appendix 6. Wheat variable production costs in RW rotation with conventional tillage

	Item	Cost (Rs/ha)
1	Seed	1,200
2	Seed treatment: Chlorpyriphos	 70
3	Manure and fertilisers: urea MOP	 1,315 223
4	Plant protection (pesticides/fungicides): Monocrotophos Karathene	 96 213
5	Herbicides: Leader	 1,813
6	Irrigations	97.5
7	Human labour	1,338
8	Tractor operations (tillage, sowing)	4,150
9	Harvesting: combine on contract straw trolley	 1,125 2,000
10	Marketing: unloading and cleaning/sieving (2) transportation	 186 169
11	Interest on operating capital @ 9% for 6 months	630
	Total cash variable expenses	14,623

Experiences with permanent beds in the rice–wheat systems of the western Indo-Gangetic Plain

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Abstract

Resource-conserving technologies with double no-till practices represent a major shift in production techniques for attaining optimal productivity, profitability and water use in rice–wheat (RW) systems in the Indo-Gangetic Plain. Permanent raised beds (PRB) and double no-till with flat layouts are under evaluation for RW systems for a range of soils, climate, cultivars and seeding / crop establishment techniques (dry seeding, transplanting). To date, results have been inconsistent and systematic information on trials with PRB is lacking. Four researcher- and farmer-managed experiments were conducted with various tillage and crop establishment techniques for RW on PRB and flat layouts. The yield of rice on PRB was significantly lower than that on double no-till flat layouts, whereas wheat yield was highest on PRB. The total RW system yield with PRB was similar to that of other tillage and crop establishment techniques. However, irrigation and input (irrigation plus rain) water productivity (kg grain/m^3 of water) of both rice and wheat was much higher on PRB. In farmer-managed trials of transplanted basmati rice on PRB, profitability was highest on PRB (US$684/ha) and lowest with traditional practices (US$531/ha). In a researcher-managed long-term experiment, the soil physical properties (bulk density, mean weight diameter of aggregates, cone index and infiltration rate) improved significantly on PRB compared with the conventional puddled transplanted rice-tilled wheat system.

Introduction

Rice and wheat have been grown as food crops for more than 6,000 years in Asia and the rice–wheat (RW) system has been practised for about 1,000 years. However, the intensive RW system that exists today evolved rapidly from the 1960s after the introduction of high-yield input responsive improved varieties. Timsina and Connor (2001) reported that nearly 85% of the RW systems of South Asia are located in the Indo-Gangetic Plain (IGP). However, as the national agricultural crop statistics are published according to individual crops rather than cropping systems, and as there are spatial and temporal variations between crops, most estimates of RW acreages are only subjective (Paroda et al. 1994; Hobbs and Morris 1996; Yadav et al. 1998; Timsina and Connor 2001). Although estimates of the RW acreage vary, most researchers seem to agree that rice and wheat together contribute more than 70% of the total cereal production. The estimated area of RW systems in the IGP totals 13.5 million hectares (Mha) (Ladha et al. 2003), of which 9.6 Mha is in India (Sharma et al. 2003). As there is meagre scope for expansion of the acreage under RW, there is increased pressure on the limited land, water and environment resources to produce more food to meet the increasing demand of the growing population. It is argued that stagnating or declining yields in both

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research stations and farmers' fields, declining factor productivity (decreased return per unit input) and degrading soil and water resources are threatening the sustainability of this system (Hobbs and Morris 1996; Sinha et al. 1998; Duxbury et al. 2000; Ladha et al. 2002). An agricultural system is regarded as sustainable if its biophysical and socioeconomic objectives are met; therefore, it is essential that performance of the system be continuously monitored for both its productivity and the condition of the natural resources (soil health and water availability) on which it depends (Powlson et al. 1998).

At the beginning of the Green Revolution, the key research priority was to accelerate the production of food grains through the development and introduction of high-yielding input responsive varieties, expansion of irrigation and increased use of agronomic inputs including inorganic fertilisers and pesticides. Investments from the public sector were crucial for making these inputs available and affordable to the farmers. Evidence is now appearing that continuous cropping of RW with traditional management has caused a decline in land and water productivity. Recently, analysis of several long-term RW experiments (Yadav et al. 1998; Dawe et al. 2000; Duxbury et al. 2000) indicated a negative yield trend in rice (–0.02 t/ha/year or 0.5% per year) under a fixed set of inputs and agronomic practices. The growing realisation that agriculture of the post-Green Revolution era will be guided by the need to produce more quality food from the same or less land and water resources while sustaining environmental quality only adds to the challenge. Thus, the major challenge for researchers is to develop alternative systems that produce more at less cost, and increase profitability and sustainability. This suggests that agricultural systems will need a mixture of new technologies that are able to unlock new sources of productivity growth and are more sustainable.

In recent years the major emphasis in RW systems has been on resource conservation technologies (RCTs) for both rice and wheat to reduce the cost of cultivation and energy consumption, sustain productivity and increase the profit margin of farmers. The RCTs under investigation include reduced and zero tillage of both rice and wheat, direct (wet, dry) seeding of rice, permanent raised beds (PRB) and residue retention. Permanent raised beds for RW represent a major shift in production practices. Changing from flat to bed layouts alters the geometry and hydrology of the system and offers greater control of irrigation and drainage and their effects on the transport and transformation of nutrients, and possibly better capture and use of rainfall (Connor et al. 2003). Reduced tillage and dry seeding with PRB can reduce the costs of labour, diesel, machinery, wheat seed and irrigation and allow more timely crop establishment (Connor et al. 2003). Hence, four studies were conducted under researcher-managed and farmer participatory trials to evaluate the productivity, profitability, water use and soil properties of RW systems using a range of tillage and crop establishment techniques including PRB.

Materials and methods

General site description

Two experiments comparing tillage and crop establishment techniques including PRB were conducted in researcher-managed trials at the Project Directorate for Cropping Systems Research (PDCSR) at Modipuram, India (29°4'N, 77°46'E, 237 m above sea level), and in two farmer participatory trials in Ghaziabad district of Uttar Pradesh and at Karnal, Haryana. The watertable was deep at all sites (23–30 m) with very good quality groundwater which was used for irrigation. The climate of the region is broadly classified as semi-arid subtropical, characterised by very hot summers and cold winters. The hottest months are May and June when the maximum temperature reaches 45–46 °C, while in December and January, the coldest months of the year, the minimum temperature often goes below 5 °C. Average annual rainfall is 863 mm, 75–80% of which is received through the north-western monsoon during July–September. In general the soils of the experimental sites and farmers' fields were sandy loams with medium fertility. The topsoil (0–30 cm) at the PDCSR sites (experiments I and II) is a sandy loam overlying a fine sandy loam (30–170 cm). The particle size distribution of the 0–20 cm soil layer is 68.6% sand, 17.1% silt and 14.3% clay. All rice yields are presented at 14% moisture and wheat yields are dry.

Experiment I, Modipuram

The experiment was initiated during with the monsoon (rice) season in 2005 in collaboration with IRRI and the RWC. The experiment compared eight treatments (Table 1) consisting of four tillage/establishment methods with and without groundcover for both crops (sesbania in rice; wheat with rice residues). All treatments were tilled and/or sown with implements powered by a 35 hp four-wheel tractor, and were irrigated prior to either the first tillage operation or to seeding in the case of zero-till wheat (ZTW). A randomised block design (RBD) with three replications was used with a plot size of 20 × 6 m (120 m^2).

The details of the treatments are:

Puddled transplanted rice and zero-till wheat (PTR-ZTW)

Rice (PTR). Conventional puddling (four tillage operations in 'dry' soil—two disc harrowings, two passes of tine harrows followed by two wet-tillage operations using rotary hoe and one planking) followed by manual transplanting of 21-day-old seedlings at 20 × 20 cm spacing. The plots were kept flooded (5±2 cm submergence) for the first 2 weeks after transplanting to assist establishment and weed control. After that the plots were allowed to dry until hairline cracks appeared on the soil surface, at which time they were irrigated until floodwater depth reached 5±2 cm.

Wheat (ZTW). Wheat was sown at 100 kg seed/ha in rows 20 cm apart using a zero-till seed-fertiliser drill with no prior tillage. The wheat was irrigated whenever tensiometer readings increased to 70 kPa at 15 cm soil depth.

Conventional tillage, dry-seeded rice and zero-till wheat (CTDSR-ZTW)

Rice (CTDSR). Five tillage operations in 'dry' soil—two disc harrowings, two passes of tine harrows and one planking, and rice seeding at 25 kg/ha in rows spaced 20 cm apart using a seed-fertiliser drill with a cup-type seed metering system. The DSR was sown on the same day as the nursery was sown for transplanted rice. The plots were irrigated immediately after sowing and again 5 days later, and subsequent irrigations (5±2 cm) were applied whenever tensiometer readings at 15 cm depth increased to 40 kPa. In 2005–06 there were five post-sowing irrigations of 5±2 cm depth.

Wheat (ZTW). As above.

Zero-till dry-seeded rice and zero-till wheat (ZTDSR-ZTW)

Rice (ZTDSR). Rice was sown on the same day as CTDSR without any prior tillage using the zero-till seed-fertiliser drill with the cup-type seed metering system. Sowing rate, row spacing and irrigation scheduling were as for CTDSR.

Wheat (ZTW). As above.

Dry-seeded rice and wheat on PRB (PBDSR-PBW)

Rice (PBDSR). At the beginning of the experiment the beds were prepared, using the raised bed planter, after harvest of the preceding wheat crop following conventional tillage, and were left to settle for 30 days. The beds were 37 cm wide (top of the bed) and 15 cm high, with a 30 cm furrow width (at top). Thus, the spacing between the centres of adjacent furrows was 67 cm. The rice was sown with the same bed planter on the same day as CTDSR and ZTDSR. Two rows (25 cm spacing) of rice were sown at 25 kg seed/ha on each bed. Two light irrigations were applied immediately after sowing and a few days

Table 1. Productivity of rice–wheat systems under various tillage and crop establishment techniques (experiment I, Modipuram; year 1 2005–06)

Crop establishment		Grain yield (t/ha)		
Rice	Wheat	Rice	Wheat	RW system
PTR+S	ZTW +R	7.50	4.34	11.84
PTR	ZTW	7.62	3.63	11.25
ZTDSR+S	ZTW +R	7.05	4.46	11.51
ZTDSR	ZTW	7.33	4.12	11.45
PBDSR+S	PBW +R	6.03	4.46	10.48
PBDSR	PBW	6.09	3.93	10.02
CTDSR+S	ZTW +R	7.44	4.34	11.77
CTDSR	ZTW	7.56	3.89	11.45
SE	(N=3)	0.49	0.12	0.51
LSD	(0.05)	1.49	0.38	1.54

PTR = puddled transplanted rice; +S = *Sesbania* as groundcover; ZTDSR = zero-till dry-seeded rice; PBDSR = permanent beds dry-seeded rice; CTDSR = conventionally tilled dry-seeded rice; +R = rice residues; ZTW = zero-till wheat; +R = rice residues; PBW = wheat on permanent beds.

later, and thereafter the plots were irrigated whenever tensiometer readings increased to 30 kPa. The tensiometers were located in the middle of the beds at 15 cm depth. The furrows were filled to about 85% depth (12–13 cm) at each irrigation.

Wheat (PBW). The beds/furrows were reshaped using the bed planter with minimal disturbance in the beds, and wheat was sown (two rows spaced at 30 cm, 80 kg seed/ha) with the bed planter at the same time as reshaping. Irrigation scheduling was as in ZTW, with the tensiometers at 15 cm depth in the middle of the beds. The furrows were filled to about 85% depth (12–13 cm) at each irrigation, as for the rice on beds.

Management of groundcover

Sesbania (+S) in rice. In the dry-seeded rice plots sesbania (*Sesbania aculeata*) was broadcast at 15 kg seed/ha on the same day as rice seeding. Thirty days after seeding the sesbania was killed by spraying with 2,4-D ester @ 400 g a.i./ha. In the transplanted rice sesbania was sown ex-situ on the same day as the dry seeding, and was applied as a green manure mulch (after cutting into 10–12 cm lengths) to the transplanted rice on the same day as it was sprayed in the DSR plots.

Rice residues in wheat (+R). Rice residues (partially anchored, partially loose) amounting to 6 t/ha were retained in the +R treatments. In the raised beds the rice residues were cut at ground level and removed before sowing, then spread uniformly as mulch after sowing. In the flat plots wheat was direct drilled into the rice residues using a double-disc drill.

General trial management

Crop residue management. All wheat residues were removed from all plots, and rice residues (to a total of 6 t/ha) were returned to the +R plots after wheat sowing.

Seeding and seed rate. Rice was sown on 1 June 2005 in DSR plots at 25 kg seed/ha on the same day the nursery was sown for transplanting. Transplanting was done 25 days after sowing. The wheat was sown on 15 November using 80 kg seed/ha. The seed-fertiliser zero-till drill and bed planter were calibrated prior to seeding. Rice hybrid PHB-71 and wheat variety PBW-343 were used.

Fertiliser application. For rice the equivalent of 150 kg N, 60 kg P_2O_5, 40 kg K_2O and 8.75 kg Zn per ha and for wheat 120 kg N, 60 kg P_2O_5 and 40 kg K_2O per ha were applied. Half the N and all the P, K and Zn were applied at sowing/transplanting and the remaining N was applied in two equal splits in both rice and wheat.

Weed management. The crop was maintained weed free using the following practices:

Rice: Weeds that germinated prior to seeding of rice and wheat in the zero-till plots were killed by spraying glyphosate @ 900 g a.i./ha. Butachlor @ 1,300 g a.i./ha was applied 2 days after transplanting (DAT) to the transplanted rice, while pendimethalin @ 1,000 g a.i./ha was applied 2 days after sowing (DAS) to the dry-seeded rice to control grassy weeds, followed by a spray application of 2,4-D ester @ 400 g a.i./ha at 25–30 DAS for broadleaf weeds. Additionally, one hand weeding was done to keep the plots weed free.

Wheat: Grassy weeds were controlled by spraying sulfosulfuron @ 35 g/ha at 21 DAS, and broadleaf weeds were controlled using 2,4-D @ 500 g a.i./ha at 35 DAS.

Maintenance of the beds. The beds were reshaped prior to wheat sowing using the bed-planter drawn by a four-wheel tractor.

Harvesting. At maturity rice and wheat were harvested manually and the grain and straw yields were determined from an area of 60 m^2 in the centre of each plot. The grains were separated from the straw using a plot thresher, dried in a batch grain dryer and weighed. Grain moisture was determined immediately after weighing. Grain yields of rice and wheat are reported at 14% and 12% moisture content, respectively.

Financial analysis

For financial analysis, all the costs involved for all the inputs (land preparation, seed, crop establishment, labour, agrochemicals, weed management, irrigation water, harvesting, threshing, transportation etc) were computed. Net profitability was calculated by subtracting the total cost of production from the gross income (at the Government of India minimum support price).

Experiment II, Modipuram

A long-term RW experiment was initiated during the monsoon season of 1998 at PDCSR research farm. Four tillage/crop establishment techniques were compared:

- PTR-CTW: puddled transplanted rice and conventionally tilled wheat
- ZTDSR-ZTW: zero-till dry-seeded rice and zero-till wheat

- CTDSR-RTW: conventionally tilled dry-seeded rice and reduced-till wheat using the rotary till drill for wheat
- PBDSR-PBW zero-till dry-seeded rice and zero-till wheat on PRB.

The PRB were reshaped before or at sowing/planting of each crop with minimal soil disturbance (zero harrowing). The seed rate for rice and wheat in all treatments was 30 kg seed/ha and 100 kg seed/ha, respectively, and there were three rows on the beds. The experiment was a randomised block design with three replicates in a plot size of 40 m^2. Rice hybrid PHB-71 and wheat variety PBW-343 were sown using the raised bed planter and zero-till drills with a fluted roller type seed metering system.

The changes in soil physical properties after eight crop cycles were determined on soil samples (0–15 cm) from the top (middle) of the beds in PRB and from between the rows in the flats. Bulk density was determined from undisturbed cores collected in rings at 5 cm intervals up to 20 cm soil depth. The samples were oven dried at 105 °C for 24 hours to calculate soil water content and bulk density. The plots were irrigated after harvest and soil strength was measured when soil water content was close to field capacity using a manual cone penetrometer with a 2 cm^2 cone. Soil penetration resistance was recorded every 5 cm up to 45 cm soil depth at three locations in each plot after harvest of rice and wheat crops. To determine soil aggregation, large clods were collected from each plot after harvest of the crop and sun dried, then oven dried. Large clods were broken by hand into small pieces ranging from 4.75 mm to 8 mm in size. Water-stable soil aggregates were determined by using the wet sieve procedure (Yoder method). Infiltration rate was measured using double ring infiltrometers in each plot (three replicates) after harvest of the eighth crop. The initial infiltration rate was measured at 5, 15, 30 and 60 minutes intervals and steady state infiltration was measured after 24 hours.

Experiment III, Ghaziabad

Farmer participatory trials on tillage and crop establishment techniques were carried out at three locations (one farmer at each location) in Ghaziabad district for 2 years. Three tillage and crop establishment techniques were studied in the RW system, with the following treatments:

- puddled transplanted rice and conventionally tilled wheat (PTR-CTW)
- puddled transplanted rice and zero-till wheat (PTR-ZTW)
- transplanted rice on PRB and wheat on PRB (PBTR-PBW)

A basmati rice variety (PB-1) and PBW-343 wheat were used at all three locations. The rice was transplanted halfway up the sides of the beds rather than on the top. Each farmer plot (0.2–0.3 ha) was considered as one replication and data were analysed using a randomised block design. Sowing and reshaping of the beds were done at the same time in wheat, while reshaping was done prior to transplanting rice. A bed planter powered by a four-wheel tractor was used.

Experiment IV, Haryana

In farmer participatory trials in Haryana, transplanted rice on PRB followed by wheat on PRB (PBPTR-PBW) was compared with puddled transplanted rice and conventionally tilled wheat (PTR-CTW) for 3 years at two locations (two farmers) on silty loam soils. The beds were reshaped for each crop using a bed planter powered by a 4-wheel tractor in the same operation as wheat sowing, and prior to rice transplanting, on the beds. The rice hybrid HKR-126 and wheat variety PBW-343 were used for the experimental purposes. The average yield of each treatment at the two locations was calculated.

Results and discussion

Experiment I

Crop yields

Profitability. Yields of zero-till and conventionally tilled dry-seeded rice and puddled transplanted rice were similar and significantly higher than yield of dry-seeded rice on beds (Table 1). There was a consistent trend for lower yields with sesbania co-culture but the differences were not significant in any tillage / crop establishment treatment. Wheat yield was similar in all four tillage / crop establishment treatments, but there was a consistent trend for higher yield with rice-residue retention. The difference was significant in the case of ZTW after PTR. The crop residues retained as surface mulch (partially anchored and partially loose) would have helped in regulating the soil temperature and moisture, but it is assumed the greater yield response was mainly due to the aberration in weather conditions during the crop growth period (winter 2005–06 was abnormal in terms of weather). Green and Lafond

(1999) reported that surface residues in a no-till system helped to buffer soil temperature and that, during winter, soil temperature (at 5 cm depth) with residue removal and conventional tillage was on average 0.29 °C lower than that with no tillage and surface retained residues. Conversely, soil temperature during summer was 0.89 °C higher under conventional tillage than the no-till situation with surface residue retained. Total system productivity was similar in all treatments except PRB without sesbania and residue retention, which had significantly lower productivity than all other treatments, including the sesbania / residues retained PTR-ZTW, ZTDSR-ZTW and CTDSR-ZTW treatments.

There was a consistent trend for higher net return for dry-seeded rice on the flat (with zero or conventional tillage), while dry-seeded rice on beds had the lowest returns, but there were almost no significant differences (Table 2). The lower net income with the beds was due to the cost of preparing the beds in the first season—further analysis spreading the cost over the life of the beds is needed. There was a consistent trend for lower net income for rice with sesbania co-culture, largely due to the trend for lower yields. There was little effect of a preceding rice treatment on net income of wheat (zero-till in all tillage / crop establishment treatments). However, there was a consistent trend for higher net income with rice-residue retention in all treatments, and the differences were always significant (or almost significant in the case of CTDSR-ZTW). Further, the profitability of wheat was significantly higher with residue retention compared with residue removal and the difference was more under PTR-ZTW compared with other practices. The maximum net income of the system was with ZTDSR-ZTW but this was only significantly higher than net income from TPR-ZTW and PBDSR-PBW.

Input water use and water productivity

The input water use includes both irrigation water applied and the rainwater that fell during the rice season (815 mm) and wheat season (81 mm), but not the pre-cultivation/sowing/planting irrigations. The total input water in rice varied with tillage / crop establishment treatment (Table 3) due to differences in irrigation amount. The conventional puddled transplanted rice consumed about 5% more water (2,687 mm) than dry-seeded rice (2570 mm) with zero conventional tillage, and 11% more water than with beds (2,410 mm). Similarly, the water use in wheat on PRB was 15–18% lower than with other tillage / crop establishment practices with the same rice-residue management. The higher irrigation water use in wheat with residue retention resulted from one good rainfall just before an irrigation was due in the residue removed treatments, saving one irrigation. The total system water input was least with PRB and about 11% less than with PTR-ZTW. There were no significant differences in input water productivity between any treatments for rice or the total system. However, input water productivity of wheat on PRB was significantly higher than in all other treatments, with and without rice mulch. There was also a consistent trend for higher wheat input water productivity with rice-residue retention, but the differences were not significant.

Table 2. Profitability of rice–wheat systems with different tillage and crop establishment methods (experiment I, Modipuram; mean of 1 year)

Crop establishment		Net returns (US$)			Benefit:cost ratio		
Rice	Wheat	Rice	Wheat	RW system	Rice	Wheat	RW system
PTR+S	ZTW +R	422	638	1,060	1.77	2.81	2.18
PTR	ZTW	442	445	887	1.81	2.26	1.99
ZTDSR+S	ZTW +R	467	661	1,128	2.05	2.87	2.41
ZTDSR	ZTW	507	566	1,073	2.14	2.60	2.35
PBDSR+S	PBW +R	300	653	953	1.62	2.88	2.15
PBDSR	PBW	312	535	847	1.65	2.54	2.03
CTDSR+S	ZTW +R	483	603	1,086	2.00	2.71	2.30
CTDSR	ZTW	502	511	1,013	2.05	2.45	2.22
SE (N=3)		63.8	31.4	71.56	0.13	0.09	0.08
LSD (0.05)		193.7	95.1	217.1	0.39	0.27	0.25

PTR = puddled transplanted rice; +S = *Sesbania* as groundcover; ZTDSR = zero-till dry-seeded rice; PBDSR = permanent beds dry-seeded rice; CTDSR = conventionally tilled dry-seeded rice; ZTW = zero-till wheat; +R = rice residues; PBW = wheat on permanent beds

Experiment II

Crop yields

In the eighth crop cycle, rice yield was significantly higher with PTR than all other tillage and crop establishment techniques (Table 4). Conversely, yield of CTW following PTR was significantly lower than yield of the three unpuddled treatments. There was no significant difference in yield of wheat in the double zero-till flat and PRB treatments and the reduced-till treatment. Total system productivity was about 10% lower with PRB than all other treatments due to lower rice yield.

Input use and saving

There were considerable savings in diesel, total cost of inputs, energy and irrigation water with double zero-till beds and flats in comparison with PTR-CTW. In PRB the savings in time, labour, diesel, cost, energy and water compared with PTR-CTW were 81%, 78%, 86%, 80%, 85% and 38% respectively (Figure 1).

Soil physical properties

After eight crop cycles the soil physical properties (bulk density, mean weight diameter of aggregates, infiltration rate, cone index) in the surface (0–15 cm) layer showed significant treatment differences (Table 5). The mean weight diameter of aggregates (MWD) was significantly higher in the double no-till systems (0.41 mm, 0.58 mm) than the initial value of 0.35, and declined significantly to 0.23 mm in the tillage treatments. However, MWD in the puddled and dry-tilled treatments was similar. Infiltration rate in PRB was more than double that in PTR-CTW, and almost double that in the flat DSR treatments. Infiltration rate with double zero tillage was similar to that with dry tillage. Infiltration in the flat DSR treatments was

Table 3. Input water use and water productivity of rice–wheat systems under different tillage and crop establishment techniques (experiment I, Modipuram; mean of 1 year)

Crop establishment		Input water use (mm)			Input water productivity (kg grain/m^3)		
Rice	Wheat	Rice[a]	Wheat[b]	RW system	Rice	Wheat	RW system
PTR+S	ZTW+R	2,687	510	3,197	0.279	0.851	0.370
PTR	ZTW	2,687	480	3,167	0.284	0.756	0.355
ZTDSR+S	ZTW+R	2,570	498	3,068	0.274	0.895	0.375
ZTDSR	ZTW	2,570	479	3,049	0.285	0.861	0.376
PBDSR+S	PBW +R	2,410	421	2,831	0.250	1.060	0.370
PBDSR	PBW	2,410	396	2,806	0.253	0.992	0.357
CTDSR+S	ZTW+R	2,570	516	3,086	0.289	0.840	0.381
CTDSR	ZTW	2,570	493	3,063	0.294	0.789	0.374
SE (N=3)		–	–	–	0.019	0.033	0.016
LSD (0.05)		–	–	–	0.057	0.10	0.050

[a] Includes rainwater (815 mm) during rice season; [b] rainwater (81.2 mm) during wheat season
PTR = puddled transplanted rice; +S = *Sesbania* as groundcover; ZTDSR = zero-till dry-seeded rice; PBDSR = permanent beds dry-seeded rice; CTDSR = conventionally tilled dry-seeded rice; ZTW = zero-till wheat; +R = rice residues; PBW = wheat on permanent beds.

Table 4. Long-term effect of tillage and crop establishment techniques on productivity of rice–wheat system techniques (experiment II, Modipuram; 8th crop)

Crop establishment		Grain yield (t/ha)		
Rice	Rice	*Rice* [A]	*Wheat* [A]	RW system
PBDSR	PBW	6.20 a	5.70 a	11.87
ZTDSR	ZTW	7.40 b	5.70 a	13.15
CTDSR	RTW	7.20 b	5.50 a	12.75
PTR	CTW	8.10 c	5.10 b	13.22
LSD (0.05)		0.23	0.27	–

[A] Values in the same column followed by different letters are significantly different from each other at 5% probability level
ZTDSR = zero-till dry-seeded rice; PBDSR = permanent beds dry-seeded rice; CTDSR = conventionally tilled dry-seeded rice; PTR = puddled transplanted rice; PBW = wheat on permanent beds; ZTW = zero-till wheat; RTW = reduced-till wheat; CTW = conventionally tilled wheat.

significantly higher than in PTR-CTW. Bulk density of the surface layer (0–15 cm) under double no-till did not change over the initial value, but under conventional dry and wet-tillage practices it increased significantly. The mean cone index (0–40 cm) increased significantly in all treatments but by significantly more under the conventional tillage systems.

Experiment III

In the farmers' fields, rice (basmati type), wheat and total system yields were similar in all three treatments (Table 6). Net profitability of rice was similar in all treatments but the profitability of wheat was significantly higher with PRB (US$329/ha). There

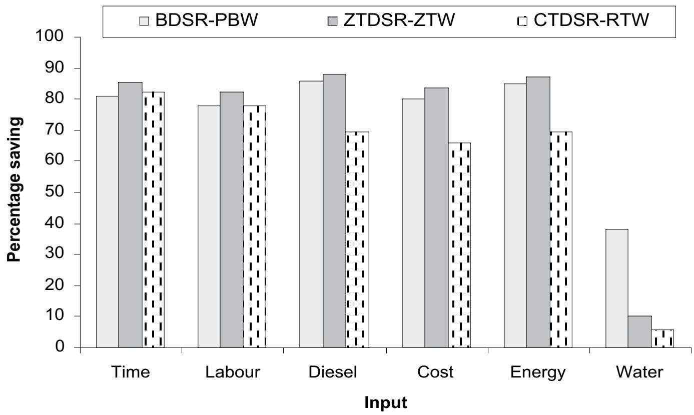

Figure 1. Relative saving of input use (%) over conventional practice of RW (PTR-CTW). Data from experiment II, Modipuram, 1998–2005.

Table 5. Physical and chemical properties in different permanent tillage techniques after 8 years (experiment II, Modipuram)

Treatment	MWD[a] (mm)	Infiltration rate (mm/hour)	Bulk density (Mg/m^3)	Cone index
PBDSR-ZTW	0.41	87.4	1.56	2.45
ZTDSR-ZTW	0.58	49.5	1.54	2.41
CTDSR-RTW	0.28	52.2	1.62	2.60
PTR-CTW	0.23	33.4	1.65	2.83
Initial	0.35	–	1.54	2.30
CD (0.05)	0.07	9.7	0.03	0.11

[a] mean weight diameter
ZTDSR = zero-till dry-seeded rice; PBDSR = permanent beds dry-seeded rice; CTDSR = conventionally tilled dry-seeded rice; PTR = puddled transplanted rice; ZTW = zero-till wheat; RTW = reduced-till wheat; CTW = conventionally tilled wheat.

Table 6. Productivity and profitability of RW under PRB planting in farmer managed plots (experiment III, Ghaziabad; average of 2 years)

Crop establishment		Yield (t/ha)			Net profit (US$/ha)		
Rice	Wheat	*Rice*[A]	*Wheat*[A]	*RW system*[A]	*Rice*[A]	*Wheat*[A]	*RW system*[A]
PTR	CTW	4.30 a	4.60 a	8.90 a	285 a	246 a	531 a
PBTR	PBW	4.08 a	4.57 a	8.65 a	355 a	329 b	684 a
PTR	ZTW	4.38 a	4.77 a	9.15 a	302 a	350 b	652 a
SE (N=3)		0.12	0.16	0.27	23.1	23.3	44.5
LSD (0.05)		ns	ns	ns	ns	80.6	153

[A] Values in the same column followed by different letters are significantly different from each other at 5% probability level; ns = treatment differences are statistically non-significant at 5% level of significance was a trend for higher total system profitability as the amount of tillage decreased, and profitability was almost significantly higher (P=0.05) with permanent beds (US$684/ha) than with conventional tillage for both crops (PTR-CTW, US$246/ha).

Experiment IV

There were only small differences in yield of wheat on PRB and with conventional RW tillage (Figure 2). Yield of rice on PRB was lower than with conventional tillage and the difference increased as the beds aged, from 10% of yield of PTR-CTW in the first year to 77% of PTR-CTW in the third year.

Conclusions

The results of the researcher- and farmer-managed experiments on PRB in RW systems across the western Indo-Gangetic Plain showed a consistent trend in crop productivity under PRB. Dry-seeded rice on PRB had significant yield penalty compared with conventional PTR. However, transplanting basmati rice on slopes of PRB (experiment III) gave yields comparable to conventional PTR. The wheat productivity on PRB across seasons and sites was comparable to conventionally tilled wheat. The overall system productivity under PBDSR-PBW was lower than conventional practice but comparable under PBPTR-PBW. Residue retention increased yield in all tillage / crop establishment treatments in the one year for which it has been assessed to date. There was saving in irrigation water with PRB but input water productivity was similar to conventional practice due to the yield penalty in PBDSR. However, input water productivity of wheat increased significantly on PRB. RW system profitability in PBDSR-PBW was lower than conventional practice but higher with PBPTR-PBW. However, these analyses did not take into account the life of the permanent beds, with all the costs of initially making the beds attributed to the first crop. Soil physical properties were improved after 8 years by avoidance of puddling, and the improvement was greatest in most properties in PRB, followed by double zero tillage on the flat. By analysing the results of experiments on PRB across the western IGP, it is concluded that for sustaining RW system productivity and profitability on PRB, more efforts are needed in evaluating genotype x tillage / crop establishment interaction, and irrigation and fertiliser management schedules, particularly in dry-seeded rice.

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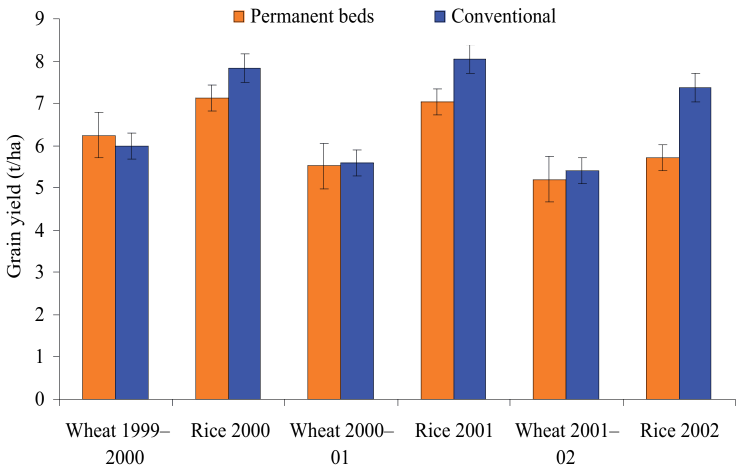

Figure 2. Yield trends in rice–wheat system with PRB and conventional tillage system (experiment IV, Haryana). Vertical bars are standard deviation.

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Performance of furrow-irrigated raised beds in rice–wheat cropping systems of the Indo-Gangetic Plain

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Abstract

A 2-year experiment was conducted to evaluate the effect of permanent raised bed (PRB) systems on productivity and income of the rice–wheat systems of the Indo-Gangetic Plain compared with conventional farmers' practices. Both dry-seeded and transplanted rice on beds yielded less, by 8–25%, than conventional puddled transplanted rice. There was no effect of tillage and establishment method on wheat yield. Total system productivity (rice equivalent yield) of the PRB systems was lower than productivity of the conventional system by 2–16%. Net returns of the PRB systems were also significantly lower than returns of the conventional systems, except in the PRB system with transplanted rice in the low rainfall year, when irrigation water use of puddled transplanted rice was very high. The results indicate that there is a need to improve bed-planting systems to increase productivity in rice while capturing the benefits of reduced irrigation requirement.

Introduction

The rice–wheat (RW) cropping systems of the Indo-Gangetic Plain (IGP) are of immense importance for food security for South Asia. However, there are emerging threats to the sustainability of RW systems, including yield stagnation/decline, water and labour scarcity, and soil, water and air pollution (Ladha et al. 2003). Therefore, the design and implementation of alternative production systems with increased resource use efficiency, profitability and productivity, and reduced adverse environmental impact, are urgently required. One of the strategies to address emerging problems, specifically shortages of water and labour, is to grow rice and wheat on furrow-irrigated, permanent raised beds (PRB). The shift from puddled transplanted rice on flat land to PRB systems affects the productivity and resource use efficiency of the RW system. Therefore, the potential benefits and constraints of PRB systems need to be quantified, and optimum layouts and management systems identified, to maximise yield and input use efficiency. The objectives of our study were to evaluate the effect of PRB systems on productivity and income of the RW systems of the IGP in comparison with conventional farmers' practices.

Materials and methods

The experiment was conducted at the research farm (29°01'N, 77°45'E, 237 m above mean sea level) of Sardar Vallabh Bhai Patel University of Agriculture and Technology, Meerut, Modipuram (Uttar Pradesh), India, during 2002–04. The climate of the area is semi-arid, with average annual rainfall of 800 mm, 75–80% of which is received during July to September, minimum temperature of 0–4 °C in Jan-

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uary, maximum temperature of 41–45 °C in June, and relative humidity of 67–83% during the year. The soil (at 0–15 cm depth) at the experimental site was a silty loam, with particle density of 2.65 Mg/m^3. The surface soil (0–15 cm) had 8.3 g/kg total C, 0.88 g/kg total N, 25 mg/kg Olsen P and 0.31 meq/100 g 1N NH_4OAC-extractable K.

Six treatment packages (TP-1 to TP-6) involving three tillage and two rice establishment methods were evaluated in the RW rotation during 2002–03 (year 1) and 2003–04 (year 2) using a randomised complete block design with three replicates (Table 1). The full experimental details and results have been given elsewhere (Bhushan et al. 2007). In this report we provide the highlights of the 2-year study with special emphasis on the raised bed system.

Results and discussion

Yields of rice and wheat

Rice either direct drill-seeded (TP-3) or transplanted (TP-4) on beds yielded 8–25% less than conventional puddled transplanting (TP-1) (Table 1). Rice on beds apparently suffered from water stress more than on flat land, resulting in lower yields. Poor panicle formation, higher sterility and poor tillering were also recorded in these treatments (data not shown). Borrell et al. (1997) observed that the raised bed system saved 16–43% water compared with puddled transplanted rice, but at the expense of yield. Similarly, a yield reduction of more than 15% was reported when rice was grown on raised beds compared with the puddled transplanted system (Sharma et al. 2003). Yields were similar when rice was conventionally transplanted (TP-1), direct drill-seeded after zero tillage (TP-5) and transplanted in slits after zero tillage (TP-6). Tillage and crop establishment methods had no effect on wheat yield. The rice equivalent yields in the raised bed systems (TP-3 and TP-4) were lower by 2–16% than in the conventional system (TP-1). The data indicated that there is a need to improve bed-planting systems to increase productivity in rice.

Net income

The highest return in year 1 was obtained in the direct drill-seeded rice after zero tillage (TP-5), whereas in year 2 conventional puddled transplanted rice (TP-1) gave the highest return (Table 2). The net returns in different treatments were largely governed by the amount of irrigation application. The larger application of irrigation water because of lower rainfall in year 1 increased the cost of cultivation in TP-1. As the irrigation requirement was lower in TP-5 than in TP-1, while yields were similar, the net return was higher in TP-5. Because of more rainfall in year 2, the irrigation cost was low in TP-1, resulting in a higher net return. Thus, the analysis showed that rainfall is an important determinant of the net return in a particular treatment. The rice on raised beds had the lowest return—about 50% of either TP-1 or TP-5. The data showed that, although savings were made in land preparation and irrigation water application in direct-seeded rice (TP-3 and TP-5), weed management incurred higher cost than with conventional systems.

Table 1. Yield of rice and wheat with various tillage and crop establishment practices

Treatment package	Rice	Wheat	Grain yield[A] (t/ha)	
			Rice[B]	*Wheat*[B]
TP-1	Conventional puddled transplanting	Conventional drill-sown	7.3 a	4.5 a
TP-2	Conventional puddled transplanting with mid-season drying	Zero-till drill-sown	6.8 ab	4.8 a
TP-3	Direct drill-seeded on raised beds	Zero-till drill-sown on beds	5.9 c	4.6 a
TP-4	Transplanted on raised beds	Zero-till drill-sown on beds	6.5 b	4.5 a
TP-5	Zero-till drill-seeded	Zero-till drill-sown	7.0 a	4.6 a
TP-6	Zero-till transplanted	Zero-till drill-sown	7.0 a	4.9 a

[A] Averages of 2 years
[B] Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by Duncan's multiple range test.

Table 2. Net returns from rice in various tillage and crop establishment practices

Treatment package[A]	Net return (US$/ha)	
	2002[B]	*2003*[B]
TP-1	270 b	409 a
TP-2	249 b	407 a
TP-3	176 c	186 c
TP-4	236 b	337 b
TP-5	324 a	354 b
TP-6	262 b	405 a

[A] Refer to Table 1 for a description of treatment packages. Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by Duncan's multiple range test.

Conclusions

The emerging shortages and increasing costs of water and labor necessitates a change in the way farmers currently grow rice and wheat crops. The furrow-irrigated raised beds system is seen as an alternative to conventional practice. However, this 2-year study showed that rice on PRB did not perform well, while the performance of wheat on beds was comparable to the double zero tillage system and conventional practice. For the total RW system, the performance of PRB was inferior to the double zero tillage system. Therefore, more effort will be needed to improve the PRB technology on a site- and season-specific basis for rice and wheat. In addition, long-term changes in the performance of crop and soil and the efficiency of various inputs should be monitored to achieve this shift in farmers' practices.

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Wheat–maize–rice cropping on permanent raised beds in Bangladesh

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Abstract

Rice–wheat (RW) cropping systems are critical to food security of the increasing population in Bangladesh. However, the sustainability of RW systems is threatened by productivity decline and environmental sustainability. Crop production on permanent raised beds (PRB) is expanding worldwide as a way to increase system productivity, diversify cropping and improve the efficiency of resource use, especially water. When coupled with raised beds, straw retention can improve soil moisture retention, soil health and crop productivity. A 3-year study was conducted at the Wheat Research Centre, Dinajpur, Bangladesh, to compare the effects of four N fertiliser rates (0%, 50%, 100% and 150% of the recommended rate) and four straw retention (SR) / tillage treatments (100% SR of all crops + permanent raised beds (PRB), 50% SR + PRB, 0% SR + PRB and 0% SR + conventional tillage on the flat (CTF)) in a RW–maize cropping system. Permanent beds with straw retention produced the highest grain yields for all three crops in the sequence. Within each N rate the total system (rice+wheat+maize) productivity was greatest with 50–100% SR on PRB and least in CTF with zero straw retention. At 100% of recommended fertiliser N rate, mean annual system productivity was 17.9–19.7 t/ha for PRB with 50–100% SR, 15.7 t/ha with PRB without SR and 14.1 t/ha with CTF without straw. For all three crops, yields of PRB with 50% and 100% SR were similar. These benefits from straw retention with PRB were established within 2–3 years. Yield in N-unfertilised plots increased when straw was retained due to increased supply and uptake of N. The results suggest that N fertiliser rates can be reduced when straw is retained. Soil organic matter in surface soil layers of the PRB had increased by 13–41% after 4 years (ie four rice+wheat+maize crop cycles) with straw retention, with a greater increase with 100% SR than 50% SR. Soil organic C in PRB without SR was similar to the initial organic C prior to bed formation. Straw retention is an important component of soil management and may have long-term positive impacts on soil quality. Compared with conventional tillage on the flat with all crop residues removed, the combination of PRB with residues retained appears to be a very promising technology for sustainable intensification of RW systems in Bangladesh.

Introduction

Land degradation and soil fertility decline are among the main causes of the stagnation and fall of agricultural production in many tropical countries, including those with intensive irrigated cropping systems. Approximately 85% of the area planted with intensive rice–wheat (RW) sequential cropping is found in the Indo-Gangetic Plain (IGP) of South Asia in India, Pakistan, Nepal and Bangladesh (Timsina and Connor 2001). Rice is transplanted in flat fields after intensive cultivation and puddling, and fields are typically ponded for long periods or continuously from transplanting until shortly before harvest. This negatively affects soil properties for the following non-puddled crop (Hobbs and Giri 1998). Wheat is then planted in these structurally disturbed soils,

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often after many tillage operations to prepare the seedbed or, increasingly, with little soil disturbance using zero-till seed drills.

A change from growing crops on the flat to raised beds offers more effective control of irrigation water and drainage. This may be particularly beneficial for non-rice crops grown in rotation with rice, allowing better rainwater management during the monsoon season for rice. Connor et al. (2003) suggested that permanent raised beds might offer farmers further significant advantages such as increased opportunities for crop diversification, mechanical weeding and placement of fertilisers; relay cropping and intercropping; and reduced tillage and water savings. There are also indications that crop yields from beds can be further increased by using higher rates of N fertiliser and later irrigation because of the reduced risk of lodging (Sayre and Ramos 1997). Raised beds are increasingly used in many developed and developing countries in mechanised agriculture but have been introduced only recently in Bangladesh, with the aim of improving system productivity (Talukder et al. 2002).

Crop residues are an important source of soil organic matter vital for the sustainability of agricultural ecosystems. About 25% of N and P, 50% of S and 75% of K uptake by cereal crops is retained in crop residues, making them valuable nutrient sources (Singh 2003). However, straw retention is not a common practice in the RW systems of Bangladesh, as is also the case elsewhere in South Asia. Wheat and rice straw are usually removed from fields for use as cattle feed and for purposes such as livestock bedding, thatching material for houses or for fuel, leaving little for incorporation into the soil. The exception is in the north-western IGP, where most of the rice residues are burnt. Due to the limited number of livestock, farmers throughout the IGP have access to very limited amounts of organic manure. As a result, soil organic matter levels have declined in these cropping systems, and optimisation of nutrient uptake and absorption efficiency has become one of the most important goals in crop production strategies. Talukder et al. (2002) reported that N use efficiency was highest in permanent raised beds, giving higher yields than a conventional system. Limon-Ortega et al. (2000) observed that permanent beds with straw retention had the highest mean wheat grain yields (5.57 t/ha), N use efficiency (28.2 kg grain/kg of N supply) and total N uptake (133 kg/ha), with positive implications for soil health.

Thus, crop residue management and beds, along with efficient N fertilisation strategies, are likely to be key components of new farming practices that can increase and maintain yields from the intensive RW system in Bangladesh. In this paper we report on station research undertaken in north-western Bangladesh to:

- evaluate yields of intensive multicrop wheat–maize–rice sequences on PRB compared with those grown on conventionally tilled flat systems
- assess the effect of mulching on crop performance and soil properties on PRB
- assess N level effects on yield and estimate N use efficiency
- study the changes in soil properties over time.

Methods

A cool season wheat (*Triticum aestivum*) – spring maize (*Zea mays*) – monsoon rice (*Oryza sativa*) cropping pattern was implemented over 5 years, starting with maize sown in April 2002, at the Wheat Research Centre, Nashipur, Dinajpur, Bangladesh (25º38'N, 88º41'E, 38.2 m above sea level). The site has a subtropical climate and is located in Agroecological Zone 1 (Old Himalayan Piedmont Plains) on flood-free high land, with course-textured, highly permeable soil (BARC 1997). The area receives 1,757 mm mean annual rainfall, about 97% of which occurs from April to October. Total rainfall was highest during the maize season and lowest in the wheat season in all years (Table 1).

Table 1. Rainfall by crop and season at Dinajpur, Bangladesh, 2004–05 to 2006–07

Crop	Rainfall (mm)		
	2004–05	2005–06	2006–07
Maize	1,113	770	846
Rice	849	958	569
Wheat	60	53	54
Total	2,022	1,781	1,469
Mean	1,757		

Mean minimum and maximum temperatures during the rice season (July to November) were 22.6 °C and 31.3 °C, during the wheat season (November to March) 13 °C and 27 °C, and for the maize season (April to July) 23 °C and 33 °C. Monthly distribution of rainfall, and minimum and maximum temperatures for the experimental period (April 2004 to

March 2007) are shown in Figure 1. The soil at the experimental site was a non-calcareous brown sandy loam Haplaquept with moderate acidity (pH 5.5), low organic matter (0.8%) and low nitrogen (mineral N 35 µg/g soil).

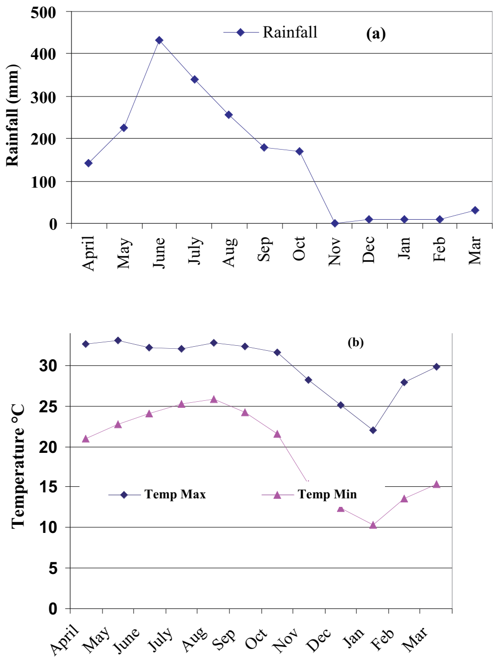

Figure 1. Mean monthly values (3 years, 2004–05 to 2006–07) of (a) rainfall and (b) maximum and minimum temperature at the Wheat Research Centre, Dinajpur, Bangladesh

The trial involved a three-crop (rice–wheat–maize (RWM)) annual rotation planted on raised beds or cultivated flats. Rice was transplanted (one 15-day-old seedling per hill) with hill-to-hill spacing of 15 cm and line-to-line spacing on the beds of 30 cm in late July and harvested in late November by hand. Wheat was planted at the nationally recommended seeding rate of 100 and 120 kg/ha for beds and conventional layout, respectively, in late November and harvested in late March. Intercropped maize and mungbean (*Vigna radiata*) were planted at the same time at the nationally recommended seeding rate of 35 kg/ha for maize and 10 kg/ha for mungbean in early April and harvested in mid July for both beds and conventional layout. The trial was originally established as a PRB experiment with three straw management practices (main plots—100% straw retention (SR), 50% SR and 0% SR) and four N levels (subplots—0%, 50%, 100% and 150% of recommended). The area of each subplot was 15 m^2 (5 × 3 m; Figure 2). After completion of two crop cycles (2002 maize to 2003–04 wheat), the experiment was modified by the introduction of conventional tillage on the flat with no straw retention (CTF + 0% SR), starting with 2004 spring maize. This treatment was applied to three new plots adjacent to the original experiment. Thus, the modified experiment consisted of 16 subplots with four tillage/straw treatments (100% SR + PRB, 50% SR + PRB, 0% SR + PRB and 0% SR + CTF) and four N levels (0%, 50%, 100% and 150% of recommended) with three replicates. After planting the wheat, maize or rice, straw from the preceding cereal crop was returned as a mulch to the plot from which it had been removed at harvest. After harvesting and threshing, the rice and wheat straw were returned without chopping. The maize stems were cut into ~20-cm-long pieces using a knife before returning them to the field. A spade was used to clean out the furrows and reshape the beds once a year, prior to sowing wheat.

The width of the beds was 75 cm (furrow to furrow) and the depth of the furrows on average was 12.5 cm. Two rows of wheat (var. Shatabdi) or rice (var. BRRI Dhan 32) with a spacing of 30 cm, and one row of maize (var. Pacific 11), were planted by hand sowing on the beds. Figure 3 shows two rows of rice on the beds, one each side of the base of the stem of the preceding maize crop in the middle of the bed. Mungbean (var. BARI Mungbean-6) was sown by hand in the furrows between the maize beds as a bonus crop and indicator plant to assess microbial activity in the soil environment. The mungbean was harvested about 60 days after sowing (DAS). Mungbean yields were not included in the analysis. In CTF, wheat, rice mungbean and maize were planted in 20 cm, 30 × 15 cm (row × plant) and 75-cm-wide rows, respectively. A basal dose of P (48, 21 and 26 kg/ha) from triple superphosphate, K (100, 35 and 33 kg/ha) from muriate of potash and S (50, 11 and 20 kg/ha) from gypsum was applied to maize, rice and wheat, respectively. In rice the entire amount of P–K–S was broadcast before transplanting and mulching on both PRB and CTF. In maize and wheat the fertiliser was dribbled on the soil surface between the plant rows (on the beds). For CFT the fertiliser was broadcast before tillage, as is the usual practice. The recommended rate of N (70 kg/ha for rice, 100 kg/ha for wheat and 167 kg/ha for maize) was applied as urea. For maize one-third of the N was applied before seeding and the remainder was applied in two equal instalments 30 and 45 DAS. With CFT rice, N was broadcast, while with beds it was banded on top of the soil between the rows in three equal instalments 15, 30 and 45 days after transplanting. With wheat, two-thirds of the N was applied before seeding and the remaining one-third at crown root initiation (CRI) (Zadoks growth stage 1.3; Zadoks et al. 1974).

Sufficient irrigation water was applied to fill the furrows between the raised beds. The flat plots were flood irrigated. The wheat received three irrigations—at CRI (Z1.3), booting (Z4.0–4.9) and grain-filling stages (Z8.0–8.9). For rice, irrigation water was applied for CFT with approximately 4 cm of irrigation and then re-irrigation when the soil was near saturation, maintaining this up to grain filling. For rice irrigation in PRB, water was applied and maintained initially over the beds for 14 days after transplanting to ensure seedling establishment. Thereafter, water was added only to fill the furrows (not over the beds). Generally, both CFT and PRB were irrigated on the same days, but less water was needed to fill the furrows with PRB compared to CFT. Both wheat and maize received pre-sowing irrigation to enhance germination. After sowing, maize was not irrigated because sufficient rain fell during its growth cycle (Table 1). Chemical weed control in all crops was administered 1 or 2 days before planting through the application of 1.4 kg/ha a.i. glyphosate [N-(phosphonomethyl)glycine]. Manual weed control was done after the first irrigation for wheat, and at 45 days after

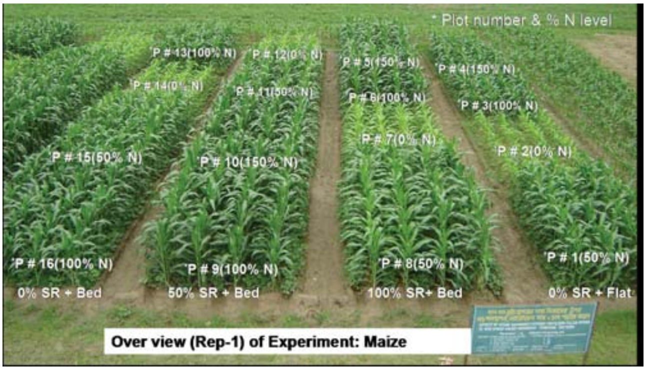

Figure 2. View of replicate 1 during the maize phase

Figure 3. Rice on beds (two rows per bed) with base of stem of old maize plant in the middle of the bed

planting for maize and rice. It is important to note that there were no additional weedings where outbreaks occurred—the treatments were compared with the same level of weed management. Grain and straw yield were determined on a 7.5 m^2 area in the centre of each plot. Samples were dried in a hot-air oven at 72 °C for 3 days. Grain yields were adjusted to 155 g/kg moisture for maize and 120 g/kg for the other crops.

The N content of grain and straw subsamples of all three crops was determined by the micro-Kjeldahl method. Potassium was analysed in di-acid (HNO_3 and $HClO_4$) digests by flame photometric methods. After rice harvest, soil samples were collected from 0–30 cm depth from three sites in both the bed tops and furrows, and from three sites in each CTF plot using a 6-cm diameter auger for the determination of nutrients. The entire soil sample was weighed and mixed thoroughly and subsampled. Subsamples were air dried and crushed to pass through a 2-mm sieve to remove roots and other inert matter. Organic C in the soil sample was determined volumetrically by the wet oxidation method of Walkley and Black (1975) and NH_4OA_C (pH 7.0) extractable K was analysed in a flame photometer (Page et al. 1982).

Agronomic efficiency (Ea) and partial factor productivity (Pfp) of applied N were estimated from grain yield and N rate as described by Cassman et al. (1994) with the following formulae:

$$Ea = \Delta EY/Nr \qquad \text{equation 1}$$

$$Pfp = Y/Nr \qquad \text{equation 2}$$

where ΔEY = grain yield increase over the unfertilised treatment (kg/ha), Nr = amount of applied N (kg/ha) and Y = grain yield (kg).

Gravimetric soil moisture content was determined from field moist weight and oven dry (105 °C) weight as follows:

$$\% \text{ moisture} = (\text{field moist weight} - \text{dry weight}) \times 100/\text{dry weight} \qquad \text{equation 3}$$

Data for the 3 years from 2004–05 to 2006–07 were analysed to compare the four tillage/straw treatments over the same years. Data were analysed for variance (ANOVA) using MSTAT-C, and treatment means were compared by Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$.

Results and discussion

Effects of straw retention and PRB on weeds

Weed infestation in each crop was reduced greatly by straw mulching, especially narrow-leaf weeds in all three crops and broadleaf weeds in wheat (Table 2). There was a consistent trend for greater reduction in weed population with 100% SR than 50% SR although the differences were generally small. Straw covering the soil surface reduced both weed seed germination and seedling growth. There are many ways by which crop residues and, in particular, mulches, can suppress weeds (Kumar and Goh 2000)—mechanically, by restricting solar radiation reaching the soil surface, by allelopathy and by reducing initial N availability through temporary immobilisation. In addition to influencing germination and growth, straw retention and reduced tillage also influence the efficiency of soil-applied pre-emergence herbicides. Zero tillage also reduces germination of weeds such as *Phalaris minor* in wheat, while mulching can reduce efficiency of herbicides applied after mulching.

In the absence of mulch, there was a consistent trend for fewer weeds in PRB than CTF. The biggest effects were in wheat, where weed counts on PRB were about 50% of those in CTF for all three types of weeds.

Table 2. Average total weed (plant number/m^2) infestation as influenced by straw retention in a rice–wheat–maize cropping system on permanent beds, Dinajpur, Bangladesh, 2004–05 to 2006–07

Treatment	Rice			Wheat			Maize		
	NL[a]	BL	Sedge	NL	BL	Sedge	NL	BL	Sedge
100% SR + PRB	10	0	7	8	11	6	13	0	6
50% SR + PRB	17	0	10	12	18	9	30	0	7
0% SR + PRB	48	0	11	35	56	11	65	0	10
0% SR + CTF	68	0	17	75	101	23	85	0	21

[a] NL = narrow-leaf, BL = broadleaf, PRB = permanent raised beds, SR = straw retention; CTF = conventional tillage on flat

Soil moisture conservation

Straw retention significantly influenced the soil moisture in wheat crops at 40 DAS (Table 3). In the 0–30 cm soil layer the maximum soil moisture (18.6%) was in 100% SR + PRB, more than double that (7.4%) of 0% SR + CTF. Retention of straw improves soil water-holding capacity, and retention on the soil surface also reduces soil evaporation (Sanchez 1976). We visually observed more rapid and greater canopy development in the mulched treatments, presumably due to both greater water availability and more efficient use of fertiliser. Without straw retention at the 0% N level, ground coverage of the crop was far less (~30% at 40 DAS). As a result, soil moisture depletion from the soil was faster due to much greater exposure of the soil surface. Similar observations were made by Kumar and Goh (2000) in India. Results from elsewhere in RW systems suggest that straw retention allows sufficient water to be saved (calculated at 25–100 mm) to either reduce the number of irrigations by one or delay irrigation time by an average of 17%, or to increase yield in water limiting situations (Zaman and Choudhuri 1995; RWC-CIMMYT 2003).

Grain yields

Commonly, conversion from conventional tillage to reduced-till systems with straw retention requires several crop cycles before potential advantages or disadvantages become apparent (Phillips and Phillips 1984). In our experiment straw retention increased yield rapidly, starting from the second crop cycle. We believe this is an important finding because, if repeated on farmers' fields, farmers will quickly realise the benefits and be more interested in adopting the technology.

Figure 4 presents the grain yields from 2004–05 to 2006–07. For all crops the highest yields occurred in PRB + 50–100% SR. Yields tended to be lower in CTF + 0% SR than PRB + 0% SR, with significant differences at all N levels in wheat, at three N levels in maize and at the two lowest N levels in rice (Table 4). Yields on PRB consistently increased as SR increased from 0% to 100%, but the differences between 50% and 100% SR were not always significant and were never significant at 100% N for any of the three crops. This is an extremely important finding in relation to practical management of such systems by farmers. Since there is high demand for straw for fodder, fuel or building materials in the IGP, especially by small- and medium-scale farmers, it is encouraging that retaining only 50% of the straw will provide adequate benefit to the crop while the remainder can be removed for other uses. Similar observations were made by Sayre et al. (2005) in Mexico.

Averaged over the 3 years, PRB + 50% SR with 100% N gave an 18% increase in maize yield over PRB + 0% SR at the same N rate (Table 4), but there was no significant maize yield increase with additional N with 50% SR. However, yield of PRB + 100% SR with 150% N was significantly higher than PRB + 50% SR with 100% N. Average rice yield on PRB + 100% SR with 50% N (5.24 t/ha) was significantly higher than with 50% SR at the same N rate, and there was no further yield increase at higher N rates. Rice yield declined with 100% SR at the two highest N rates, mostly due to lodging.

Table 3. Average gravimetric soil water content (0–30 cm) in wheat 40 days after sowing as influenced by straw retention, tillage and N level, Dinajpur, Bangladesh, 2004–05 to 2005–06

N level (% of recommended)	Permanent raised beds			Conventional tillage on flat
	100% SR	50% SR	0% SR	0% SR
0	11.8 def	10.9 fg	9.4 g	5.1 i
50	13.7 c	12.9 cde	10.2 fg	4.2 i
100	18.6 a	13.9 c	10.2 fg	7.4 h
150	17.0 b	12.8 cd	11.1 efg	7.6 h
CV (%)	4.95			

Note: Within the treatment interactions, the numbers having the same letters are not significantly different at 5% level by Duncan's multiple range test
SR = straw retention

The maximum average wheat grain yield (4.43 t/ha) was obtained on PRB with 150% N and 100% SR, 17% higher than on PRB + 0% SR (Table 4). These yield increases with straw retention are probably due to suppression of soil evaporation, less weeds and more efficient use of fertilisers. Limon-Ortega et al. (2000), working in the Yaqui Valley of Sonora in north-western Mexico, reported that permanent beds combined with retaining all crop residues increased both wheat and maize yields when grown with higher rates of N fertiliser.

Wheat and maize yields were comparatively low under the CTF system due to waterlogging and the resultant acute weed stress (poor crop growth could not compete as well with weeds) in early as well as late growth stages. On the other hand, insufficient rain during the rice season leads to mealybug (*Brevennia rehi*) infestation in well-drained, drying conditions such as on raised beds without straw retention. Mealybug infestation results in isolated patches of stunted plants within fields and is difficult to control. Variability in wheat yields in Bangladesh is mostly the result of the high temperature that can occur during the grain filling phase, especially for late-sown crops (Midmore et al. 1984). Additionally, growers are now reluctant to grow wheat because heavy pre-monsoon rain and strong winds prior to harvest make it more vulnerable and risky. The introduction of zero tillage, with or without PRB, will help because the crop can be planted earlier, reducing the risk of early storms before maturity.

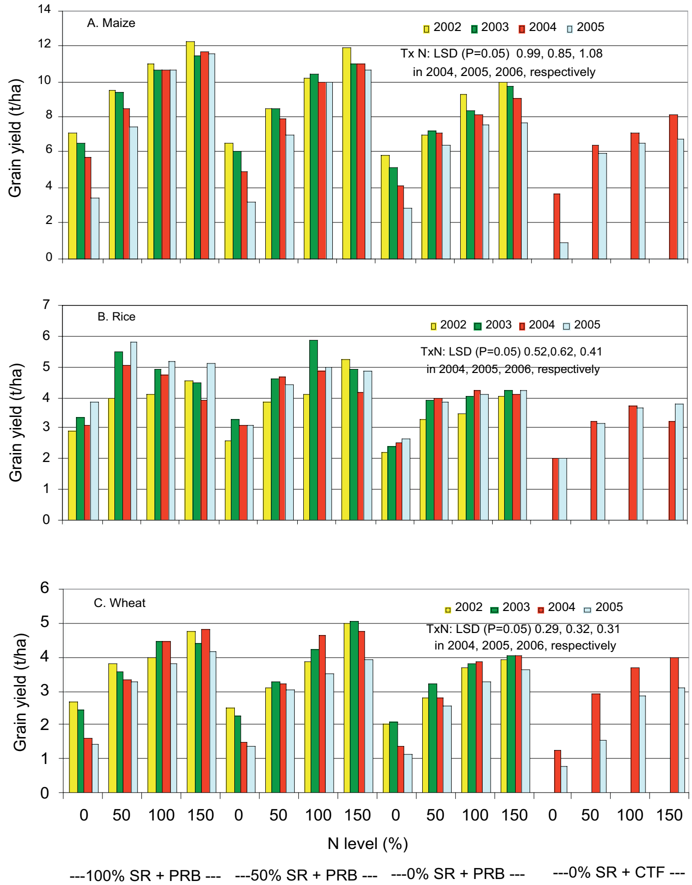

Figure 4. Annual grain yields of maize, rice and wheat as affected by N level (% of recommended) and tillage/straw treatments (T). LSDs are for comparing T × N level within years

Table 4. Grain yields of rice, wheat and maize as influenced by straw retention, tillage and N level (% of recommended) in a rice–wheat–maize cropping system, averaged over 3 years (2004–05 to 2006–07), Dinajpur, Bangladesh

N levels (%)	Rice (t/ha)				Wheat (t/ha)				Maize (t/ha)			
	PRB			CTF	PRB			CTF	PRB			CTF
	100% SR[A]	50% SR[B]	0% SR[C]	0% SR	100% SR[A]	50% SR[B]	0% SR[C]	0% SR	100% SR[A]	50% SR[B]	0% SR[C]	0% SR
0	3.42 h[D] (+8)	3.18 h (+16)	2.74 i (+33)	2.06 j	1.64 j (+12)	1.47 j (+18)	1.25 k (+33)	0.94 l	4.19 g (+8)	3.87 gh (+19)	3.25 h (+69)	1.92 i
50	5.24 a (+20)	4.35 def (+11)	3.93 g (+17)	3.37 h	3.29 ef (+6)	3.09 g (+11)	2.78 h (+36)	2.04 i	7.72 cd (+6)	7.31 de (+10)	6.65 ef (+10)	6.05 f
100	4.85 b (+2)	4.75 bc (+7)	4.37 de (+8)	4.06 efg	4.04 c (+4)	3.89 cd (+12)	3.47 e (+9)	3.18 fg	9.80 b (+6)	9.26 b (+18)	7.84 cd (+15)	6.84 e
150	4.45 cd (+0)	4.45 cd (+7)	4.17 d–g (+4)	4.00 fg	4.43 a (+4)	4.24 b (+12)	3.79 d (+10)	3.45 e	10.82 a (+10)	9.88 b (+21)	8.16 c (+11)	7.33 de
CV (%)	2.91				2.24				3.43			
LSD	0.3328				0.1846				0.6907			

[A] Numbers in parentheses represent percentage increase over 50% straw retention (SR) + permanent raised beds (PRB).
[B] Numbers in parentheses represent percentage increase over 0% SR + PRB.
[C] Numbers in parentheses represent percentage increase over 0% SR + conventional tillage on flat (CTF).
[D] Within the treatment interactions, figures with the same letters are not significantly different at 5% level by Duncan's multiple range test.

Nitrogen uptake and nitrogen use efficiency

Retention of straw resulted in increased N uptake in both N fertilised and zero N plots (Figure 5). Nitrogen uptake was significantly ($P \leq 0.05$) influenced by straw retention and N level. In PRB + 100% or 50% SR plots, total N uptake by rice was maximum at 50–100% N, by maize at 100% N and by wheat at 100–150% N. In contrast, in both PRB and CTF without straw retention, there was a consistent trend for increasing N uptake up to 150% N rate in all crops. Limon-Ortega et al. (2000) also observed that permanent beds with straw retention gave the highest average wheat grain yields (5.57 t/ha), N use efficiency (28.2 kg grain/kg of N supply) and total N uptake (133 kg/ha).

N use efficiency (calculated both as Ea and as Pfp) decreased as N rate increased in all treatments (Table 5). At the lowest N rate there was a consistent trend for higher Ea on PRB with 100% SR than 50% SR, and for similar values with 50% SR and 0% SR. There was a consistent trend for higher Pfp on PRB as the amount of SR increased from 0% to 100% across all crops. Similar observations were made by Yadvinder-Singh et al. (2004). They reported that Ea was significantly higher in straw retained + green manure cultivated treatments than other treatments for wheat. The availability of N and its uptake and utilisation by crops are closely related to system productivity, but are controlled by numerous abiotic and biotic factors in the soil–plant system. These include cultivar, fertiliser input, weather, pests, and management of soil, crop residues, irrigation and drainage (Dobermann and White 1999; Witt et al. 2000; Yadvinder-Singh et al. 2005). Given the complexity of the RW cropping system associated with the pronounced anaerobic–aerobic cycles, an important question concerns how N use efficiency can be improved. Good N management and straw retention in a PRB system may allow this. Compared to other parts of the IGP, such as the Punjab, our Dinajpur site received far more spring and summer rainfall (1,415–1,962 mm from April to October during the 3 years) in the maize and rice seasons (Table 1) and has a higher shallow watertable (only 80–90 cm depth). The result is a much wetter upper soil profile that is favourable for rice growth. It also helps the decomposition of retained straw, resulting in a higher uptake of nutrients and more efficient use of water.

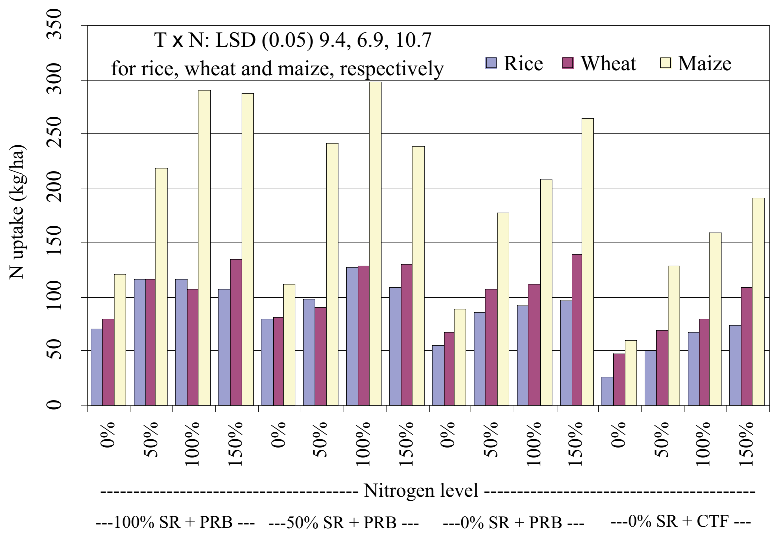

Figure 5. Effects of tillage/straw treatment and N level on total N uptake in rice, wheat and maize in 2004–05

Table 5. Nitrogen use efficiency of rice, wheat and maize yields (2004–05 to 2006–07) as influenced by straw retention, tillage and N level at Dinajpur, Bangladesh

Treatment		Agronomic efficiency (Ea) N			Partial factor productivity (Pfp) N		
		Rice	Wheat	Maize	Rice	Wheat	Maize
100% SR + PRB							
	N_0	--	--	--	--	--	--
	N_{50}	52.0	33.0	42.3	149.7	65.8	92.5
	N_{100}	20.4	24.0	33.6	69.3	40.4	58.7
	N_{150}	9.8	18.6	26.5	42.4	29.5	43.2
50% SR + PRB							
	N_0	--	--	--	--	--	--
	N_{50}	33.4	32.4	41.2	124.3	61.8	87.5
	N_{100}	22.4	24.2	64.6	67.9	38.9	55.4
	N_{150}	12.1	18.5	24.0	42.4	28.2	39.4
0% SR + PRB							
	N_0	--	--	--	--	--	--
	N_{50}	53.4	30.6	40.7	112.3	55.6	79.6
	N_{100}	23.2	22.2	27.5	62.4	34.7	46.9
	N_{150}	20.1	16.9	19.6	39.7	25.3	32.6
0% SR + CTF							
	N_0	--	--	--	--	--	--
	N_{50}	47.1	22.0	49.5	96.3	40.8	72.4
	N_{100}	28.6	22.4	29.5	58.0	31.8	40.9
	N_{150}	18.5	16.7	21.6	38.1	23.0	29.3

PRB = permanent raised beds, SR = straw retention; CTF = conventional tillage on flat

Soil organic matter (SOM)

After 4 years (2002–03 to 2005–06), retention of straw from all three crops in the zero-till PRB system had increased the soil organic C by 13–41% (Figure 6). While some of the increase may have been due to formation of the beds from topsoil, the change in organic C increased as the rate of residue retention increased from 50% to 100%, indicating that straw retention also affected organic C on the beds. At low N levels (0% and 50% of recommended) there appeared to be a slight decline in soil organic C. After 2 years of CTF without residues, soil organic C had decreased by a few per cent at all N

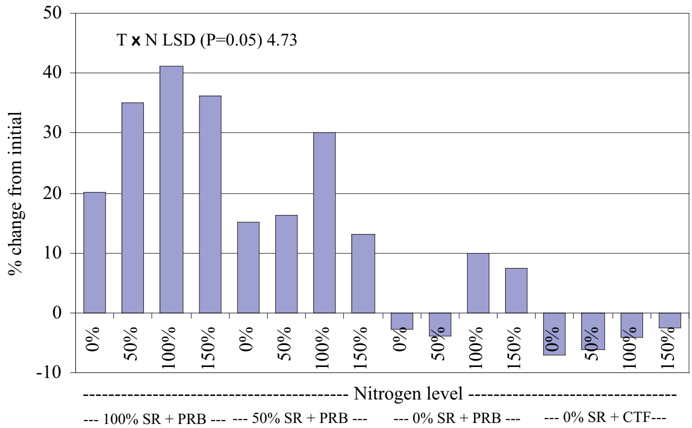

Figure 6. Effect of tillage/straw treatment and N level on soil organic C after 4 years (PRB) or 2 years (CTF) in a rice–wheat–maize cropping system at Dinajpur, Bangladesh

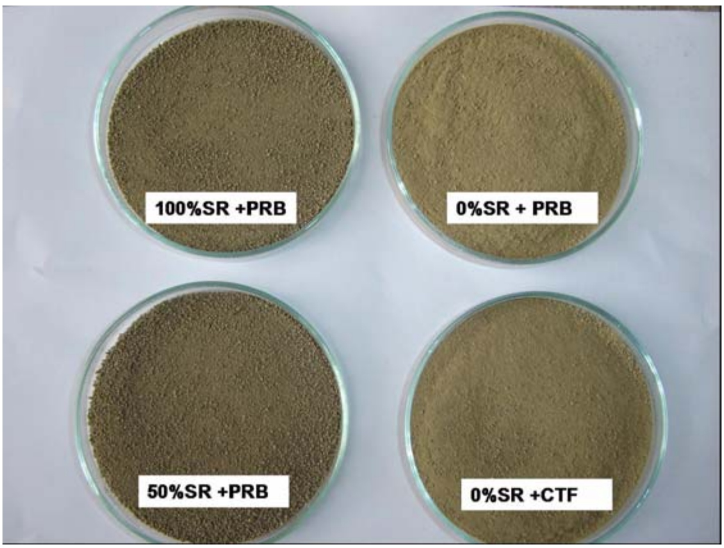

Figure 7. Soil colour after 4 years of PRB with different amounts of straw retention, and after 2 years of CTF

rates and there was a consistent trend for a large decline at lower N rate. The increase in soil organic C with 100% SR at 50–150% N was almost double that with 0% N. Kumar and Goh (2000) reported that, in the longer term, residues and untilled roots from crops can contribute to the formation of SOM. It seems clear that further increases in the productivity of the RW system will depend on improvements in soil fertility through proper management and use of crop residues and other agricultural wastes. After the four RWM crop cycles, the soil colour had darkened, presumably due to the build-up of organic matter in the topsoil (Figure 7).

System intensification with maize

Maize was included in the Dinajpur PRB system because its cultivation is rapidly expanding in Bangladesh due to demand for grain from an expanding poultry industry. However, for the maize to be a successful third crop in RW sequences, grown during the pre-monsoon Kharif-1 season, cultivars that are tolerant to waterlogging are essential during crop establishment and then increasingly so during later stages of crop development. In the IGP and particularly in Bangladesh during the spring Kharif-1 season, unpredictable heavy early rains (20% of yearly rainfall; Figure 1) damage germination and reduce establishment, while more frequent later monsoon rains (77% of yearly rainfall; Figure 1) damage maize cobs and reduce grain yield and quality. Planting of maize on PRB has great potential to overcome these problems (Talukder et al. 2004), as confirmed in our present study.

Expansion potential of permanent raised beds + residue retention

In the 2006–07 Rabi season in Bangladesh there were about 80 ha of bed-sown wheat, of which about 10 ha were maintained as PRB. There is large potential for area expansion due to the improved yields, ease of irrigation, less rat damage and other reasons stated in this paper. Although straw retention is a key to maintaining system productivity, especially with the permanent bed system, this may be difficult because Bangladeshi farmers have traditionally used their straw as a livestock feed and for various other purposes. Thus, there are competing demands for residues that may make it hard for sufficient residue retention to be adopted. Furthermore, the lack of appropriate mechanical seeders for permanent beds remains a constraint to the adoption of permanent bed planting in Bangladesh. Prototype bed planters and zero-till drills are currently being developed and tested by the Wheat Research Centre of BARI in Bangladesh. There is also an urgent need to further screen for rice varieties that perform better under PRB. The future success of PRB with straw retention can only be assured if farmers find that it works for them, and that its economic performance and sustainability are adequate.

Planting on PRB has also been tried in Pakistan and India but with limited success. Reasons for the relatively better performance in Bangladesh are not clear yet. The small scale and high management levels of our study, including initial construction and reshaping of the beds by hand and only after rice, compared with initial construction and occasional trafficking with large-tyred four-wheel tractors in the other countries, is a likely limiting factor on the performance of RW on PRB in the north-western IGP. Additionally, in the other countries rice was sometimes transplanted on the sides of the beds to ensure a wetter rootzone, but compaction may have been greater on the sides of the beds. In contrast, we transplanted on top of the bed because the rainfall patterns and high watertable provided plenty of water, with only occasional irrigation needed.

Summary and conclusions

Retention of at least 50% of crop residues together with zero-till permanent bed soil systems offer an important soil restorative management strategy likely to have a long-term positive impact on soil quality and crop productivity in intensive rice–wheat–maize (RWM) cropping systems in Bangladesh. Lignified residual straw and roots added more organic matter and nutrients into the soils under PRB, resulting in increased nutrient uptake by the crops. Crop yields on beds with 50% straw retention rose by about 7% for rice, 12% for wheat and 18% for maize at 100% N rates over a 3-year cycle of the RWM cropping pattern compared with 0% SR + PRB at the same N rate. Compared with conventional tillage on the flat, crop yields on PRB with 50% straw retention rose by 17%, 22% and 35% for rice, wheat and maize crops, respectively, at 100% N rates over a 3-year cycle of the RWM cropping pattern. Yield in N-unfertilised rice, wheat and maize increased when straw was retained, and this appeared to be due to an increased uptake of N. This increase in soil N supply led to a reduction in N use efficiency in the N-fertilised plots, suggesting that N fertiliser application rates can be reduced when straw is retained. Retention of crop residues as a mulch reduced moisture depletion and increased SOM content over relatively short periods of time. Fertiliser use efficiency may be increased by implementing permanent bed management in addition to reducing weed and crop lodging problems. Permanent raised beds will also help ameliorate the adverse effects of tillage on soil structure, which lead to waterlogging under excess water conditions and hamper establishment, growth and development of most crops including maize. The use of PRB reduced the overall cost of production and long turnaround time (data not presented). Thus, our results showed that PRB with straw retention can help to sustainably intensify RW systems to RWM systems under high degrees of management on research stations in Bangladesh. Further on-farm adaptive research with farmers now appears warranted.

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Research station and on-farm experiences with permanent raised beds through the Soil Management Collaborative Research Support Program

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Abstract

Permanent raised bed cultivation for rice–wheat cropping systems of South Asia is a paradigm shift from the conventional practice of planting on puddled flat land. Permanent beds offer the opportunity to reduce tillage, rebuild soil aggregates and organic matter, reduce irrigation water inputs and improve nitrogen (N) use. The Soil Management Collaborative Research Support Program, together with National Agricultural Research System partners in Bangladesh and Nepal, compared conventional and permanent bed cultivation in replicated experiments at Ranighat, Nepal; Rajshahi, Bangladesh; and Nashipur, Bangladesh. Permanent beds outperformed conventional flat practice for all crops with the exception of wheat at one site. At Nashipur wheat yields on beds declined over time, but no declining trends were seen at the other sites. Mean yield response to N fertilisation was generally greater on beds than on the flat, and greater with rice than wheat. At the same level of N fertiliser input, N uptake in wheat grain at Nashipur and wheat and rice grain at Rajshahi was higher for the bed treatments than the flat. Reduced inputs of irrigation water were documented, with furrow irrigation of permanent beds at all three sites. Consistent improvements in yield and reductions in irrigation inputs, together with cost savings in labour, land preparation, fertiliser and seed inputs, on permanent beds have convinced a group of Bangladeshi farmers to adopt this innovative technology.

Introduction

The Soil Management Collaborative Research Support Program (SMCRSP), funded by the US Agency for International Development, has been working with National Agricultural Research System (NARS) partners in Bangladesh and Nepal since 1996 to diagnose and address sustainability problems in the rice–wheat (RW) cropping system.

In the first phase of the project we identified a number of management factors contributing to stagnating/declining yields and declining factor productivity in the system:

- extensive root health problems caused by high levels of soil-borne pathogens
- conventional tillage and puddling operations that hinder timely planting and good stand establishment, destroy soil aggregates and promote soil organic matter degradation

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- inefficient use of nutrients and water
- an emphasis on cereal production, which discourages diversification of the cropping system.

At the farm level, labour shortages as well as high labour and fuel costs also constrain crop production.

Permanent raised beds were introduced as a resource conserving technology to address the economic, water and soil constraints of conventional RW cropping systems. The technology employs a bed and furrow planting configuration that is maintained for all crops with only periodic reshaping. We anticipated that less tillage with the bed system would reduce farmers' labour and diesel input costs while rebuilding soil aggregates and organic matter over time. We hypothesised that water inputs (and costs) would be reduced substantially by moving to a furrow irrigation system compared to the conventional flood irrigation, and fertiliser N recovery would be improved on beds. Also, we expected that timely planting, good crop stands and an improved rooting environment with permanent beds would increase yields and crop diversification opportunities.

Experimental work was initiated in 2001 to test the feasibility and effectiveness of permanent beds for the RW cropping system at experiment stations in Nepal and Bangladesh. In 2003 farmers from three Bangladeshi villages began to use the bed technology on their own farms. This paper presents results from the experimental trials and a brief summary of our on-farm experiences.

Methods

Conventional flat (CF) and permanent bed (PB) cultivation practices were compared in replicated experiments at Ranighat, Nepal; Rajshahi, Bangladesh; and Nashipur, Bangladesh. Table 1 provides the climatic and soil characteristics for each site.

The experiments began with the 2001 Rabi season and followed a triple crop rice–wheat–mungbean rotation (mungbean was added in 2002 at Ranighat). The experiment at Rajshahi was discontinued after rice in 2003 but those at Nashipur and Ranighat were continued to assess the temporal evolution of permanent bed practices. All experiments used a strip plot design with PB and CF as the main factors. There were four replications of each treatment at Ranighat and three at Rajshahi and Nashipur. At Rajshahi and Nashipur broadcast and banded N placement treatments were applied as subplots along with three levels of N (50%, 100% and 150% of recommended doses) in sub-subplots. Ranighat also had a subplot treatment of no mulch or mulch at 4 t/ha using straw residues from the previous crop. In 2005 a straw mulch treatment was added to the experiment at Nashipur. Other than these specific residue treatments at Ranighat and Nashipur, all crop residues were removed from the plots at harvest.

Raised beds were initially formed after conventional tillage using a four-wheel tractor with a furrow-irrigated raised bed system (FIRBS) bed former cum seeder attachment, a two-wheeled power tiller with bed former attachment, or by hand. The beds were maintained permanently from crop to crop with reshaping as necessary, usually before wheat planting. At Ranighat beds 15 cm high and 65 cm wide (furrow to furrow) were formed, reshaped and planted by four-wheel tractor. At Rajshahi beds 75 cm wide (furrow to furrow) by 15 cm tall were formed, reshaped and sown with a two-wheeled power tiller. Beds at Nashipur with the same dimensions as at Rajshahi were formed by hand after tillage with a two-wheel power tiller. Reshaping and planting of all crops at Nashipur was by hand. For all PB treatments, rice, wheat and mungbean were planted in two rows per bed (20 cm row spacing at Ranighat; 30 cm row

Table 1. Climatic and soil characteristics at experimental sites

Site/location	Temperature		Mean rainfall	Soil texture	Soil organic carbon	Soil pH
	Mean maximum	Mean minimum				
Ranighat, Nepal/ 27.02˚N 84.88˚E	30.0 °C	18.3 °C	1,735 mm 86% May– Sept	Silty loam	0.66%	7.4
Rajshahi, Bangladesh/ 24.39˚N 88.69˚E	31.0 °C	20.4 °C	1,607 mm 84% May–Sept	Silty clay loam	0.85%	7.3
Nashipur, Bangladesh/ 25.63˚N 88.68˚E	29.9 °C	19.6 °C	1,893 mm 88% May–Sept	Sandy loam	0.67%	5.5

spacing at Rajshahi and Nashipur). At all sites CF treatments were established for each crop after multiple tillage operations and puddling before rice. Seeding rates and additional planting details for each site are displayed in Table 2.

Nitrogen fertiliser was applied in basal and top dressed splits for wheat and rice according to recommendations or treatment levels. At Rajshahi and Nashipur band N treatments involved placing urea on the soil surface in a narrow band between two adjacent rows, while broadcast treatments involved scattering urea uniformly over the soil surface. No N was applied to mungbean at Nashipur but a basal dose of 20 kg N/ha was applied at Ranighat and Rajshahi. Recommended P, K, S and Zn fertiliser doses were applied before tillage for CF treatments and broadcast on top of the beds before seeding for the PB treatments. Weeds were controlled manually or with herbicides.

Irrigation was applied as needed to supplement rainfall. Irrigation applications were measured manually with a calibrated drum and a stopwatch. At all sites irrigation inputs were applied at the same time to PB and CF treatments. During the rice season, irrigation occurred when standing water was no longer visible in CF treatments. CF treatment plots were flooded to ~3–5 cm depth, while for PB treatments water was applied until it reached the top of the furrow. During the wheat season, irrigation scheduling was based on crop growth stage—crown root initiation, booting and flowering.

Crop productivity

Averaged over the duration of these experiments, bed yields outperformed conventional practice for all crops with the exception of wheat at the Ranighat site

Table 2. Seeding rates and planting details for experimental sites

Site		Wheat	Mungbean	Rice
Ranighat	Variety	Bhrikuti	C-5	Radha-4
	PB CF	80 kg/ha (after 2003) 120 kg/ha (after 2003)	30 kg/ha 30 kg/ha	50 kg/ha 20–25-day seedlings; 20 × 15 cm spacing
Rajshahi	Variety	Protiva, Shatabdi	BARI Mung 5	BR-33
	PB CF	100 kg/ha 120 kg/ha	35 kg/ha 35 kg/ha	20-day single seedlings; 30 × 15 cm spacing 20-day single seedlings; 25 × 15 cm spacing
Nashipur	Variety	Kanchan, Shatabdi	BARI Mung 5,6	BR-32
	PB CF	100 kg/ha 120 kg/ha	30 kg/ha 30 kg/ha	15-day single seedlings; 30 × 15 cm spacing

Table 3. Effect of cultivation practice on wheat, rice and mungbean crop productivity at experimental sites (average over years)

Site/crop	Years	Yield (t/ha)		SEM[a]	P value
		PB	CF		
Ranighat					
Wheat	6	4.06	4.11	0.13	0.803
Rice	5	5.68	5.14	0.10	0.0004
Mungbean	5	0.75	0.67	0.04	0.133
Rajshahi					
Wheat	3	3.65	3.17	0.03	0.0001
Rice	3	6.27	4.74	0.09	0.0001
Mungbean	3	1.25	1.09	0.01	0.0001
Nashipur					
Wheat	5	3.90	3.41	0.06	0.0001
Rice	5	3.55	2.99	0.10	0.002
Mungbean	5	1.07	0.81	0.04	0.0001

[a] Standard error of the mean

(Table 3). Wheat and rice yield increases on beds were associated with significantly higher plant biomass; increased tillers/m^2, panicles/hill, and spike and panicle length; and greater thousand grain weight (Talukder et al. 2002; Hossain et al. 2005; Meisner at al. 2005). These improvements in growth parameters on beds are consistent with a better rooting environment, improved light interception and more efficient nutrient and water use.

High seeding rates and crop variety may have contributed to the poorer performance of wheat on beds at Ranighat compared with the other sites. Seeding rate adjustments made in 2003 (120–150 kg/ha to 80 kg/ha) improved wheat yields in PB relative to CF, yet it is unsure whether the wheat variety Bhrikuti was optimal for permanent beds at this site. Separate varietal trials conducted in Bangladesh confirmed that the wheat variety Shatabdi performed equally well or better on the beds compared with the flat. However, no varietal comparisons on beds and flat were done at Ranighat.

At all sites permanent beds improved rice and mungbean productivity more than wheat productivity. Differences in mean wheat yields ranged only from –0.1 to 0.5 t/ha (–1.2% to 15%), whereas mean rice yields were increased by 0.5–1.5 t/ha (11% to 40%). Mean mungbean yield was increased by 0.1–0.3 t/ha (12% to 32%), which is important given the nutritional and economic benefits associated with pulse crops.

South Asian farmers often perceive pulse production as risky because of low yields and susceptibility to biotic and abiotic stresses. We used the mungbean variety BARI Mung 5 (known as C-5 in Nepal) in these experiments. This recently released variety is of short duration (60 days) and resistant to yellow mosaic virus. So with the right variety and the substantial increases in mungbean yields achieved with PB compared to conventional practice, opportunities for farmers to diversify their cropping system with pulses are significantly improved.

Temporal yield pattern

Rice and wheat yields over time were compared to assess the sustainability of permanent beds relative to conventional practice at each site. At Ranighat and Rajshahi PB treatment yields followed the variation observed with conventional practice (Figure 1). No declining yield trends were apparent for either treatment. At Ranighat wheat yields were higher in CF treatments during the second and third years but, with the seeding rate change after 2003, yields from PB tended to be higher than CF. In the case of Rajshahi wheat yields, both CF and PB treatments demon-

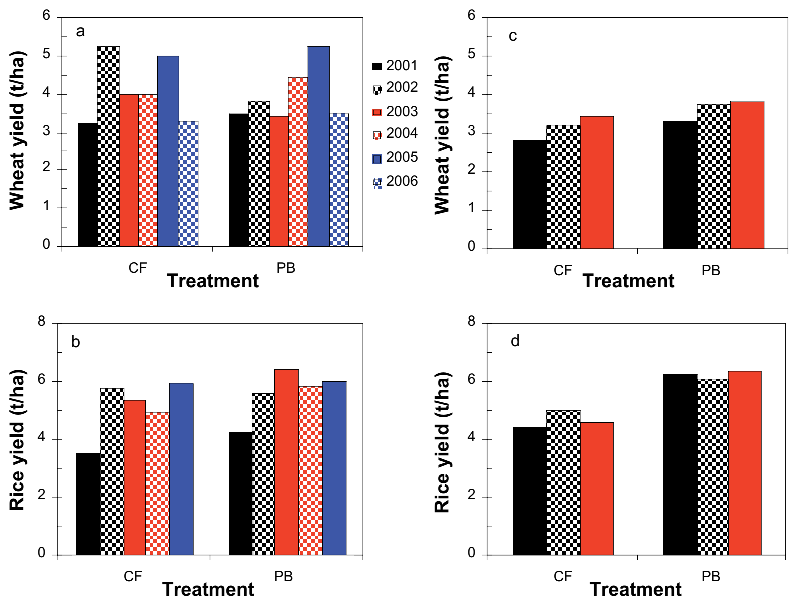

Figure 1. Wheat and rice yield trends 2001–06 at Ranighat (a, b) and Rajshahi (c, d) for conventional (CF) and permanent bed (PB) treatments

strated an increasing trend (Figure 1c). Also, for rice at Rajshahi, PB yields appeared more stable than CF during the 3 years of the experiment (Figure 1d).

No temporal patterns in rice yields were evident at Nashipur (Figure 2b) but wheat yields on beds declined 15% between 2001 and 2004 (Figure 2a). This trend was not observed with the conventional practice wheat yields. We hypothesise that the decline in wheat yields with PB may be due to a lack of nutrients in the root zone, coupled with drier soil surface conditions that limit access to surface-applied fertiliser nutrients. The sandy loam soil texture at Nashipur does not retain soil moisture like the soils at the other sites, especially at the surface. Consequently, wheat roots would tend to concentrate at depth while fertiliser nutrients remain near the soil surface unable to diffuse to the root zone. More rapid drying of the beds than the flat was also observed in Punjab, India, on sandy loam and loam soils, but to a greater extent on the sandy loam (Prashar et al. 2004).

Experiences in Mexico (Limon-Ortega et al. 2000) and Bangladesh (Talukder et al. 2008) have shown that crop residue mulches can sustain crop production on permanent beds by suppressing weeds, conserving soil moisture and increasing nutrient use efficiency. To address the declining wheat yield problem observed at Nashipur, a mulch treatment (4 t/ha straw from the previous crop) was introduced in 2005. We expected that the mulch would help retain moisture at the soil surface, thereby improving access to applied nutrients and increasing yields on the beds.

Straw mulch increased yields in the PB treatment by 14% in 2005 and 7% in 2006. However, a similar impact was also found for the CF treatment (Figure 3), which is not consistent with our hypothesis. Furthermore, it appears that the downward trend in PB wheat yields without mulch stabilised between 2004 and 2006, while unmulched CF wheat yields showed an 18% decrease during the same period. Clearly, a factor common to both cultivation practices is causing yields to decline over time. Additional research is necessary to explain the cause for this unexpected trend in wheat yields.

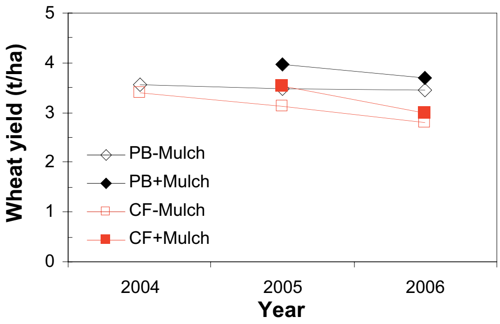

Figure 3. Wheat yield response to permanent bed (PB) and conventional (CF) cultivation practices with and without straw mulch at Nashipur, Bangladesh (2004–06)

The mulch results at Nashipur are consistent with our experience to date at Ranighat, where mulch has increased rice and wheat yields (6–8%) and mungbean yields (28%) for both PB and CF treatments. No enhanced impact of mulch was found for the PB treatment with any of the crops.

Nitrogen response and uptake

Mean yield responses to fertiliser N over the duration of the Nashipur and Rajshahi experiments were greater on beds than on the flat, and greater with rice than wheat (Figure 4), especially at the higher N levels. The greater impact on rice yields suggests that

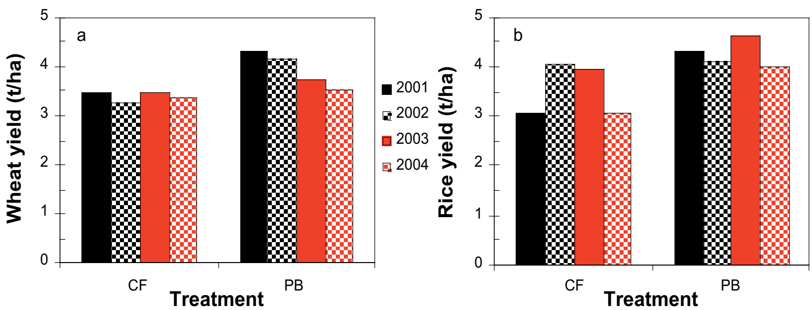

Figure 2. Wheat and rice yield trends 2001–04 at Nashipur for conventional (CF) and permanent bed (PB) treatments

the beds reduce high N losses that are associated with conventional paddy rice cultivation. However, without a zero N level control to determine soil N contributions, it is unclear whether PB improved fertiliser N recovery compared with CF practice.

Band placement of N fertiliser had a significant beneficial effect on wheat and rice yields in the lighter textured soil at Nashipur but not at Rajshahi. Banding increased wheat yields 7–18% and rice yields 8–16% relative to broadcast fertiliser, which is consistent with what we already know about managing fertiliser N losses from light-textured soils. While interactions between cultivation practice and N placement treatments were not significant at either site, we observed that differences in rice yields between band and broadcast treatments at Nashipur were higher on the beds (0.42 t/ha) than on the flat (0.25 t/ha).

Rice and wheat grain samples were collected at Nashipur and Rajshahi for N analysis in 2001 and 2002. Grain N uptake was significantly higher in the beds for rice at Rajshahi and for wheat at both sites (Figure 5). Averaged across N levels, wheat grain N uptake was 39% and 16% higher in PB treatments compared to CF at Nashipur and Rajshahi, respectively. Rice grain from permanent beds at Rajshahi recovered 15% more N compared to grain from conventional practice. These experimental plot results confirm our hypothesis of improved N recovery on beds compared to conventional practice for a given level of applied fertiliser N.

Irrigation inputs

Several of the research efforts with permanent bed systems in other parts of the Indo-Gangetic Plain scheduled irrigation inputs according to predetermined soil matric potential or cumulative pan evaporation levels. We did not take this approach. Wheat received three or four irrigations, and mungbean two or three inputs, per crop, while rice was given four to eight supplemental irrigations depending on rainfall. A pre-sowing irrigation was necessary for the sandy loam soil at Nashipur to ensure adequate moisture for wheat growth. Stored soil water was not measured at Rajshahi or Ranighat but, based on measurements reported by others (BARI 1994; Subbarao et al.

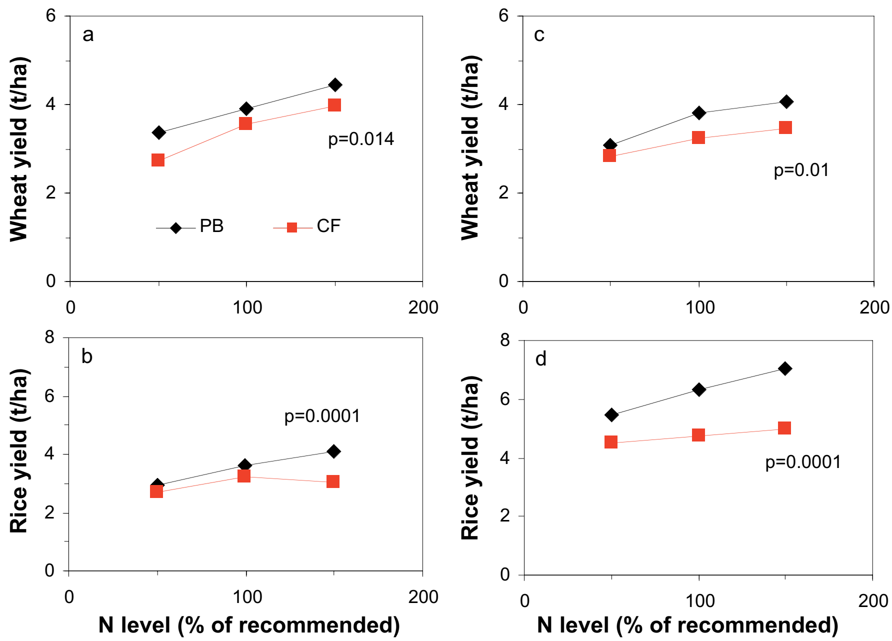

Figure 4. Mean response of rice and wheat yields to nitrogen fertilisation at Nashipur (a, b) and Rajshahi (c, d) for conventional (CF) and permanent bed (PB) treatments. Data are means of 5 years at Nashipur and 3 years at Rajshahi.

2002), we estimate that an additional 60–80 mm of residual soil water was available for wheat growth at the beginning of the Rabi season at these sites.

Because irrigation water advances faster in untilled than tilled soil, and furrow irrigation was used rather than flood inundation, we expected a substantial savings in water applications with PB compared with CF treatments. Irrigation inputs were measured at all three experimental sites to document the potential savings in water applications achievable with permanent bed systems (Table 4). Quantities varied depending on rainfall and soil type. Nevertheless, the furrow irrigation approach of the PB treatments consistently reduced inputs by 14–33% for wheat, 14–38% for rice and 16–28% for mungbean relative to CF treatments. On a per hectare basis, these reductions translate into annual irrigation input savings of between 0.6 and 3.1 ML. Furthermore, farmers would probably have significant cost savings for fuel by pumping less water.

On-farm experiences with permanent beds

Farmer experimentation with permanent raised beds was initiated in response to farmers' needs to reduce labour/input costs and to diversify their cropping system for more profitable production. Twenty-six farmers from three villages in the Rajshahi–Natore districts of Bangladesh were recruited to learn about the technology and to use it on their own farms. Hands-on training was given at the Rajshahi experiment station to teach the farmers how to prepare the beds using a power tiller with a bed former / seed drill attachment. The farmer groups provided the power tiller and our project loaned each group a bed former / seed drill. Farmers agreed to compare the bed practice with their conventional practice on the flat. Technical backstopping was provided throughout by M.I. Hossain, an agronomist from the Rajshahi experiment station.

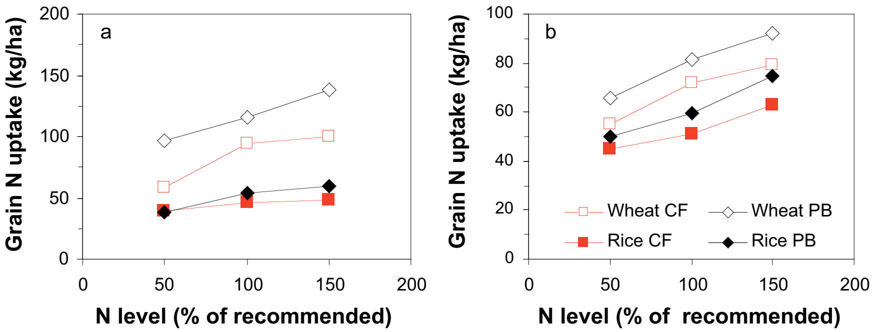

Figure 5. Nitrogen uptake by wheat and rice grain harvested from Nashipur (a) and Rajshahi (b) experiments for conventional (CF) and permanent bed (PB) treatments

Table 4. Irrigation and rainfall inputs by crop at experimental sites for permanent bed (PB) and conventional (CF) treatments

Site	Crop/year	Irrigation (mm)		Change (%)	Rainfall (mm)	Total (mm)	
		PB	CF			PB	CF
Nashipur	Wheat/2002[a]	170	197	–14	51	221	248
	Rice/2002	144	167	–14	928	1,072	1,095
	Mungbean/2001	21	29	–28	548	569	577
Rajshahi	Wheat/2002	70	105	–33	64	134	169
	Rice/2002	223	361	–38	840	1,063	1,201
	Mungbean/2002	36	48	–25	333	369	381
Ranighat	Wheat/2004	102	142	–28	16	118	158
	Rice/2004	401	643	–38	1,077	1,478	1,720
	Mungbean/2004	162	193	–16	509	671	702

[a] Includes a pre-sowing irrigation

Participating farmers are enthusiastic about permanent raised beds because the practice has improved livelihoods and food security for their families (Figure 6). They report yield increases in wheat and rice of 15–25% along with decreased costs for irrigation (by 39%), seed (by 20%) and fertiliser/pesticides (by 15%). Farmers also noted significantly less rat damage, which is normally a major problem for wheat cultivation in Bangladesh. Although initial land preparation costs for beds were twice that for conventional practice, in subsequent crops permanent beds saved US$11/ha in tillage costs compared with conventional practice in the first year, and US$28/ha in subsequent years. Net income from sales of wheat or rice was US$17/ha/crop higher using permanent beds compared to conventional practice. These Bangladeshi farmers are also diversifying their crop production by growing mungbean, maize, sesame and jute on beds during the spring and early summer. Mungbean or maize production on beds during normally fallow periods generated US$49–53/ha net income.

Interest in permanent raised beds has expanded beyond the initial groups to farmers in the surrounding communities. Tillage and bed formation services are being provided on a for-hire basis by members in one of the initial farmer groups. As a result, the use of permanent beds spread to 127 farms on 74 acres in 2006. We also initiated farmer-to-farmer transfer of permanent bed technology to other groups. A constraint to further expansion was lack of credit for purchasing two-wheel tractors and bed formers. Although our project provided a loan to the initial group, we did not feel that this approach was sustainable. Attempts to get group loans from banks failed, but four farmer groups recently obtained loans for purchasing power tillers and bed formers from a local NGO.

Conclusions

Permanent beds have proven to be a viable new management option for RW cropping patterns in Bangladesh and Nepal. Results have included higher crop

Figure 6. Farmer fields using permanent beds for rice (top left), jute (above) and mungbean (bottom left) in Natore district, Bangladesh

yields than conventional flat practice in a majority of cases, increased opportunities for crop diversification, improved N use, lower irrigation inputs and reduced costs. Initial use of beds by smallholder farmers in Bangladesh has been received enthusiastically with good scope for expansion.

Our experience with permanent raised beds has been quite different from others in South Asia. The reasons for these differences are unclear but irrigation and crop variety may be two possibilities. We did not deliberately seek water savings by growing rice or wheat crops on beds substantially below irrigation levels recommended for conventional practice. Rice was grown with adequate water but was not flooded except when rainfall was plentiful. Reduced irrigation inputs on beds were achieved only by applying water to untilled soil and to furrows instead of flooding whole plots. Thus, the permanent beds in our experiments were not exposed to prolonged dry periods which could negatively impact rice growth.

Current rice and wheat crop varieties in South Asia have been selected under conventional flat conditions (e.g. flooded, puddled soils, closer spacing) and may grow differently under permanent bed conditions (e.g. alternating wet/dry soil conditions, different rooting environment, wider spacing). The crop varieties used in Bangladesh and Nepal for the most part performed well on beds despite the different growing conditions of beds versus conventional flat. Nevertheless, different varietal responses to beds have been seen (Meisner et al. 2005), which indicates that not all conventionally selected varieties are well adapted to the different conditions of permanent beds.

Acknowledgments

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Direct-seeded rice in the Indo-Gangetic Plain: progress, problems and opportunities

R.K. Malik[1] and Ashok Yadav[1]

Abstract

Rice–wheat cropping in the irrigated agroecosystem of India occupies 10.5 million hectares and contributes about 40% of the country's total food grain requirement. Rice in the Indo-Gangetic Plain is principally cultivated by two methods—transplanting and direct seeding. Transplanting rice seedlings on puddled soils is very common and widespread in the irrigated ecosystem. Constraints to productivity and sustainability in the rice–wheat system include delayed planting, limited water and labour availability, residue burning, and nutrient mining and imbalances. Yield stagnation and declining total factor productivity and farm profit margins are well recognised as results of current practices. The traditional practice of manual transplanting in puddled soil requires higher labour costs but plant population in this system is generally low (18–20 plants/m^2) compared with the recommended 35–40 plants/m^2. Direct seeding of rice offers an alternative to transplanting that can reduce both the delays and costs of rice establishment. This paper summarises the key findings of the last 5–6 years' research on direct seeding and transplanting, with and without tillage, for rice in the state of Haryana in north-western India.

The advantages of direct seeding include more efficient use of water, higher tolerance of water deficit through less soil cracking and percolation and leaching losses upon reflooding, less methane emission, earlier crop maturity (7–15 days) and often higher profit in areas with an assured water supply. The impact of direct seeding of rice on the long-term productivity and sustainability of the system, however, requires careful evaluation within the context of the production system. In direct-seeded rice the major challenges are effective weed management and appropriate water management for successful crop establishment. Farmers, particularly in north-western India, are keen to grow direct-seeded rice under zero-till or unpuddled conditions provided yields are close to those with conventional transplanting. Good land levelling, short duration varieties and integrated weed management are key needs for direct seeding to be widely adopted in the near future.

Introduction

In India rice is grown on an area of 43 million hectares (Mha) with total production of 87 Mt, which is 41.8% of India's total food grain (Singh 2001). Out of 30 important cropping systems in India (Yadav 1998) the major contribution to the national food basket comes from those based on rice–wheat (RW) (10.5 Mha), rice–rice (RR) (5.9 Mha) and coarse grain (10.8 Mha). Of all these systems the total share of rice and wheat is the highest, contributing about 65% of food grain production (Singh et al. 2004), while the RW system contributes 40% (Shukla et al. 2004). Unfortunately, most of the high productivity systems are cereal-based with high resource demand, and have been practised continuously over several decades in major parts of the country—RW in the Indo-Gangetic Plain, RR in coastal and high rainfall areas and coarse grain systems in low rainfall areas. This has resulted in second generation problems like yield stagnation,

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soil degradation, decline in factor productivity and profitability, mining of soil nutrients, declining groundwater tables and build-up of pests.

In most of South Asia the common practice of establishing rice in the RW systems is through puddling followed by transplanting. Puddling reduces percolation losses and helps maintain ponded water, which is beneficial for controlling weeds (Adachi 1992; Singh et al. 1995). But puddling is costly, cumbersome and time consuming, and it degrades soil structure for the succeeding wheat crop in rotation. The disadvantages associated with puddled transplanted rice include the development of a hardpan at a depth of 10–40 cm (Sharma and De Datta 1986; Sawhney and Sehgal 1989), increased bulk density and soil compaction (Balloli et al. 2000), impaired root growth of wheat due to the hardpan (Boparai et al. 1992), a high labour requirement and drudgery among women workers (Budhar and Tamilselvan 2001).

To avoid the need for puddling and/or transplanting, other rice crop establishment techniques need to be explored, for example direct seeding either in puddled soil (wet seeding) or in dry soil with or without tillage (dry seeding). Direct seeding of rice may be cost-effective and give higher net returns because production costs are lower. Short duration varieties, appropriate water management for good establishment and, most importantly, good weed management, particularly during early growth stages, are some of the key factors needed to achieve satisfactory yields under direct seeding. Monitoring the changes in weed flora shifts under direct seeding is essential to identify appropriate weed management tools. Weed infestation due to poor management of irrigation water is one of the major constraints in direct-seeded rice (Mukhopadhyay et al. 1978; Singh, Y. et al. 2005). Micronutrient deficiencies (Zn and Fe) and high infiltration rate in direct-seeded rice are other causes of concern. However, due to water and labour shortages (Pandey and Velasco 1999), and soil and environmental degradation under intensive production techniques like puddled transplanted rice (Sinha et al. 1998), growers' interest in direct seeding is increasing. The benefits of the resource conservation technologies that have already been realised in wheat (Malik et al. 2002) are likely to be greater under rice. With these ideas in mind, direct-seeded rice was studied in Haryana, north-western India, using a farmer participatory approach. The findings of this work from 2001–05 are presented here. Relevant results from other parts of north-western India are also included to broaden the findings on current progress, problems and opportunities of direct-seeded rice in the Indo-Gangetic Plain.

Methods

Different establishment techniques for rice grown during the Kharif (monsoon) season were evaluated in replicated experiments and in multi-locational trials in farmers' fields in Haryana during 2001–05. Coarse rice varieties (as opposed to basmati types) were grown in all trials.

2001

Experiment 1

Three trials were established at three locations: I. Teek (Kaithal), II. Ferozpur (Kaithal) and III. Ferozpur (Kaithal). The soils of the experimental fields were slightly alkaline (pH 8.2–8.5) clay loam with medium fertility. The 1-acre fields were divided into five equal parts and rice was established using five methods: 1. puddle–transplant, 2. puddle–broadcast, 3. zero-till (ZT)–broadcast, 4. ZT–drill sown and 5. ZT–transplant (Table 1). Glyphosate (1.0% solution) was sprayed on 1 June 2001 to knock down the pre-germinated weeds in the three zero-till treatments. Rice variety HKR 126 was grown at location I, and PR115 at the other two locations. The seed was soaked for 48 hours and kept moist under shade for the next 12 hours. The direct-seeded treatments and the seedling nursery for the transplanted treatments were then all sown using the sprouted seeds on 3 June 2001. The direct-seeded treatments were sown at the recommended rate in Haryana of 75 kg/ha. However, it was later recognised that this rate was too high and two thinnings were conducted (25 and 40 days after sowing (DAS)). The transplanted plots were planted with 24-day-old seedlings on 27 June 2001. The herbicide pretilachlor (with safener) @ 0.5 kg/ha was applied 3 DAS or 3 days after transplanting (DAT) in all treatments. The direct-seeded treatments were harvested 12–15 days earlier than the puddled transplanted treatments.

2002

Experiment 2a

Treatments 1–4 from 2001 were repeated at location I in 2002, while treatment 5 (ZT–drill sown) was replaced with treatment 6 (ZT–transplant–furrow, which involved opening a furrow (slot) followed by transplanting). The furrows were formed with the zero-till drill (Figure 1) and were 4–5 cm deep and spaced 17.5 cm apart. The variety of rice was HKR 126, with sowing of the direct-seeded plots and seedling nursery on 16 June 2002 and transplanting on 15 July 2002. The direct-seeded treatments were sown at 30 kg/ha.

Experiment 2b

Multi-locational trials with several rice crop establishment techniques were also conducted in farmers' fields at 2 to 11 locations across three districts (Kaithal, Kurukshetra and Fatehabad) (Table 2). The fields all had a long history of RW systems using puddled transplanted rice. The crop establishment techniques used were treatments 1, 2, 3 and 5, as in 2001. In addition, rice transplanted into dry-tilled soil (dry-till–transplant) was evaluated at seven locations. A range of rice varieties (Sarbati, HKR 126, PR 115, PR 116 etc.) was grown across locations. Each treatment was conducted on at least 1 acre and compared with the conventional puddled transplanted rice. Direct-seeded rice was sown at 30 kg seed/ha. The ZT–transplant fields were ponded 48 hours prior to transplanting to soften the soil. In the direct-seeded treatments, particularly the broadcast seeding onto puddled soil, care was taken to drain the irrigation water out of the field in the evenings and to irrigate the next day for a week or so to facilitate establishment. The farmers' reactions to the different establishment methods and the problems encountered were recorded, as well as the yields.

Table 1. Grain yield (t/ha) of paddy rice with different crop establishment techniques during 2001 and 2002 in 0.2-acre unreplicated plots in farmers' fields in Haryana

Establishment method	2001 (experiment 1)				2002 (experiment 2a)
	Location I[a]	Location II[b]	Location III	Mean ±STD	Location I
1. Puddle–transplant	8.86	5.28	8.83	7.56±2.06	7.70
2. Puddle–broadcast	9.28	5.46	8.76	7.83±2.07	6.77
3. ZT–broadcast	8.62	4.88	7.88	7.12±1.98	7.55
4. ZT–drill sown	8.65	Crop failed	Crop failed	–	n/a
5. ZT–transplant	7.56[c]	4.93	8.14[c]	6.88±1.71	7.96
6. ZT–transplant–furrow	n/a	n/a	n/a		8.04

[a] Field was under zero-till wheat for the last 2 years.
[b] Poor supply of irrigation water and poor weed management.
[c] Thin transplanting and lower supply of irrigation due to undulating field and poor weed management.

Figure 1. Zero-till drill used for creating slits for transplanting rice

Table 2. Grain yield of paddy under different crop establishment techniques at farmers' fields in Haryana during 2002 (experiment 2b)

Crop establishment technique	No. of locations	Mean ± STD (t/ha)
1. Puddle–transplant	11	6.19±1.49
2. Puddle–broadcast	9	6.03±1.82
3. ZT–broadcast	2	6.15±1.20
5. ZT–transplant	5	6.74±1.58
7. Dry-till–transplant	7	6.46±1.20

Experiment 2c

During 2002 and 2003 rice establishment techniques and their impacts on the succeeding wheat crop established with zero tillage were investigated in a replicated experiment in village Dhons, Kaithal (Table 3). The study examined three factors—variety (HKR 126 and IR 64), rice tillage (puddled and zero-till) and planting method (transplanting and broadcast seeding). The plot size was 20 × 33 m and there were three replicates. After wheat harvest the tilled plots were cultivated with tractor-powered implements as follows: three cultivations with tine harrows in dry soil followed by flooding with 15 cm water, then puddling with two harrowings followed by one pass of a cultivator and one planking in the standing water. One-month-old seedlings were transplanted on 14 July each year. The direct-seeded plots were sown with sprouted seeds broadcast at 40 kg/ha on 14 June each year. After rice harvest the loose straw was partially burnt while retaining the anchored stubbles, and wheat was sown using the zero-till drill across all rice crop establishment treatments. The wheat cultivar PBW 343 was sown on 1 November in both years at 125 kg/ha with a row spacing of 17.5 cm.

2004

Experiment 4a

Forty-one farmer-field trials comparing dry-till–transplant with puddle–transplant treatments were conducted in different villages of Sonipat district of Haryana, with collaboration between the Rice-Wheat Consortium-CIMMYT, India, and CCS Haryana Agricultural University, Hisar, during 2004 (Table 4). Four rice varieties were grown in these trials.

Experiment 4b

Forty-three other trials using zero-till transplanted rice were also conducted in Ambala and Fatehabad districts of Haryana under an Asian Development Bank (ADB) project. Dry-till transplanted and direct-seeded rice were compared with puddled transplanted rice in 16 trials in Kurukshetra, Kaithal and Karnal districts of Haryana (Table 5).

2005

Experiment 5

Zero-till transplanted (4 locations) and dry-till transplanted rice (12 locations) were compared with puddled transplanted rice (14 locations) in Kaithal and Fatehabad districts of Haryana during Kharif 2005 (Table 6).

Studies on weed management strategies in direct-seeded rice, including components of herbicides and

Table 3. Grain yield of rice under different crop establishment techniques and succeeding zero-till wheat at farmers' field (experiment 2c)

Treatments	Grain yield of rice (t/ha)		Grain yield of wheat (t/ha) in Rabi 2003–04
	2002	2003	
Variety			
IR 64	5.59	5.90	–
HKR 126	6.07	6.41	–
CD at 5%	0.22	0.26	
Crop establishment technique			
1. Puddle–transplant	6.33	6.72	4.90
2. Puddle–broadcast	5.33	5.60	5.07
3. ZT–broadcast	5.29	5.56	5.26
5. ZT–transplant	6.36	6.74	5.15
CD at 5%	0.31	0.38	NS

Source: Reddy (2004)
NS = non-significant

growing of sesbania, were undertaken during 2004. Water savings under different resource conservation technologies (Table 7) were also recorded under the ADB-funded project.

Results

In 2001 growth and yield of puddled broadcast rice were comparable with puddled transplanted rice at three locations (Table 1, Figure 2). ZT–drill sown rice was also successful at one location but it failed at the other two locations due to heavy rains and water stagnation 23 DAS. It was also realised that the recommended seeding rate of 75 kg/ha was too high and should be reduced to 30–40 kg/ha. There was a consistent trend for lower yields with the ZT–broadcast and ZT–transplant treatments. The crop stand and yield were less under ZT–transplant at location I because of thin planting (low plant population), poor weed control and water deficit due to the undulating topography of field. The labourers were reluctant to transplant with ZT because they were afraid of being injured by the standing stubble of the previous wheat crop (Figure 3). They charged 100 Rs/acre more for ZT–transplanted than puddled transplanted rice in both 2001 and 2002.

Table 6. Grain yield of paddy under ZT–transplant and dry-till–transplant treatments compared with puddle–transplanting during 2005 (experiment 5)

Crop establishment technique	No. of locations	Mean ± STD (t/ha)
1. Puddle–transplant	14	5.84±1.43
5. ZT–transplant	4	6.16±1.45
7. Dry-till–transplant	12	5.82±1.40

Trends in the results in 2002 were inconsistent with those in 2001 in that grain yields were highest with the ZT–transplant and ZT–transplant–furrow treatments (Tables 1 and 2), while broadcast seeding into puddled soil or with ZT were the lowest yielding treatments. Other reports showed similar or higher yields with direct seeding than puddled transplanting in other parts of the IGP, around Pant Nagar, Uttaranchal (Singh et al. 2002b), and in the village Pirthla (Fatehabad), Haryana (Punia et al. 2005).

Outside India the performance of direct-seeded broadcast rice relative to puddled transplanted rice has also been variable, with similar yields reported by some workers (Bollich 1991; Smith 1992; Piggin et al. 2002) and lower yields of broadcast direct-seeded rice reported by Diop and Moody (1989) in the Philippines.

Table 4. Grain yield of rice transplanted under puddled and unpuddled conditions in 2004 (experiment 4a)

No. of trials	Variety	Grain yield ± STD (t/ha)	
		7. Dry-till–transplant	1. Puddle–transplant
25	HBC 19	2.45±0.35	2.44±0.44
10	Pusa I	4.67±0.45	4.77±0.44
3	Sarbati	4.87±0.31	4.80±0.27
3	Sarbnam	5.23±0.15	5.23±0.15

Source: Singh S. et al. (2005b)

Table 5. Effect of different crop establishment techniques on grain yield (t/ha) of rice in 2004 (experiment 4b)

Location	No. of trials	Mean yield ± STD (t/ha)		
		1. Puddle–transplant	7. Dry-till–transplant	Direct seeded
Ambala	20	6.59±0.68	6.01±0.42	–
Fatehabad	23	6.77±0.47	6.86±0.56	–
Kurukshetra	3	5.85±0.43	6.13±0.19	5.62±0.44
Kaithal	11	5.63±0.99	5.81±0.85	5.21±0.90
Karnal	2	6.02±0.16	6.16±0.13	5.57±0.20
Mean	–	6.17	6.33	5.47

Observations of the trials in 2001 and 2002 showed that there was almost no cracking in soil for rice grown under ZT when irrigation was delayed. From these trials the farmers also realised that the grain yield of rice grown with alternative establishment techniques could be equal to or higher than puddled transplanting provided that suitable solutions could be found for the various problems they encountered. Farmers realised that, with direct seeding, sowing has to be at least 20–30 days earlier than transplanting of puddled transplanted rice, and that the entire area has to be sown earlier than the very small area required for the seedling nursery for later transplanting. However, it was also found and argued that the direct-seeded crop matured 10–15 days earlier than transplanted rice (seed to seed) and that this could compensate for the extra water required for early sowing. The farmers' argument was that it was easier to meet the water demand of the crop around maturity time than at the time of sowing direct-seeded rice (summer) when the temperature is very high.

The replicated experiment (2c) in 2003 and 2004 showed no interaction between rice cultivar and establishment method. Yield of HKR126 was significantly higher than yield of IR64 in both years (Table 3). Transplanting gave significantly higher yields than broadcasting sprouted seeds regardless of tillage. However, there was no effect of tillage on yield with either broadcast seeding or transplanting. Similar results were obtained by Yadav et al. (2005) in farmers' fields in Haryana. Grain yield of zero-till wheat in 2003–04 was not affected by rice establishment method. The findings again implied that puddling is not essential to realise higher yields of rice, and that wheat yields could be maintained in the double zero-till system. A shift to zero tillage would save time and energy, reduce the cost of cultivation and increase net returns, in addition to benefits for soil health.

Results in farmers' fields in 2004 showed that there was also no advantage of puddling over dry tillage for transplanted rice for a range of varieties (Tables 4, 5). There was less soil cracking with dry-till transplanting compared to puddled transplanting when irrigation was delayed (Figure 4).

Results of 16 trials conducted at Karnal, Kurukshetra and Kaithal districts of Haryana showed a consistent trend for slightly lower yield of direct-seeded rice, averaging 0.7 t/ha less than puddled transplanted rice (Table 5). But this loss in yield can be compensated for by lower planting cost and potential savings in irrigation water provided effective weed control measures that avoid the need for prolonged ponding can be developed.

Zero-till transplanted rice also produced similar yields to puddled transplanted rice in 2005 (Table 6). However, transplanting under ZT was difficult and the need to explore mechanised transplanting for ZT–transplanted rice was realised. Using the zero-till drill to open a furrow (Figure 1) followed by transplanting can be a viable option for this purpose. Another option could be mechanical transplanting with zero tillage or into dry-tilled soil using a rice transplanter (Figure 5).

Table 7. Grain yield and water productivity at different watercourse levels under different crop establishment techniques in rice in 2005

Watercourse level	No. of irrigations	Total time (hours)	Water applied (m^3/ha)	Gross water (m^3/ha)	Yield (t/ha)	Water productivity of irrigation (kg/m^3)	Gross water productivity (kg/m^3)
(A) Saving at watercourse levels							
Raogarh (head)	24.0	307	14,400	19,100	5.78	0.40	0.30
Pabnawa (middle)	30.1	295	14,400	19,000	5.86	0.41	0.31
Faral (tail)	23.0	258	12,000	16,700	5.44	0.45	0.33
(B) Saving by crop establishment techniques							
Puddle–transplant	25.5	283	13,900	18,500	5.87	0.42	0.32
Dry-till–transplant	25.2	292	12,700	17,400	5.78	0.45	0.33
Direct seeding	26.9	279	14,200	18,800	5.44	0.38	0.29

Source: Singh S. et al. (2005b)

Discussion

Weed management in direct-seeded rice

Singh, Y. et al. (2005) reported similar yields for transplanted, dry-seeded and zero-till rice, and slightly higher yields under wet seeding, in the fields where satisfactory weed control was achieved. Where weeds were not controlled, however, there was low yield in all the direct-seeded treatments, whereas yield losses were only 20% in the transplanting treatments. Similar yields in transplanted and direct-seeded (wet-seeded and dry-seeded) rice were obtained where weeds were well controlled at farmers' fields in Haryana, Punjab, Uttar Pradesh, Uttaranchal and Bihar (Singh et al. 2002; Punia et al. 2005). This illustrates the importance of effective weed management in direct-seeded systems. The following options may be useful for effective weed management under direct-seeded rice, and need to be explored for further refinement in farmers' fields under different agroecological rice growing regions.

Sequential application of herbicides

Trichlopyr at 500 g a.i./ha, bensulfuron at 60 g a.i./ha, ethoxysulfuron at 18 g a.i./ha, almix at 4 g a.i./ha or 2,4-D at 500 g a.i./ha provided effective control of broadleaf weeds (Singh, S. et al. 2005b). The sequential application of pendimethalin at 1000 g a.i./ha at 3 DAS followed by almix at 4 g a.i./ha at 21 DAS controlled the weeds to the same extent as a tank mixture of fenoxaprop + ethoxysulfuron at 50+18 g/ha at 21 DAS, but use of cylohalofop with trichlopyr either as a tank mixture or a follow-up treatment gave poor weed control and consequently lower yields compared to propanil+trichlopyr at 1,750+50 g/ha (Singh, S. et

Figure 2. Direct-seeded broadcast rice (right) and puddled transplanted rice (left) at location III in 2001

Figure 3. Farmers manually transplanting rice under zero tillage after wheat

Figure 4. Cracking of soil under puddled transplanting (left) and no cracking of soil under dry-till transplanting (right)

al. 2005b). Pre-emergence application of anilofos, butachlor or pretilachlor at 3–6 DAS followed by a sequential application of almix at 4 g/ha, ethoxysulfuron at 18 g/ha or 2,4-D at 500 g/ha at 20–25 DAS could be other alternatives for effective control of complex weed flora in direct-seeded rice. However, standing water (3–5 cm) at the time of application of pre-emergence herbicides is essential for better efficacy. Suitable recommended herbicide(s)/mixtures for the weed flora present may be used. This will not impose any additional cost compared with puddled transplanting. Pendimethalin applied at 7–13 DAS was found to be highly phytotoxic to wet direct-seeded rice (Yadav and Yadav 2007). Bispyribac (PIH 2023) at 25 g a.i./ha sprayed at 15–25 DAS was very effective against complex weed flora in direct-seeded rice. Azimsulfuron at 30 g a.i./ha applied at 15 DAS was promising against broadleaf weeds and sedges, and penoxulam at 25 g a.i./ha was moderately effective against all types of weeds (Yadav et al. 2007).

Integrated weed management including Sesbania *and herbicides*

Mulching with *Sesbania aculeata* (sesbania), sown as an intercrop at the time of rice seeding and then killed ~30–40 DAS, could be effective against weeds in direct-seeded rice. Sesbania should be broadcast using a seeding rate of 25 kg/ha at the time of rice seeding and then knocked down 30 DAS with 2,4-D at 1.25 kg/ha. Mulching and intercropping with sesbania reduces weed infestation by ~40% compared with no weeding, and hand weeding at 30–40 DAS can further reduce weed infestation. Pre-emergence application of pretilachlor with safener at 500 g/ha in wet direct-seeded rice, and pendimethalin at 1.0 kg/ha in dry-seeded rice, coupled with a sesbania cover crop, has been proved to be effective against weeds (Singh, S. et al. 2005b). This treatment may prove best under direct seeding because it will not only be effective against weeds but will also help improve soil health.

Water requirements and savings under different crop establishment techniques in rice

Singh, S. et al. (2005b) compared water use and yield of different rice establishment methods at multiple sites in the upper, middle and lower reaches of a canal watercourse (Table 7). Differences in average yield, irrigation water use, and irrigation and gross (rain plus irrigation) water productivity were generally small (usually within 10%). Grain yields of dry-tilled and puddled transplanted rice were similar but the yield of direct-seeded rice was 7% lower. Because irrigation applications were similar for puddled transplanted and direct-seeded rice, the irrigation water productivity of direct-seeded rice was 10% lower than for puddled transplanted rice. Irrigation water input of dry-tilled transplanted rice was 9% lower than puddled transplanted rice; thus, dry-tilled transplanted rice had the highest irrigation

Figure 5. Mechanical transplanting of rice after wheat with zero tillage

water productivity. Grain yields were similar at the head and middle reaches and 7–8% higher than at the tail. Trends in gross and irrigation water productivity obtained under dry-tilled transplanted rice followed by puddled transplanted rice were similar. Dry-tilled transplanted rice had 18% higher irrigation water productivity than direct-seeded rice.

Variable results with direct-seeded rice

The above results over several years show that sometimes yield of direct-seeded rice was comparable with puddled transplanted rice, but in other years it was inferior. The problems with direct seeding (or any other alternative establishment techniques without puddling) appeared to be worse in years when monsoon rainfall was only about half the normal amount (2002 and 2004), and in the areas with fine-textured soils. Submergence for at least 15 days was essential to achieve satisfactory weed control with herbicides. The grain yield of rice during the relatively dry year of 2004 at Meerut, Western Uttar Pradesh, India, was higher, while irrigation water requirement was less under the conventional puddled transplanted treatment compared with direct seeding or transplanting on raised beds (Singh, S. et al. 2005a). Based on 17 multi-locational farmers' field trials, Yadav et al. (2005) also reported lower grain yield of rice transplanted on raised beds. This was mainly due to unsuitable varieties (susceptible to lodging) and poor irrigation supply coupled with drought (during 2002), ultimately leading to poor weed management and high investment (5,000 Rs/ha) on manual weeding.

Direct seeding in residues with new generation machines

Farmers usually burn rice crop residues before sowing wheat because the tough, loose residues block up the seed drill. Many farmers even burn wheat residues before planting rice. This creates air pollution and wastes nutrients and organic matter. To tackle such a problem, second generation drills fitted with improved seed metering devices for multicrop seeding in loose crop residues are now available (Sharma et al. 2008; Sidhu et al. 2007, 2008). Double-disc and rotary disc drills have proved more suitable for direct seeding of rice in loose residues of 3–4 t/ha but the star wheel / punch planter still needs some modification (Singh, S. et al. 2005b). Retention of crop residues on the soil surface will help reduce weed infestation, conserve soil moisture and add organic manure to the soil. The Happy Seeder, which cuts crop residue and throws it behind as a mulch over the seeded bed, may also prove useful both for wheat and rice seeding. Yield penalties and difficulties in operation of such drills, particularly in fields with heavy residues, call for further research effort in this direction.

Conclusions

Puddling followed by transplanting is the most common and widely used practice of rice cultivation in the entire Indo-Gangetic Plain; however, it results in several constraints to the productivity and sustainability of RW systems. Five years' research work in Haryana, Punjab, Uttar Pradesh and Uttaranchal has shown that puddling is not necessary for achieving high grain yields. Transplanting under zero-till and dry-till situations may be suitable alternatives, and farmers can adopt them if given proper guidelines and information. Direct seeding of rice is cost-effective and can equal the yield from conventional planting provided effective weed management is achieved. Before introducing direct seeding, there is a need to identify niche areas where the technology will work well, such as medium-textured soils with assured water availability. A survey is required to identify leading farmers interested in the direct seeding of rice. Research and extension efforts are needed on weed management including evaluation of herbicides and integrated weed management. This should include evaluation of the use of tank mixtures or sequential application of herbicides supplemented with hand weeding, and of cover crops like sesbania and mulches. Research is required on irrigation scheduling with direct seeding. There is also a need for further development, refinement and evaluation of drills for sowing directly in standing stubbles. Sowing time (mid June), suitable varieties (short duration and high yielding), seeding rate (30 kg/ha), depth of seeding (not more than 2–3 cm), laser levelling, 'stale bed technique' (pre-irrigation to germinate weeds which are killed using herbicide prior to sowing), application of micronutrients (Fe and Zn) and other plant protection measures may further help make direct seeding successful in the future. This calls for further research and evaluation of direct seeding in different pockets of the country by integrating the experience gained at national and international levels.

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Part 2:

Direct drilling wheat into rice residues

Direct drilling of wheat into rice residues: experiences in Haryana and western Uttar Pradesh

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Abstract

Field experiments and farmer participatory trials were conducted to evaluate the possibility of direct drilling wheat into rice crop residues and the effect of residue management practices on soil properties. For seeding into loose residues, four machines were tested—rotary disc drill, double-disc drill, punch planter and Happy Seeder. The performances of the double-disc drill and punch planter were not satisfactory, whereas the rotary disc drill and the Happy Seeder gave similar or higher yields than the zero-till drill after partial straw burning or conventional tillage after complete straw burning. The rotary disc drill and Happy Seeder can enable conservation agriculture through minimum tillage while leaving the crop residues at the soil surface. Retention or incorporation of rice, wheat or both crop residues increased soil organic C by 19–32% (absolute increases of 0.06–0.1% organic C) in the top 15-cm soil layer after 2 years (four crops) in comparison with both the initial soil organic C and 2 years of burning the residues of both crops. The other benefits of residue retention were decreased soil strength and lower weed infestation.

Introduction

The Indo-Gangetic Plain (IGP), the food basket of India, is of great significance in the food security of the country. It extends over a length of about 1,600 km and a width of 320 km, including the arid and semi-arid environments in Rajasthan and Punjab and the humid and perhumid deltaic plains in West Bengal (Shankaranarayana 1982). A decline in land productivity, particularly of the rice–wheat (RW) system, has been observed over the past few years in the northern and north-western IGP despite the application of optimum levels of inputs under assured irrigation (Paroda 1997). Reflecting this, the fertiliser recommendation has been revised upwards for both rice and wheat crops.

Agriculture in north-western India has, until now, been focused on achieving food security through increased area under high-yielding varieties of rice and wheat, expansion of irrigation and increased use of external inputs like chemical fertilisers and pesticides (Woodhead et al. 1994; Yadav et al. 1998; Ladha et al. 2000). The support price system for rice and wheat crops, coupled with subsidies on fertilisers and irrigation water, made the RW system the most profitable option. This enabled rice and wheat crops, covering an estimated area of around 10 million hectares (Mha), to emerge as the major cropping system in the IGP, leading to the Green Revolution. These two crops together contribute more than 70% of total cereal production in India from an area of around 25 Mha under wheat and about 40 Mha under rice. The small states of Punjab

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and Haryana contribute 20% of the total national grain production and 50% and 85% of the government procurements of rice and wheat, respectively (Singh 2000). With unabated increases in population, more and more land will be required for urbanisation, and productivity needs to be increased to meet the rising domestic and industrial demand.

The indiscriminate use, or rather misuse, of natural resources, especially water, has led to pollution and depletion of groundwater resources (Nayar and Gill 1994). The situation is serious; if it is not improved, India may face water wars in the near future. There are early signs of this already visible in the surface water dispute between Punjab and Haryana, and between some other states in India. Depleting soil organic C status, decreasing soil fertility and reduced factor productivity are other issues of concern (Yadav 1998). This evidence indicates that the RW system, especially residue burning, intensive tillage and injudicious use of water, has weakened the natural resource base. If exploitation of natural resources at the current level continues, productivity and sustainability are bound to suffer. Therefore, to achieve sustainable or higher productivity, efforts must be focused on reversing the trend in natural resource degradation.

Crop residues—a key to sustainability

Crop residues could be an important component of soil fertility management. They are currently burnt, especially rice residues in the high-yielding states like Punjab and Haryana, leading to degradation of natural resources. Rice residues can be converted to high-value manure of a better quality than farmyard manure, and their use, along with chemical fertilisers, can help sustain or even increase yield (Sidhu et. al. 1998). Inorganic fertilisers have played a highly significant role in intensive cropping systems, bringing about varied increases in crop production. However, with the increased use of inorganic fertilisers alone, often in an unbalanced manner, problems such as diminishing soil health and multiple nutrient deficiencies have started appearing recently in various pockets of the highly productive IGP (Fujisaka et al. 1994). Efficient crop residue management can play a vital role in refurbishing soil productivity as well as in increasing the efficiency of inorganic fertiliser. Residue management is receiving a great deal of attention because of its diverse and positive effects on soil physical, chemical and biological properties. Crop residues must be considered a natural resource and not a waste.

Crop residue management options

The management of crop residues must be an integral part of future tillage practices for sustainable RW production systems. There are several options available to farmers for the management of crop residues, including burning—the common practice, baling and removal, incorporation and surface retention. Burning, in addition to promoting loss of organic matter, nutrients and soil biota, also causes air pollution (Figure 1) and associated ill effects on human and animal health. Baling is not practised at the farmer level. Removal of crop residues, especially of wheat and scented rice, is a loss of organic sources for soil health but is necessary to feed livestock and sustain mixed farming. Incorporation is a better option but it requires large amounts of energy and time; leads to temporary immobilisation of nutrients, especially nitrogen; and the C:N ratio needs to be corrected by applying nitrogen at the time of incorporation (Pathak and Sarkar 1994; Sharma and Bali 1998). Farmers resort to burning as it is an easier disposal option and allows a shorter turnaround time between crops than incorporation, which is especially important between rice harvest and wheat sowing. Incorporation is also a more costly operation and, until recently, surface retention was not a viable option due to the lack of suitable machines able to seed into the loose residues left after combine harvesting. However, two machines are now available (see below) that are capable of seeding into full, surface-retained rice residues.

Deep tillage for incorporation of crop residues has been shown to reduce soil bulk density (Kumar et al. 2004a) as well as penetration resistance of the plough layer (Walia et al. 1995). It also helps to decrease soil pH (Sidhu and Beri 1989). Moreover, residue incorporation improved soil fertility by increasing the content of available N, P, K, S, DTPA-extractable Fe and organic C. It also increased the soil water-holding capacity (Bhat et al. 1991; Beri et al. 1992; Walia et al. 1998; Prasad et al. 1999). The increased availability of essential plant nutrients with associated improved physicochemical properties enhanced crop growth and yield (Verma 2001; Das et al. 2002; Kumar et al. 2004b).

Figure 1. Burning of crop residues causing environmental pollution

Why seed into crop residues?

Leaving crop residues on the soil surface seems to be a better option than incorporation as it reduces soil erosion and soil evaporation, avoids short-term tie-up of nutrients and suppresses weeds. Moreover, the slower decomposition compared with incorporation also helps build up soil organic C (Hooker et al. 1982; Havlin et al. 1990; Wood et al. 1990; Unger 1991). Machines are now available for seeding into standing stubble in the presence of loose surface-retained residues (see below). But an issue that needs to be resolved is the amount of crop residues that can effectively be managed by surface retention and the effect this has on soil properties and productivity of the RW system.

Crop residue and tillage practices may influence weed germination and establishment. Tillage is mainly practised to prepare a seedbed and to control weeds that have already germinated at the time of sowing. But tillage also stimulates the germination and emergence of many weeds through providing brief exposure to light (Ballard et al. 1992). Crop residues may influence the weed seed reserve in the soil directly or indirectly and also the efficiency of soil-applied herbicides (Crutchfield et al. 1986). Incorporated plant residues may also release allelochemicals, which can be toxic to weeds (Inderjit and Keating 1999); however, under field conditions the occurrence of allelopathy is influenced by numerous factors (Einhellig 1996). Residue type also influences weed growth. For example, Eguchi and Hirano (1971) found that rice straw mulch reduced the population of the weed *Polygonum lapathifolium* in wheat. Residue retention on the soil surface in combination with a zero-till system may also significantly contribute to the suppression of weeds (Teasdale 1998; Liebman and Mohler 2001). Zero-till systems help reduce weed emergence through avoiding exposure to light and through mechanical impedance to the weed seed. Residue retention also influences soil temperature and soil moisture, which may increase or decrease weed germination depending on the types of weeds, soil conditions, and type and quantity of crop residue. At lower residue levels the weed population may be higher than in residue-free conditions, but at higher residue levels weeds will be reduced considerably.

Availability of crop residues in the rice–wheat system

Factual information on the availability of crop residues is not available, and what is reported is based on estimates taken from grain production and grain to straw ratios, which vary from report to report. Thus, Pal et al. (1985) estimated annual total crop residue production in India of 250 Mt, of which only about one-fifth is available for energy conversion. Bhardwaj (1981) estimated residue production of 185 Mt and Sarkar et al. (1999) estimated 356 Mt, of which one-third is available for soil incorporation or surface retention. Of the total crop residue production in India, wheat and rice together contributed about 60% (213 Mt). Recently, Pal et al. (2002) estimated the crop residue produced by rice and wheat crops to be 240 Mt, of which one-third is available for recycling. Using the same methodology (Pal et al. 2002), estimates were made for the RW system (Table 1). The total residue produced in the system was 126 Mt, of which 42 Mt is available for recycling. By taking the prevailing price, in Indian rupees (Rs), of 1 kg N as 9.35 Rs, of P as 15.40 Rs and of K as 7.45 Rs, the fertiliser replacement value was estimated to be 3.58 billion Rs/year.

Machines for seeding into rice residues

Over the period 2004–06 we tested four types of machines for seeding both wheat and rice into loose residues. The first machine to be tried in Haryana for seeding wheat into loose rice residues was the double-disc coulter (Figure 2). It was a nine-row-seeding ferti-seed drill weighing about 0.3 t, which was not sufficient to cut through the rice residues. The second machine tested was the star wheel / punch planter (Figure 3), which also did not work in rice residues due to problems of rolling and collecting of rice straw by the star wheels. The other two machines tested were the Happy Seeder (Figure 4) (Sidhu et al. 2007), developed in Ludhiana through collaboration between CSIRO, Punjab Agricultural University and Dashmesh Mechanical Works Pvt. Ltd; and the rotary disc drill (Figure 5), developed at the Directorate of Wheat Research in Karnal (Sharma and Mongia 2004). These machines work satisfactorily in combine-harvested farmers' fields with loose residues but still have some problems. The Happy Seeder does not work well if the residues are wet or completely loose, or in heavy stubbles if the header windrows of loose straw are not uniformly spread across the field. This machine also cannot be used for seeding wheat or some pulse crops into sugarcane ratoons. Moreover, it requires a tractor of more than 45 hp with a dual clutch. The rotary disc drill is more versatile and works under almost all situations including sugarcane ratoons with full trash, but has a problem of blunting of the front powered discs. This problem can be solved by using discs of greater strength like those being used in Brazilian disc drills. The Happy Seeder and the rotary disc drill are the only machines capable of coping with heavy rice-residue loads >6 t/ha.

Results of trials in farmers' fields

The performance of second-generation machines for seeding wheat under loose residue conditions, after combine harvesting of rice, was evaluated with farmer participation in their fields. These trials were conducted both in Haryana around Karnal and in western Uttar Pradesh (UP) around Meerut. Wheat yield was determined by manually harvesting areas of 1 m^2 in three to five representative locations in each treatment, separating the grain from the straw with a portable thresher and calculating the average yield. An overview of the trials and their site characteristics are provided in Table 2.

Trials 1 and 2 were carried out during Rabi 2004–05 in fields with a rice-residue load of 6–7 t/ha in village Nidana, about 20 km from Karnal. In Trial 1 the recently released variety PBW 502 was sown with a

Table 1. Availability of rice and wheat crop residues and their nutrient contents in rice–wheat systems in India (Pal et al. 2002)

	Rice	Wheat	Total
Total crop residues (Mt)	70.9	55.1	126.0
Residues available for use (Mt)	23.6	18.4	42.0
Nutrient content (% oven-dry basis)			
Nitrogen	0.61	0.48	
P_2O_5	0.18	0.16	
K_2O	1.38	1.18	
Total nutrients (Mt)	1.29	1.20	2.49
Nutrients available for use (Mt)	0.43	0.40	0.83
Fertiliser replacement value (Mt)	0.22	0.20	0.41
Fertiliser replacement value (billion Indian rupees)	1.86	1.72	3.58

rotary disc drill in five farmer fields (Table 3). Grain yield ranged from 5.18 t/ha to as low as 2.88 t/ha in a field severely infested by army worm (Figures 6a,b,c). The wheat was resown in the army-worm-infested field in the last week of December, resulting in a large reduction in yield due to the very late sowing. When sowing into loose residues, the incidence of pests and pathogens with the potential to affect the crop needs to be considered, and appropriate controls applied to prevent problems developing.

The second trial compared two versions of the rotary disc drill (RDD—eight-row normal drill and RDD-TC—six-row controlled-traffic drill), the double-disc drill (DD) and the star wheel / punch planter (SW) sowing into 6–7 t/ha of combine-harvested rice residues. These treatments were compared with sowing into partially burnt rice residues (loose burnt straw with only anchored straw remaining) using the zero-till drill (ZT). The star wheel / punch planter collected the residues, which rolled over the star wheels and caused frequent blockages, whereas the other two machines had no such problem. The double-disc drill and rotary disc drill had problems of penetration, leaving the seed and fertiliser on the residue wherever loose residue was concentrated in swathes left by the combine harvester during harvesting. However, the problem was considerably less severe with the rotary disc drill than the double-disc drill.

Two varieties, i.e. PBW 343 (the predominant variety in Punjab and Haryana) and PBW 502, with similar plant type and yield potential, were evaluated for their performance under various tillage options at eight farmer fields (Table 4). The number of replicates for each treatment varied from one to four. The standard error (SE) of the means of all treatments was

Figure 2. Double-disc drill for seeding into loose residues

Figure 4. Happy Seeder for seeding into loose residues

Figure 3. Star wheel / punch planter for seeding into loose residues

Figure 5. Rotary disc drill for seeding into loose residues and sugarcane ratoons

calculated for comparing the treatment means. The results suggested that the rotary disc drill was the best performer among the three new machines tested. The eight-row rotary disc drill gave higher yield than the controlled-traffic rotary disc drill, and similar yield to the zero-till drill, after partial residue burning. Yield with the double-disc drill was almost 1 t/ha lower than with the zero-till or rotary direct-drill machines, and the lowest yield was with the drill fitted with star wheels.

In another set of trials in four farmer fields (trial 3, Table 5), the rotary disc drill, double-disc drill and star wheel / punch planter were tested in rice-residue loads of 4–6 t/ha and compared with the farmer practice of partial burning followed by zero and conventional tillage (CT). The rotary disc drill was capable of drilling in a residue load of 6 t/ha and produced a yield similar to zero tillage after partial burning. In 4 t/ha residues the double-disc drill gave similar yield to the rotary disc drill. The star wheel / punch planter gave the lowest yields, mainly due to poor establishment, and was statistically inferior to all the other seeding options, which had similar yields.

The rotary disc drill was the only machine with satisfactory performance when sowing into combine-harvested full rice residues in 2004–05. Therefore, only this machine was evaluated in farmer participatory trials at two locations during 2005–06, along with a recently acquired Happy Seeder (trial 4). The mean yields of wheat seeded using these machines were 4.22 t/ha with the Happy Seeder and 4.23 t/ha with the rotary disc drill.

Table 2. Overview of trial and site characteristics of on-farm experiments conducted to test the ability of selected drills to plant into rice residues

Trial no.	Location	Treatments	Planting date	Soil type	Plot size (ha)	No. of replicates	Residue loads (t/ha)
1	Nidana, Karnal	RDD		Sandy loam	0.4	5	6–7
2	Nidana, Karnal	RDD, RDD-TC, SW-TC, DD-TC, ZT		Sandy loam	0.1–0.4	1–4	6–7
3	Four villages in Karnal and Kurukshetra	RDD-TC, DD-TC, SW-TC, CT, ZT-TC	1–14 November	Sandy loam to sandy clay loam	0.1–0.4	4	4–6
4	Two villages around Karnal	RDD and HS	1–7 November	Sandy loam	0.2 –0.4	2	6–8
5	Four villages around Karnal	RDD, RDD-CT	1–7 November	Sandy loam	0.2	4	0–7
6	Meerut, Ghaziabad, UP	DD-TC, RDD-TC, SW-TC	1–14 November	Sandy loam	0.2 –0.4	1 –3	3–4
7	Meerut, Ghaziabad, UP	HS, RDD-TC, DD-TC	1–14 November	Sandy loam	0.2–0.4	1–3	3–4

RDD = rotary disc drill, HS = Happy Seeder, TC = traffic control, SW = star wheel, DD = double disc, CT = conventional tillage, ZT = zero-till drill; UP = Uttar Pradesh

Table 3. Performance of wheat sown in surface retained residue using the rotary disc drill (trial 1)

Farmer name	Variety	Sowing method	Tillers/m^2	Biomass (t/ha)	Grain yield (t/ha)	1,000 grain weight (g)	Protein (%)
Surjeet Singh	PBW-502	RDD	373	14.4	4.08	38.9	11.3
Sukhwant Singh	PBW-502	RDD	361	13.5	4.27	37.4	11.2
Avtar Singh	PBW-502	RDD	420	12.1	4.16	36.2	10.7
Jasbir Singh	PBW-502	RDD	370	13.3	5.18	34.2	10.3
Lakhbir Singh	PBW-502	RDD	245	9.8	2.88	30.9	11.9
	SE		29	0.8	0.37	1.4	0.3

RDD = rotary disc drill

The performance of wheat sown using the rotary disc drill with residue retention of 4–6 t/ha and conventional tillage (around 10 tillage operations with various implements after residue burning) was also evaluated at four sites on farmer fields (trial 5). Mean yields (4.8–4.9 t/ha) were similar for both methods of crop establishment.

Three drills (rotary disc drill, double-disc drill and star wheel / punch planter) were evaluated with a partial residue load of 3.5–4.0 t/ha at five locations around Meerut and Ghaziabad in western UP in 2004–05 (trial 6, Table 6). At this low residue load, yield was comparable with all the drills including the star wheel / punch planter.

During Rabi 2005–06, the Happy Seeder, double-disc drill and rotary disc drill gave similar yields (trial 7, Table 7), although there was an observed problem with the double-disc drill—it was not able to cut through the residue for proper placement of seed and fertilisers.

Table 4. Comparative performance of second generation tillage machines (trial 2)

Sowing method	Tillers/m^2	Biomass (t/ha)	1000 grain weight (g)	Yield (t/ha)
RDD	381	13.3	36.7	4.42
RDD-TC	319	11.7	33. 7	4.12
DD-TC	260	9.8	35.0	3.39
SW-TC	228	8.3	32.8	2.96
ZT	371	12.2	35.9	4.22
SE	30	0.9	0.7	0.28

RDD = rotary disc drill, TC = traffic control, SW = star wheel, DD = double disc, ZT = zero-till drill

Figure 6. Incidence of army worm in wheat sown into loose residues: (top left) larvae of army worm, (top right) damaged seedlings and (bottom) farmer with cut seedlings

Results of trials on research stations in Haryana and Uttar Pradesh

Residue management experiment at Karnal

Site description and methodology

A long-term experiment was initiated at the Directorate of Wheat Research (DWR), Karnal, during Kharif 2004 to evaluate the effect of various residue management options and nitrogen levels on crop performance and soil properties. The soil was sandy loam with a pH of 8.3, EC = 0.28 dS/m, low organic C (0.31%), and medium P (18.25 kg/ha) and K (269 kg/ha) in the top 0.15 m of soil. The treatments included seven residue management practices (removal, burning, incorporation or surface retention of full crop residues of either rice or wheat or both) in main plots of 64 m^2 with three replicates. There were three nitrogen levels (100, 150 and 200 kg/ha) in subplots. Wheat (PBW 343) was sown using the rotary disc drill at a row-to-row spacing of 0.20 m. Phosphorus and potash were uniformly applied @ 60 and 30 kg/ha respectively. The source of P and K used was NPK (12:32:16) mixture, which was drilled at the time of seeding. The rest of the nitrogen was applied in two splits, one at crown root initiation with the first irrigation and the second around the first node stage with the second irrigation. The soil physicochemical properties are being monitored to evaluate the changes, if any, due to residue management practices. Soil organic C of the experimental field was determined at the time of initiating the experi-

Table 5. Performance of second-generation machines during 2004–05 in four farmer fields (trial 3)

Sowing method	Grain yield (t/ha)				Mean (t/ha)
	Farmer 1	Farmer 2	Farmer 3	Farmer 4	
RDD-TC	4.00	2.95	4.23	5.25	4.11
DD-TC	3.41	2.65	4.25	5.00	3.83
SW-TC	2.68	1.98	–	–	2.33
CT	3.50	2.70	4.10	4.20	3.62
ZT	4.13	3.15	4.20	4.80	4.07
LSD (0.05)					0.61

RDD = rotary disc drill, TC = traffic control, SW = star wheel, DD = double disc, CT = conventional tillage, ZT = zero-till drill

Table 6. Comparative performance of new generation drills in wheat under partial rice residue (2004–05) (trial 6)

Sowing method	Yield attributes			Yield (t/ha)	
	Effective tillers/m^2	Spikelets/spike	Grains/spike	Grain	Straw
DD	427	18.1	45.0	5.18	7.23
RDD	431	17.4	43.7	5.24	7.44
SW	407	17.7	45.6	5.12	7.11

DD = double disc, RDD = rotary disc drill, SW = star wheel

Table 7. Yield performance of wheat drilled with different new generation drills under full rice residues with low straw load (2005–06) (trial 7)

Sowing method	Yield attributes				Yield (t/ha)	
	Plant height (cm)	Effective tillers/m^2	Spike length (cm)	Spiklets/ spike	Grain yield	Straw yield
Happy Seeder	84.7	388	9.81	17.5	4.22	7.08
Rotary disc drill	86.9	395	9.53	17.2	4.21	7.05
Double-disc drill	86.2	375	9.46	17.0	4.03	7.00
Mean	85.9	386	9.60	17.2	4.16	7.04

ment in May 2004 and again after 2 years (four crops) in May 2006. Soil strength was also measured in May 2006 after two RW crop cycles using a recording penetrometer. The measurements were made when the soil was moist, 5 days after irrigation. Measurements were made at 1 cm increments from the surface to 40 cm depth at three locations in each subplot in all three replicates. The data were averaged across nitrogen levels; therefore, each data point in Figure 8 is the mean of 27 determinations.

Effect on wheat yield

Pooled analysis of the wheat yield data over the first 2 years was done as the year and the year × treatment effects were not significant. There was no interaction between residue treatment and nitrogen rate on yield, nor any significant difference between surface residue retention, incorporation, removal or burning treatments (Table 8). There was a significant response to increasing nitrogen rate up to 150 kg N/ha.

Effect on soil properties

There are numerous reports that residue incorporation helps increase soil organic C and improves many soil physicochemical properties. Soil organic C (at 0–15 cm) increased significantly in all residue retention and incorporation treatments compared with initial soil organic C status (Figure 7). The organic C build-up was highest with residue incorporation, followed by surface retention. The increase in soil organic C was about 0.1% after 2 years with full residue incorporation of rice or both rice and wheat crops. The soil organic C content increased from 0.31% to 0.37% with surface residue retention of rice alone and to 0.38% when residue of both rice and wheat crops was retained. There was no change in soil organic C in any of the burnt treatments.

There was a consistent trend for lower soil strength from just below the soil surface to a depth of 28 cm with surface residue retention of both crops, followed by retention of only rice residue (Figure 8). Residue incorporation resulted in much higher soil strength at 7–15 cm depth than in all other treatments. This might be due to the fact that the residue was incorporated (after chopping) using a rotary tiller, which has a working depth of about 10 cm, and which might have resulted in some compaction at this depth. In the residue removal treatment the compaction layer was at around 17 cm depth, probably as a result of puddling for rice.

Effect of residue retention on weed infestation

Another experiment at the Directorate of Wheat Research (DWR) research farm, Karnal, in 2005–06 evaluated the effect of rice-residue load on the weed infestation in wheat. Wheat was sown in rice residues of 0–8 t/ha using the rotary disc drill. Weed biomass was highest with 0 t/ha and 2 t/ha of rice residues, and decreased rapidly with residue loads higher than 4 t/ha (Figure 9).

Tillage experiments at PDCSR, Modipuram

A long-term experiment was established at the research station of the Project Directorate for Cropping Systems Research (PDCSR), Modipuram, comparing three tillage/sowing treatments with and without rice-residue retention. The three tillage treat-

Table 8. Wheat yield (t/ha) in various residue management options (mean of 2 years)

Residue management option	Nitrogen levels (kg/ha)			Mean
	100	150	200	
Removal of rice (puddled) and wheat (zero-tilled)	4.00	4.28	4.31	4.20
Incorporation of both rice and wheat	3.71	4.03	4.35	4.03
Incorporation of rice and removal of wheat	3.79	4.07	4.14	4.00
Burning of both rice and wheat	3.97	4.16	4.31	4.14
Burning of rice and removal of wheat	3.96	4.24	4.26	4.15
Retention of both rice and wheat	3.76	4.10	4.08	3.98
Retention of rice and removal of wheat	3.84	4.09	4.14	4.02
Mean	3.86	4.14	4.23	
LSD (0.05)	Residue NS	Nitrogen 0.11	Interaction NS	

ments were: zero-till drill with inverted T-type openers, a strip-till drill and conventional tillage. The performance of the drills was compared in rice-residue retention and removal situations (Table 9). The rice-residue load was maintained at 4.5 t/ha, with partially anchored (3.0 t/ha) and partially loose (1.5 t/ha) residues. There were three replicates.

The grain yield of wheat (average of 4 years) indicated that, irrespective of tillage (drilling) practice, rice-residue retention gave higher wheat grain yield. However, there was a significant interaction between tillage and residue treatments, and the effect of residue retention was less with conventional tillage than with zero and strip tillage. Yield with strip tillage was significantly higher than that for zero tillage, both with and without residues. There was also a trend for lower yield with zero tillage than conventional tillage but the differences were not signifi-

Table 9. Tillage and residue interaction effects on wheat yield (average of 4 years) at PDCSR, Modipuram

Tillage practices	Wheat grain yield (t/ha)	
	Residue retention	Residue removal
Zero tillage	4.75	4.47
Strip tillage	5.04	4.75
Conventional tillage	4.88	4.65
Mean	4.89	4.62

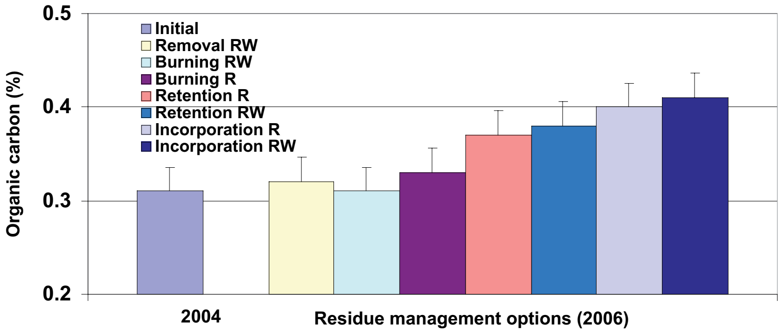

Figure 7. Effect of residue management on soil organic C (at 0–15 cm) after 2 years (four crops). Vertical bars on each column represent the LSD (0.05).

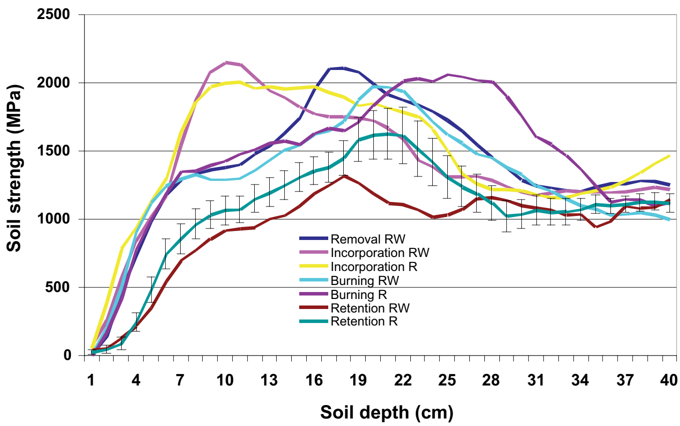

Figure 8. Effect of residue management options on soil strength (data are means of 27 determinations, vertical bars are standard error of the mean for one treatment)

cant. The higher yield with strip tillage was associated with better crop establishment due to pulverisation of the soil in the seeding row and better placement of seed and fertilisers. The results of this experiment showed that wheat drilling using the zero-till drill with rice-residue retention is a suitable option for low straw loads.

Conclusions

It has been widely reported that crop residue retention on the soil surface has many benefits. It conserves soil moisture, moderates temperature, suppresses weeds, improves soil physicochemical properties and helps make the system sustainable. The results from Haryana and Western UP, both in research station experiments and trials in farmers' fields, show similar or slightly higher yields with residue retention. The potential benefits in terms of cost reduction, timeliness of planting and similar or higher yield are proving to be of interest to farmers in India's north-western states. The on-farm trials are helping to convince farmers that residue retention is making their soil more friable and productive. In addition, the controlled experiments from research station trials confirm the benefits of residue retention in increasing soil C, reducing soil strength and weed infestation. However, there are still some problems with the capability of the available machines to seed into loose residues after combine harvesting at higher residue loads. The next step will be to further refine the most promising machinery (rotary disc drill and Happy Seeder) in partnership with farmers and manufacturers. Moreover, further intensive investigations are required on the size of residue load that can be sustained for a long time, as well as the potential effects on insect pests, diseases and weeds, if any. Researchers working with residue retention must remain vigilant and should adopt an interdisciplinary approach to address the issue of residue management in a holistic manner.

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Development of the Happy Seeder for direct drilling into combine-harvested rice

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Abstract

Tens of millions of tonnes of rice straw are burnt each year in the north-western Indo-Gangetic Plain in preparation for wheat sowing. Straw burning results in widespread and severe air pollution and loss of nutrients and organic matter, leading to a decline in soil organic carbon levels to very low values. The majority of the rice is harvested by combine harvesters, leaving standing stubble and windrows of loose straw that interfere with tillage and seeding operations for wheat. Therefore, there is an urgent need for technologies for direct drilling wheat into combine-harvested rice residues.

The development of the Happy Seeder commenced in 2001 and has included three major prototypes to date. The first two versions cut and lift the standing stubble and loose straw ahead of the sowing tines so that they 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, and a seed drill attached behind by a 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 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 tines. In the Combo machines only an 8-cm strip in front of each tine (tine 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 the 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, and feeding it past, the tines. Considerable testing of the Combo Happy Seeder has shown that wheat yields are maintained or increased with direct drilling into rice stubble in comparison with the farmers' practices of straw burning followed by tillage or direct drilling. 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, particularly straw and soil moisture.

There is an urgent need for a major program to promote and facilitate adoption of the Happy Seeder technology. To ensure success, such a program needs to include widespread farmer participatory trials of the technology, development of a package of practices for optimum results, and suitable policies and incentives. This paper summarises features of the three prototypes as well as results of experiments to test the designs and operating configurations.

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Introduction

Rice–wheat (RW) is the major cropping system in the Indo-Gangetic Plain (IGP), grown on about 13 million hectares (Mha) each year (Timsina and Connor 2002). About 2.6 Mha are under RW in the small state of Punjab, India, alone. The large increases in rice and wheat area and yield since the 1960s have also led to the production of large quantities of crop residues. Wheat straw is valuable throughout the IGP as it is used as fodder. However, rice straw has no economic uses in the north-western IGP, and the majority is burnt in the field as this is a rapid and cheap management option, allowing for quick a turnaround between crops. About 17 Mt of rice straw is burnt each year in Punjab, India. Rice straw retention (incorporation) is practised by less than 1% of farmers as the straw interferes with tillage and seeding operations for wheat. In addition to huge loss of plant nutrients and organic matter, burning causes severe air pollution with deleterious effects on human and animal health. There is an urgent need to retain crop residues to improve soil health and productivity while reducing air pollution.

Tillage is a major contributor to the total cost of crop production. Tillage and sowing consume about 25% of the total operational energy in wheat production (Sidhu et al. 2004). There is an urgent need to reduce the cost of cultivation and increase profitability by developing and adopting reduced tillage technologies. Minimum and zero-till technologies for wheat are beneficial in terms of economics, irrigation water saving and timeliness of sowing in comparison with conventional tillage (Malik et al. 2004; Humphreys et al. 2007; Singh et al. 2008). However, there are problems with direct drilling wheat into combine-harvested paddy fields—straw accumulates in the seed drill furrow openers, seed meter drive wheel traction is poor due to the presence of loose straw, and the depth of seed placement is non-uniform due to frequent lifting of the implement under heavy trash conditions. Considerable effort is underway to develop suitable equipment to enable direct drilling in combine-harvested paddy fields (Garg 2002; Gupta and Rickman 2002; Sharma et al. 2008; Sidhu et al. 2007). This includes the development of the Happy Seeder at Punjab Agricultural University, India, in collaboration with CSIRO Land and Water, Australia. This paper summarises the development of the Happy Seeder technology since it was first conceived in 2001.

Development of the Happy Seeder

The development of the Happy Seeder has included three major prototypes to date, each one being an improvement on earlier versions and each having its own particular advantages. The first two versions cut and lift the standing stubble and loose straw ahead of the sowing tines so that they engage bare soil, and then deposits the stubble as mulch on the sown area behind the seed drill. The features of the three prototypes are summarised below, followed by the results of experiments to evaluate design and operating configurations for the second version, the Combo Happy Seeder.

Mark 1—the Trailing Happy Seeder

The first prototype of the Happy Seeder was a trailing machine constructed by John Blackwell and helpers at Punjab Agricultural University in July 2001, and first tested in Punjab in October 2002 (Blackwell et al. 2003). Mark 1 consists of two separate units—a forage harvester with a modified chute (the ‘straw management unit’) and a seed drill (the ‘sowing unit’) attached behind the forage harvester via a three-point linkage mechanism built onto the rear of the harvester (Figure 1). The optimum operating speed of the rotor is 1,500 rpm, which generates sufficient impact and air flow (5–6 m/second) to shear the standing straw and convey the residues through the chute. Other specifications are provided in Table 1. A particular advantage of this version is the ability to readily interchange seed drills, including the standard zero-till drill (Rautaray 2002) and the bed planter initially developed for sowing wheat after rice in north-western India (Figures 1 and 2). The first trailed prototype was successfully demonstrated using a 35 hp Massey Ferguson tractor (Figure 1). An early improvement to this prototype was the addition of a PTO-driven hydraulic lift arrangement to overcome the problem of procuring remote hydraulics on Indian tractors of low horsepower. This improvement was also included in future prototypes. The number of rows of flail blades was also increased from two to three to increase air flow through the chute and reduce the likelihood of blockages.

A small replicated experiment in rice on beds, with residues redistributed after sowing to create mulches of 0, 4 and 8 t/ha, showed similar growth and yield with all straw loads (Blackwell et al. 2003) despite delayed emergence through the straw (Figure 3).

Table 1. Specifications of the Happy Seeder prototypes

	Mark 1 (Happy Seeder)	Mark 2 (Combo or Combo+ Happy Seeder)	Mark 3 (Turbo Happy Seeder)
Type	Trailed	Tractor mounted	Tractor mounted
Power required (hp)	45 +	45	40
Transmission system	Tractor power take-off to right-angled gearbox then via jack shaft and V-belts and pulleys	Tractor power take-off to right-angled gearbox then via jack shaft and V-belts and pulleys	Tractor power take-off to right-angled gearbox then via jack shaft and V-belts and pulleys
Gear box	Bevel crown wheel and pinion, ratio 1.8:1	Bevel crown wheel and pinion, ratio 1.8:1	Bevel crown wheel and pinion, ratio 1.8:1
Working width (mm)	1,800	1,800	1,800
Total width (mm)	2,180	2,200	2,370
Mounting category	Cat I and II	Cat I and II	Cat I and II
Capacity (ha/hour)	0.2–0.24	0.26–0.30	0.3–0.4
Price (Indian rupees)	60,000 + 20,000 for zero-till drill	60,000	60,000
Manufacturer	Dasmesh Mechanical Works, Amargarh	Dasmesh Mechanical Works, Amargarh	1.Dasmesh Mechanical Works, Amargarh, Punjab 2.National Agro Industry, Ludhiana, Punjab
Straw management unit			
Rotor shaft material	High-pressure steel pipe	High-pressure steel pipe	High-pressure steel pipe
External diameter (mm)	145	120	145
Thickness (mm)	5	5	5
Transmission shaft diameter (mm)	55	60	50
Blade type	Flat flail	Flat flail	Gamma flail
Straw cut	Full	Partial	Partial
No. of blades	28 (high-speed steel)	18 (high-speed steel)	18 (high-speed steel)
Blade working diameter (mm)	545	500	485
Working rpm	1,800–1,900	1,300–1,500	1,200–1,400
Peripheral tip speed (m/second)	51–54	40–45	30.5–35.5
Blade mounting	Hinged (high-tensile pin)	Hinged (high-tensile bolt)	Hinged (high-tensile bolt)
Cutting height (mm)	50–60	50	50
Straw conveying technique	Sufficient air current is required to carry the material (6–8 m/second)	Sufficient air current is required to carry the material (6–8 m/second)	Not required
Biomass size reduction	No size reduction	No size reduction	Partial size reduction
Working conditions	Very dusty Cannot work in wet straw	Dusty, but less than Mark 1 Cannot work in wet straw	Very low dust formation Works in both wet and dry straw
Blade working width (mm)	60	65	50
Strip tillage rotor	Absent	Present	Absent
Sowing unit			
No. of tool bars	According to machine attached behind the unit	2 — spaced 445 mm apart	1
No. of furrow openers	According to machine attached behind the unit	9 — 4 on front tool bar, 5 on rear tool bar	9 in a row
Type of furrow openers	According to machine attached behind the unit	Inverted T-type straight	Inverted T-type with curved J shape
Row spacing	According to machine attached behind the unit	200 mm (adjustable)	200 mm (adjustable
Sowing depth (mm)	40–60	40–50	40–50
Seed metering device	According to machine attached behind the unit	Fluted feed rollers	Fluted feed rollers
Fertiliser metering device	According to machine attached behind the unit	Fluted feed rollers	Fluted feed rollers
Seeded row condition	Fully covered with loose straw	Relatively less cover	Seeded row remains clear from straw mulch

Mark 1 was improved by balancing the rotor to reduce vibration and adding safety guards for the drive belts. Replicated experiments with the improved Mark 1 machine (with the zero-till drill) were conducted in the 2003–04 wheat season to compare crop performance for wheat sown into either bare soil or 5–6 t/ha of combine-harvested rice residues. Establishment and yield were similar with and without residues within three sowing dates, while yield declined from ~4.8 t/ha to ~3.9 t/ha as sowing was delayed from 20 October to 17 November (Sidhu et al. 2007). Weed biomass prior to spraying was also reduced by almost 50% in the mulched treatments compared to the control for all sowing dates (data not presented).

Mark 1 also included the option of attaching a spray unit to apply pre-emergent herbicide at the same time as sowing and mulching. In the trailed configuration the forage harvester function is not lost and was also found to be useful for collecting rice residues for other uses (e.g. cardboard manufacture; Figure 4) and for cutting and collecting grass and weeds from vacant land and recreational areas.

However, the Trailing Happy Seeder has poor manoeuvrability and visibility problems as the driver is not able to see the seeding unit. To overcome this, the straw management and sowing functions were combined into a single, compact Combo Happy Seeder which can be lifted on the three-point linkage.

Figure 1. The first Mark 1 Happy Seeder with zero-till drill, powered by a 35 hp Massey Fergusson tractor, sowing on the flat in October 2002

Figure 2. The first Mark 1 Happy Seeder with bed planter, sowing wheat into rice stubble on beds in October 2002

Mark 2—the Combo and Combo+ Happy Seeders

The Combo Happy Seeder was developed by PAU and Dasmesh Mechanical Works and first tested in 2004. This version is lighter (540 kg) and can be easily mounted and lifted on the three-point linkage of a 45 hp tractor (Figure 5). The machine has the same sowing configuration as the standard zero-till drill (11 inverted T-tines spaced 20 cm apart in a staggered configuration on two tool bars). The flails of the straw management rotor were rearranged so that the centre of each flail (blade) is exactly in front of the furrow opener of the seeding machine. The number of rows of flails was reduced to two at 180° to reduce the load on the tractor, as the air flow with two rows was sufficient to convey the straw. The load on the tractor and the thickness of the resultant mulch were also reduced by reducing the cutting width of the flails from 20 cm to 8 cm, leaving a 12 cm strip of standing stubble between the furrow openers (Figures 6a–c).

The Combo+ Happy Seeder (Figures 7a–d) includes strip tillage in front of the inverted T-tines, as past experience has shown better establishment on the coarse-textured soils of Punjab with strip tillage (after burning or removal of rice residues) in comparison with zero tillage.

Figure 3. Establishment of wheat on beds through 8 t/ha of rice residues (left) and residues removed (right), sown with the Mark 1 Happy Seeder in October 2002

Figure 4. The straw handling unit of the Mark 1 Happy Seeder with modification for harvesting rice straw into a trolley

The Combo+ Happy Seeder was tested extensively in replicated experiments and farmers' fields in 2004–05 and 2005–06 (Figure 7e). The results showed similar or higher yields by sowing into rice residues with the Combo+ compared with the farmers' practice of burning and conventional tillage, with an average yield increase of ~10% (Sidhu et al. 2007). However, the Combo design has some disadvantages, including considerable dust generation and difficulty in lining up adjacent sowing passes accurately. The sown rows are difficult to see, especially with partial cutting of the standing straw. Also, both Combo machines require a minimum of 45 hp to power and lift the machines, and a dual clutch tractor, whereas the majority of tractors in north-western India are currently 35 hp and without a dual-stage clutch. However, this is increasingly becoming a requirement for tractors in India with the introduction of a range of PTO-driven machines (e.g. rotivators, strip-till drills, wheat straw combines) on the market in recent years.

Figure 5. The Combo Happy Seeder sowing into wheat straw in May 2004 with full cutting

Mark 3—the Turbo Happy Seeder

In 2005 PAU and Dasmesh Mechanical Works developed a different approach, the Turbo Happy Seeder (Figure 8a). In this version there is no chute, which greatly reduces the amount of dust. Instead, the straw is chopped finely by the inclusion of fixed blades on the inside of the rotor volute and concave rotor blades in front of the inverted-T sowing tines of improved design. All the furrow openers (tines) are now on the same bar and are curved so that there is only a very small clearance (15 mm) between the rotating flails and tines, which are swept clean with each pass of the flails. The rotor speed is only marginally higher than that in the Combo (1,300–1,500 rpm). The tines are swept clean twice with every revolution of the rotor and the straw is fed between the tines. As a result, the sowing lines are now more exposed and visible. The Turbo does not have a strip-till mechanism and the tines are on a single toolbar. Preliminary field trials of this machine in 2005–06 in farmers' fields showed excellent establishment in light- and medium-textured soils with about 100 acres sown (Figures 8b,c). The original version of the Turbo was a full-cut machine. However, partial cutting has now been implemented to reduce the power requirement. A nine-row Turbo Happy Seeder that can be powered by a 45 hp tractor has also been developed. Machines suitable for 35 hp tractors and walk-behind tillers are also on the design drawing board.

Further testing is needed to determine the strengths and weaknesses of the Turbo, Combo and Combo+ Happy Seeders in a range of operating conditions including soil type, soil and stubble moisture, and straw load.

Evaluation of design and operating configurations of the Combo Happy Seeders

Three replicated field experiments were conducted on the PAU farm in 2004–05 to study the effects of various design and operating configurations of the Combo Happy Seeder for sowing wheat into combine-harvested rice residues. These variations were: partial versus full cutting of the standing stubbles, strip versus zero tillage, and depth of seeding.

Experiment 1. Partial versus full cutting

Experiment 1, on a loamy sand, compared three methods of residue management: complete removal, full straw retention with partial cutting (8 cm strips) in front of the sowing tines, and full straw retention with full cutting. All treatments were sown with the same Combo Happy Seeder but different rotor blades were used for partial and full cutting (Figure 6c). The wheat was sown on 25 October into 5.3 t/ha of rice straw. Plot size was 30 × 6 m and there were four replicates in a randomised block design.

Experiment 2. Zero tillage versus strip tillage

Strip tillage was compared with zero tillage using the same Combo+ Happy Seeder, with or without the strip-tillage rotor engaged, on a sandy loam. There were two straw loads (6.3 and 8.1 t/ha) which had been created by applying different N rates (100 and 150 kg N/ha) to the preceding rice crop. The wheat was sown on 3 November and there were four replicates in each straw load. Plot size was 25 × 6 m.

Experiment 3. Sowing depth

Wheat was sown with the Combo Happy Seeder into 5.1 t/ha rice residues on a loamy sand at three depths: 0 cm (surface seeding), 2.5 cm and 5 cm. These were compared with a control treatment sown with the same machine at 5 cm after straw removal. The ability to adjust sowing depth was achieved by attaching a steel plate with several different positions for bolting on the tines. Plot size was 30 × 8 m.

Management of rice residues

The rice was harvested with a combine harvester with a cutting height of approximately 50–60 cm. After rice harvest the windrows of loose residues were manually spread evenly across the areas to be sown with residues retained, and removed at ground level from the other areas to be sown into bare soil. Straw load was estimated from grain yield and variety-specific harvest index.

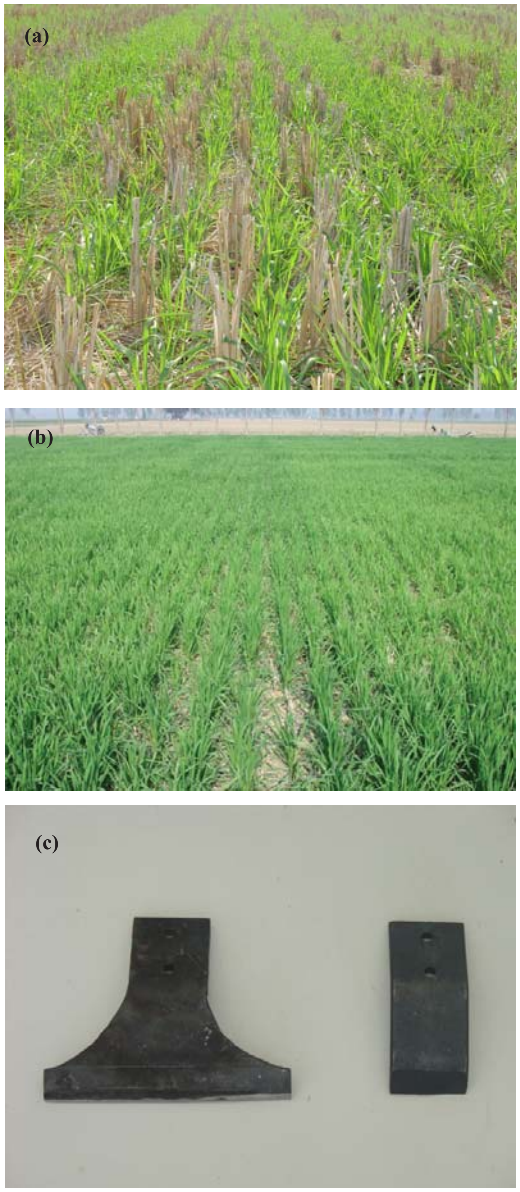
Wheat cultural practices

Wheat variety PBW 343 was sown in the last week of October to mid November and harvested in mid April of the next year. Sowing, fertiliser, weed and irrigation management were as per recommended practice. All fields were irrigated prior to sowing. Seeding rate was 100 kg/ha, row spacing 20 cm and sowing depth 5–7 cm except in the sowing depth experiment. Urea (50 kg N/ha) was broadcast before sowing and a further 60 kg N/ha as urea was broadcast 21–25 days after sowing (DAS), shortly before the first irrigation at the crown root initiation stage (Zadoks stage 1.3; Zadoks et al. 1974). Weeds were controlled by spraying fenoxaprop-p-ethyl (15 WP) 35–45 DAS.

Monitoring

Establishment

The number of emerged plants through the soil (non-mulched plots) and through the mulch was counted after establishment was complete, just prior to the first irrigation. Counts were made on 1-m rows in 10 randomly selected locations within each plot. The data presented are for established plants through the soil (and through the straw in the mulched plots) after establishment was complete.



Figures 6a–c. Establishment of wheat by Combo Happy Seeder with: a) partial and b) full cutting, and c) the flail blades used for full and partial cutting

Figures 7a–e. The Combo+ Happy Seeder showing: a) the strip tillage drive belt on the right, b) sowing wheat in rice residues, c) close-up of the sowing tines (foreground) and strip-till rotor and blades (rear), d) the slots created by the strip-till mechanism, e) a 7-acre field sown in November 2005

Grain yield

At maturity an area of 10 m^2 was harvested manually from within each plot. Grain was removed from the straw by hand threshing and weighed.

Weed biomass

All weeds were harvested at ground level from one 0.25 m^2 quadrat in each plot shortly prior to herbicide application around 45 DAS. Weed biomass was determined after drying at 60 °C.

Results

Partial versus full cutting

Plant density was similar with partial and full cutting, and with sowing into bare soil (Table 2). However, plant stand variability was much greater with full cutting (CV 51%) compared with partial cutting or no mulch (CV 21–26%). The greater variability with full cutting was probably due to the greater amount of mulch and its variable distribution (thickness). There was a trend for lower weed biomass with mulching but the differences were not significant. Weed biomass at this site was relatively low, probably because the site had not grown the RW rotation in the past. Grain yield was similar in all treatments at around 4 t/ha.

Experiment 2. Zero tillage versus strip tillage

Plant density and yield were significantly lower with the zero-till Combo Happy Seeder than with the strip-till Combo+ or the unmulched control (Table 3). There was a consistent trend for higher yield with higher straw load but the differences were not significant. Weed biomass in all mulched treatments was about 50% of that in the unmulched control.

Figures 8a–d. The Turbo Happy Seeder showing: a) sowing with full cut in November 2005, b) establishment of wheat sown in November 2005, c) excellent crop in farmers' field sown in November 2005, d) sowing wheat in rice residues with partial cutting of the standing stubble

Experiment 3. Sowing depth

There was a trend for higher plant density as sowing depth increased from 0 cm to 5 cm in the presence of mulch (Table 4). Plant density prior to the first irrigation was significantly lower with surface seeding (by 45–52%) than for all other sowing depths. The poor establishment with surface seeding was probably due to insufficient soil moisture at the surface. However, plant stand variability with surface seeding was similar to that of sowing at 5 cm with no mulch (~8%) and less than that from sowing deep with mulch (~18%). There were no significant differences in grain yield (~4.7 t/ha) between treatments.

Table 2. Comparison of partial and complete cutting of standing rice stubble for wheat sown with Combo Happy Seeder (mean ± standard deviation)

Treatment	Plant density (number/m^2)	Weed dry weight (t/ha)	Grain yield (t/ha)
Partial cutting	102±21	0.11±0.03	4.2±0.8
Full cutting	79±40	0.13±0.05	4.1±0.5
Control (no mulch)	101±26	0.14±0.01	3.9±0.4
LSD (0.05)	NS	NS	NS

Discussion

There is now considerable evidence that it is possible to successfully establish wheat in rice residues of up to about 8 t/ha by direct drilling and mulching in the agr-oecological environments of the IGP (Blackwell et al. 2003; Rahman et al. 2005; Sharma et al. 2008; Sidhu et al. 2007). Yields are comparable to or higher than those with rice straw removal and conventional tillage, and the mulch confers several advantages including moisture conservation and weed suppression (e.g. Bilalis et al. 2004; Rahman et al. 2005). The results presented in this paper are consistent with these findings. Furthermore, the Happy Seeder provides the advantage of a quick turnaround between rice harvest and wheat sowing. This provides potential yield benefits where wheat sowing would otherwise be delayed beyond the climatically dependent critical date due to the extra time taken for straw drying before burning and/or cultivation for conventional sowing.

While the Trailing Happy Seeder provides more flexibility in terms of ability to change seed drills for different purposes (e.g. flat or bed layouts) or conditions (e.g. rapidly drying coarse-textured soils or wet, plastic fine-textured soils), poor manoeuvrability and visibility are its major limitations. The compact, lightweight Combo and Turbo Happy Seeders have greatly improved manoeuvrability. However, they

Table 3. Comparison of Combo (zero tillage) and Combo+ (strip tillage) for wheat sown into rice stubble (data are means ± standard deviation)

Treatment	Straw load (t/ha)	Plant density (number/m^2)	Weed dry weight (t/ha)	Grain yield (t/ha)
Control (no mulch)	–	139±36	0.46±0.21	4.6±0.3
Zero tillage	6.0	82±26	0.18±0.09	3.9±0.7
Strip tillage	6.0	132±18	0.24±0.15	4.9±0.6
Zero tillage	8.1	88±7	0.20±0.07	4.5±0.4
Strip tillage	8.1	130±27	0.19±0.03	5.5±0.5
LSD (0.05)	–	38	0.16	0.8

Table 4. Effect of sowing depth on wheat sown into rice residues with the Combo Happy Seeder (data are means ± standard deviation)

Straw load (t/ha)	Sowing depth (cm)	Plant density (number/m^2)	Weed dry weight (t/ha)	Grain yield (t/ha)
5.1	0	58±7	0.06±.02	4.6±0.2
5.1	2.5	100±15	0.04±.04	4.7±0.4
5.1	5	130±22	0.08±.05	4.7±0.3
0 (control)	5	107±8	0.25±.07	4.7±0.4
LSD (0.05)	–	26	0.08	NS

require a tractor of at least 45 hp while the majority of tractors in the IGP are 35 hp. There is a need for the development of Happy Seeders that can be powered by 35 hp tractors. The Turbo Happy Seeder appears to be an improvement on the Combo design in terms of reduced dust production and visibility of the sowing lines. However, the configuration of the tines on the Turbo (20-cm spacing on a single toolbar) may not be practical on moist clay soils, based on our experience on a heavy clay in Australia (Figure 9). The Turbo 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, soil types and soil moisture conditions.

The limited experimentation on machinery configuration reported here suggests that there is no agronomic disadvantage of partial cutting instead of full cutting of the standing straw, and partial cutting has the additional advantage of reduced operating costs (wear and tear of blades). In addition, partial cutting probably reduces dust and power requirements; however, whether these are significant benefits is yet to be quantified. Our comparison of the Combo and Combo+ Happy Seeders support previous experience that strip tillage ahead of the inverted-T tines improves wheat establishment and yield on coarse-textured soils. However, strip tillage may be more or less appropriate depending on soil type and conditions, and further evaluation with mulching in a range of soil types and moistures is warranted. Our results suggest that the recommended sowing depth of 5 cm for conventional tillage and direct drilling after rice stubble burning is also suitable for direct drilling with mulching, and that surface seeding is risky and can lead to significantly lower plant density on coarse-textured soils. Nonetheless, the initial sowing on the flat depicted in Figure 1 was largely sown on the surface due to inability of the tines to penetrate the hard soil, which had not been pre-irrigated in contrast with normal practice in this region. This crop was watered up with good establishment and yield. Rahman et al. (2005) obtained excellent wheat establishment with surface seeding and mulching on a loam soil in Bangladesh.

The Happy Seeder technology provides the opportunity to greatly reduce the severe air pollution and associated problems from burning stubble. However, while there are likely to be long-term financial benefits to the farmer (Singh et al. 2008), adoption of the technology will be at an initial cost to the farmer in comparison with burning and zero tillage. Therefore, there is an urgent need for a major program to promote and facilitate adoption of the Happy Seeder technology. To ensure success, such a program needs to include widespread farmer participatory trials of the technology, development of a package of practices for optimum results, and suitable policies and

Figure 9. Build-up of mud and straw on Turbo Happy Seeder tines in wet clay soils

incentives. The package of practices needs to include guidelines for irrigation and nitrogen fertiliser management because of the interaction between mulching and water and nitrogen dynamics, and the potential for nitrogen immobilisation and/or losses depending on the method of application. Reduction in stubble burning will lead to significant environmental and economic benefits for society (Singh et al. 2008), and this should also be considered when formulating incentives and policies to encourage adoption.

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Straw mulch, irrigation water and fertiliser N management effects on yield, water use and N use efficiency of wheat sown after rice

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Abstract

Two replicated field experiments were conducted during 2005–06 to investigate options for optimising irrigation and N management for wheat mulched with rice straw. The first experiment investigated the interactions between irrigation scheduling and mulching. There were two mulching treatments (±mulch) and four irrigation schedules based on recommended practice, the ratio of irrigation water to cumulative pan evaporation minus rainfall, and soil matric potential (SMP). Wheat grain yield was not significantly affected by mulching or irrigation scheduling treatment. The total amount of irrigation water was not influenced by mulching within any irrigation scheduling treatment. However, using SMP-based scheduling, irrigations of the mulched treatment were always delayed, by up to 24 days compared with the non-mulched treatment.

The second experiment investigated N management (method and time of application, using the recommended rate of 120 kg N/ha) for wheat mulched with rice straw. There were eight 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 an unmulched control treatment with N applied using recommended practice. Fertiliser application with three split doses (50% drilled at sowing + 25% broadcast before the each of the first and second irrigations) resulted in significantly higher grain yield, agronomic efficiency and N recovery efficiency than all other treatments. In the presence of mulch, drilling the urea at sowing gave higher yields and efficiency than broadcasting.

The effect of irrigation scheduling on crop performance, irrigation amount and water productivity will vary depending on the incidence and amount of rain, and requires further investigation in field and modelling studies for wheat mulched with rice straw. Likewise, development of guidelines for optimum N management for wheat mulched with rice straw will depend on seasonal conditions and requires further investigation with field and modelling studies.

Introduction

Rice–wheat (RW) is the largest agricultural production system in Asia, occupying about 20 million hectares (Mha) in the Indo-Gangetic Plain in South Asia and China. Increasing constraints of labour and time have led to wide-scale adoption of mechanised farming in the intensive RW system in north-western India. After combine harvesting of rice and wheat, the crop residues remain in the field until they are burnt or removed mechanically. At present, wheat straw is valuable fodder for animals, and more than 70% of the wheat straw from combine-harvested fields is collected by farmers using straw combines to pick up the loose straw and deposit it in a trolley trailing behind the combine (Gajri et al. 2002). There are currently

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few uses for rice straw because of its poor quality for forage, bioconversion and engineering applications. Rice straw thus remains unused and is generally burnt in the field as the loose straw interferes with tillage and seeding operations for the subsequent wheat crop. Approximately 16 Mt of rice straw are currently burnt in situ each year by the farmers in Punjab, India, alone. This practice has serious implications for recycling of plant nutrients, soil organic matter content, air quality and emission of greenhouse gases. Rice growers therefore need alternative straw management options, such as retention of the straw in the field.

Along with the worldwide interest in minimum tillage and conservation agriculture, there is increasing interest in the direct drilling of wheat after rice in South Asia (Hobbs et al. 2004). The sowing of wheat into rice stubble using the zero-till seed drill is, however, impaired by blockages due to accumulation of the loose straw, and inadequate closure of the seed slots. The only option for zero-till wheat with rice residue retention is to leave the rice residues on the soil surface as mulch. Recently, Punjab Agricultural University in Ludhiana, India, and CSIRO in Griffith, Australia, developed a machine (the Happy Seeder) that simultaneously cuts and spreads the rice straw on the surface as mulch while sowing wheat with zero or strip tillage (Sidhu et al. 2007, 2008). Extensive evaluation of the Happy Seeder in Punjab, India, showed that yields of wheat sown into rice residues using the Happy Seeder were always comparable to or higher than yields with conventional sowing (Sharma et al. 2008; Sidhu et al. 2007, 2008). Financial evaluation suggests that the technology is more profitable for farmers than conventional tillage or sowing with the zero-till drill after burning (Singh et al. 2008).

Straw mulch reduces the amount of radiation reaching and leaving the soil surface, and therefore reduces the maximum soil temperature and increases the minimum temperature (Prihar and Arora 1980). The effect of straw mulch on soil temperature can be an advantage where soil temperature is above the optimum for germination and growth, and a disadvantage where temperatures are lowered below the optimum (Lal 1989). On a clear sunny day during the hot months in northern India, the temperature reduction due to mulch can be 5–8 °C at 5 cm depth (Sandhu et al. 1980). Straw mulch also lowers soil evaporation, leading to higher soil water content and/or crop water use (Rahman et al. 2005; Sidhu et al. 2007). The magnitude of the reduction in evaporation depends on the straw load, soil water content and evaporative demand. The effects that mulching has on soil moisture and temperature will influence many soil and plant processes that ultimately determine the growth and yield of crops. Straw mulch may also reduce weed growth by mechanisms such as reduced light, effects on soil temperature, physical suppression and allelopathy (Dhima et al. 2006).

Besides introducing an extra cost, rice straw incorporation in the soil can reduce the availability of N to the succeeding wheat crop by causing immobilisation of soil and fertiliser N (Yadvinder-Singh et al. 2005). Therefore, strategies to counteract nutrient immobilisation are an important component of efficient crop residue management programs. For example, allowing adequate time (10–20 days) for decomposition of the rice residues before planting the next wheat crop can alleviate the adverse effects of incorporation on N immobilisation and wheat yield (Yadvinder-Singh et al. 2004). However, a delay of 10–20 days while the stubble begins to break down, plus the additional time taken to incorporate the stubble, can delay wheat sowing well beyond the optimum date, leading to yield loss (Ortiz-Monasterio et al. 1994). The effect of mulching with rice straw on N dynamics and optimal N fertiliser management for wheat is little studied in RW systems. Surface retention of straw and zero tillage may cause slower N mineralisation, greater N immobilisation and higher N losses via ammonia volatilisation and denitrification compared with conventional tillage (Philips et al. 1980; Rice and Smith 1982, 1984; Patra et al. 2004). Reducing fertiliser N contact with the straw by placing the fertiliser below the soil surface can reduce N immobilisation and ammonia volatilisation and increase N use efficiency (Rao and Dao 1996). Another practical approach for increasing N use efficiency in wheat under straw mulch could be delayed topdressings of N fertiliser after significant straw decomposition has taken place and the canopy is well developed.

The optimum strategy for irrigation scheduling may also be affected by mulching due to suppression of soil evaporation by the mulch. A simple approach based on the ratio of irrigation water (IW) to cumulative Class A pan evaporation (CPE) minus rain since the previous irrigation has been recommended for irrigation scheduling of wheat grown with conventional tillage in Punjab, India (Prihar et al. 1974, 1976; Prihar and Sandhu 1987). However, in reality, the strategy for optimum irrigation scheduling will be affected by the availability of water for irrigation, soil type and the water requirement of the crop as affected by the amount of growth and growth stage. The use of soil matric potential (SMP) to identify when to irrigate is based on crop need, integrating the effects of soil type and mulch, and needs to be tested for wheat in RW systems. SMP has been used successfully to schedule irrigations for rice in RW systems in north-western India, resulting in significant irrigation water savings (Kukal et al. 2005). However, this approach has undergone little testing for wheat in the same regions. Preliminary studies showed that irrigating non-mulched wheat when SMP increased to –35 kPa at 15–20 cm depth for the first irrigation and at 35–40 cm depth for subsequent irrigations gave similar yield to scheduling on the basis of cumulative pan evaporation (CPE – rain = 80 mm, with irrigation amount = 0.9 × (CPE – rain) or 72 mm) with similar irrigation water use (S.S. Kukal, unpubl. data). However, the applicability of this technique in the presence of mulch, which suppresses soil evaporation, needs to be tested in wheat.

To facilitate adoption of the Happy Seeder, farmers need clear guidelines for optimum irrigation and fertiliser management. Therefore, two experiments were initiated to evaluate irrigation scheduling and fertiliser N management for wheat sown with the Happy Seeder, with and without straw mulch, in terms of crop performance and N and water use efficiency.

Methods

Two field experiments were conducted at Punjab Agricultural University (PAU), Ludhiana, India (30°56'N, 75°52'E and 247 m above mean sea level) during 2005–06. Total rainfall during the wheat growing season was 55 mm, which is below the long-term average of 144 mm.

Both experimental sites grew rice which was combine harvested prior to wheat establishment. Two straw management treatments were established at each site—straw retained (mulched) and straw removed (no mulch). In the ‘no mulch’ treatments the straw was removed mechanically in experiment 1 and burnt in experiment 2 prior to sowing wheat. In the mulched treatments the loose straw in windrows from the combine harvester was distributed evenly across the plots prior to sowing with the strip-till Happy Seeder. The wheat (PBW343) was sown at 100 kg/ha with 20-cm row spacings in both experiments.

Experiment 1. Irrigation scheduling

The soil was deep alluvial loam (Typic Ustochrept) with pH of 8.4, low organic C (3.4 g/kg), medium 0.5 M $NaHCO_3$-extractable P (13.7 kg/ha) and medium available K (145 kg/ha) in the top 15 cm.

The experiment, with four replications, was laid out in split-plot design in October 2005. Plot size was 6 × 20 m. The treatments in the main plots were: direct drilling of wheat into combine-harvested rice residues using the strip-till Happy Seeder; and wheat sown with the zero-till drill after manually removing the rice straw from the field. Straw load in the mulched treatments was 7.3 t/ha (dry weight). The irrigation amount for all treatments was fixed at 75 mm. The irrigation scheduling treatments (subplots), which commenced after a common irrigation 33 days after sowing (DAS), were:

(i) IW/CPE = 0.75—75 mm irrigation when CPE-rain = 100 mm
(ii) IW/CPE = 0.9—75 mm irrigation when CPE-rain = 83 mm
(iii) SMP—irrigation when SMP < –30±5 kPa at 15–20 cm soil depth for the 1st irrigation, and at 35–40 cm depth for subsequent irrigations
(iv) Control—irrigation at 33, 52 and 131 DAS, as in the guidelines for farmers (which are based on the recommended practice above). Irrigations were delayed by 2 days for every 10 mm of rain received up to the end of February and 1 day for every 10 mm of rain received thereafter.

SMP was measured using tube tensiometers and a SoilSpec® vacuum gauge. Consistent with the irrigation scheduling rules, the mulched and unmulched treatments were irrigated on the same day for treatments (i), (ii) and (iv), respectively, and on different days for the SMP treatments. The irrigation water was applied directly to each plot via pipes and measured with a flowmeter at the tube-well outlet (Figure 1). Details of the irrigations are provided in Table 1.

Wheat was sown on 6 November 2005 into the residual soil moisture after rice. Fertiliser management and weed control were according to recommended practice. Diammonium phosphate (26 kg P/ha, 23 kg N/ha) was drilled with the seed at sowing. Urea (37 kg N/ha) and muriate of potash (25 kg K/ha) were broadcast on the soil surface prior to sowing. Urea (60 kg N/ha) was broadcast 33 DAS prior to the 1st irrigation. Thus, all treatments received a total of 120 kg N/ha. Weeds were controlled by spraying fenoxaprop-p-ethyl (15WP) 45 DAS.

The number of emerged plants was counted 20 DAS in 1-m rows at five randomly selected locations in each plot to determine plant density. Spike density, the number of grains per spike and 1,000-grain weight were determined at harvest. Spike density was measured from three randomly selected locations (0.5 × 0.5 m) within each plot. The number of grains per spike and average grain weight were determined from 20 randomly selected spikes in each plot. For grain and straw yield, an area of 30 m^2 was harvested manually in the centre of each plot and the grain and straw were separated with a stationary thresher. Weed biomass (above-ground) was determined by harvesting all weeds at ground level in 0.5 m^2 quadrats in each plot 45 DAS (prior to herbicide application) and drying at 60 °C. Soil water content to 150 cm depth was determined one day before the first, second and fourth post-sowing irrigations by collecting augered soil samples at increments of 0–7.5, 7.5–15, 15–30, 30–60, 60–90, 90–120 and 120–150 cm. The mulched and unmulched treatments were sampled on the same day before irrigation in the IW/CPE and control treatments, whereas the SMP mulched and unmulched treatments were sampled on different dates, as irrigations were on different dates. Soil water stored in the profile was calculated assuming a uniform bulk density of 1.5 Mg/m^3. Soil temperature at 7 cm depth was monitored daily at 10 am (minimum) and 2.30 pm (maximum) from date of sowing to 28 DAS in four replicates of the mulched and unmulched treatments.

Figure 1. Experiment 1 — flowmeter and piped irrigation system with individual outlets to each plot

Table 1. Time and amount of irrigation water and rain in experiment 1

Treatment		Time of irrigation application (DAS)				Total irrigation (I) or rain (R) (mm)	Total input (I + R) (mm)
		1st	2nd	3rd	4th		
Control	No mulch	33	67	106	134	300	360
	Mulch	33	67	106	134	300	360
SMP	No mulch	33	88	112	–	225	285
	Mulch	38	100	136	–	225	285
IW/CIE 0.75	No mulch	33	101	–	–	150	210
	Mulch	33	101	–	–	150	210
IW/CPE 0.90	No mulch	33	95	135	–	235	285
	Mulch	33	95	135	–	235	285

Rain	mm	6	8	9	5	5	20	7	Total	60
	DAS	56	62	53	71	125	128	138		

DAS = days after sowing; SMP = soil matric potentia63l

Experiment 2. N fertiliser management

The experiment was a randomised complete block design with three replicates and plot size of 48 m^2. The soil was a sandy loam with a pH of 8.1 (1:2 soil:water) and 4.3 g/kg soil organic C. Average rice straw load was 7.9 t/ha (dry weight). All treatments were direct drilled into rice residues with the strip-till Happy Seeder except the control (T9), in which the straw was burnt prior to direct drilling according to recommended practice. Details of the N fertiliser treatments are provided in Table 2. All treatments received a total of 120 kg N/ha as urea in a range of splits (from one to three). All urea applied at sowing was drilled 5–6 cm below the soil surface the day before sowing using a hand drill, except for T8 and T9 which used the recommended practice of broadcasting 60 kg N/ha before sowing. The purpose of drilling the fertiliser the day before sowing was to minimise contact of the seed with high concentrations of urea and so avoid fertiliser damage. Post-sowing applications of urea were broadcast immediately before the first and/or second irrigations. A basal dose of 26 kg P/ha as single superphosphate and 25 kg K/ha as muriate of potash was drilled below the seed at the time of sowing on 14 November 2005. No herbicide was used. The plots were irrigated 15 and 46 DAS. No further irrigations were required because of timely rainfall.

All weeds were harvested from an area of 1 m^2 within each plot 70 DAS. Weed biomass (above ground level) was determined after drying at 60 °C. An area of 20 m^2 from the centre of each plot was harvested for grain and straw yield. Wheat grain and straw yields are reported on a dry weight basis. Grain and straw subsamples were collected at wheat harvest on 18 April 2006 for analysis of total N.

Results and discussion

Experiment 1. Irrigation scheduling

Effect of straw mulch on soil temperature

Maximum soil temperature with mulching was 1.5–2 °C lower than without mulching, while minimum soil temperature was higher by 0.5–1.0 °C during the first 21 DAS (Figure 2). The differences in maximum temperature between the two treat-

Table 2. Details of treatments in experiment 2 on N fertiliser management

Treatment	N rate			Treatment details	
	Sowing	1st irrigation 15 DAS	2nd irrigation 46 DAS	Straw management	N management
T1 (no N)	0	0	0	mulch	No N control
T2	120	0	0	mulch	120 kg N drilled at sowing
T3	90	0	30	mulch	90 kg N/ha drilled at sowing and 30 kg N/ha topdressed at second irrigation
T4	60	60	0	mulch	60 kg N/ha drilled at sowing and 60 kg N/ha topdressed at first irrigation
T5	60	30	30	mulch	60 kg N/ha drilled at sowing and 30 kg N/ha topdressed at first and second irrigation
T6	60	0	30	mulch	60 kg N/ha drilled at sowing and 30 kg N/ha topdressed at the time of irrigation when the leaf colour chart (LCC) threshold value falls below 5
T7	30	30	60	mulch	30 kg N/ha drilled at sowing, 30 kg N/ha topdressed at first irrigation and 60 kg N/ha at second irrigation
T8	60	60	0	mulch	60 kg N/ha applied as surface broadcast at sowing and 60 kg N/ha topdressed at first irrigation
T9 (control)	60	60	0	burn	60 kg N/ha applied as surface broadcast at sowing and 60 kg N/ha topdressed at first irrigation

ments decreased beyond 21 DAS. The results are consistent with the earlier findings of Sidhu et al. (2007) for wheat mulched with rice straw in this environment.

Effect of straw mulch on crop establishment

There was no significant effect of straw mulch on plant density. Average plant density at 21 DAS in mulched and unmulched plots was 137/m^2 and 133/m^2, respectively. Similarly, Sidhu et al. (2007) observed no significant differences in wheat plant density between mulched and unmulched plots sown at the optimum time with the Happy Seeder in straw loads up to 7.3 t/ha. Figure 3 shows establishment in the mulched and unmulched plots about 4 weeks after sowing.

Effect of straw mulch on weed growth

Weed dry weight 45 DAS in the mulched treatments was about 25% of that without mulch (0.13 t/ha compared with 0.50 t/ha), which is consistent with other reports of suppression of weeds in wheat mulched with rice straw (Rahman et al. 2005; Sidhu et al. 2007).

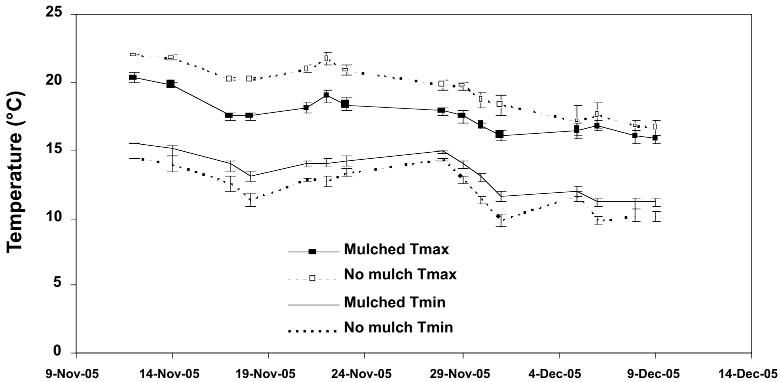

Figure 2. Minimum and maximum soil temperature at 7 cm depth with and without mulching (experiment 1); vertical bars are standard errors

Figure 3. Experiment 1 — plots sown with the Combo+ Happy Seeder with rice residues removed prior to sowing (left) and retained (right)

Effect of irrigation scheduling and straw mulch on yield components and yield

Spike density, the number of grains per spike, average grain weight and grain yield were not influenced by mulching or irrigation scheduling (Table 3). Earlier studies by Prihar et al. (1976) also showed that irrigation scheduling based on growth stage or IW/CPE of 0.90 or 0.75 produced similar yields. However, the results are likely to vary depending on seasonal conditions, especially the incidence of rain in addition to the total irrigation amount. Grain yield in all treatments was low, probably reflecting the low soil fertility at this site (organic C of 0.34 g/kg).

Effect of irrigation scheduling method on the time and amount of irrigation water applied

The number of irrigations after sowing ranged from two with IW/CPE 0.75 to four with irrigation based on the guidelines for farmers. The amount of irrigation water applied after sowing thus ranged from 150 mm to 300 mm (Table 1). The findings are consistent with those of Prihar et al. (1976), who found that irrigation scheduling of wheat based on IW/CPE required 80–120 mm less irrigation water than stage-based irrigation. They also found that IW/CPE 0.75 saved 40 mm of irrigation water compared with IW/CPW 0.9, whereas the difference was 75 mm in our experiment 1. SMP scheduling used the same amount of irrigation water as IW/CPE 0.9, but the second and third irrigations of the unmulched SMP treatment were 7 and 23 days earlier than with IW/CPE 0.9, respectively. Whether scheduling irrigations based on SMP or IW/CPE reduces the number of irrigations and total amount of irrigation water depends greatly on the incidence and amount of rainfall, and needs to be studied for a range of seasonal conditions using field and modelling studies.

The total amount of irrigation water was not influenced by mulching within any irrigation scheduling treatment in this experiment. This is inherent in using IW/CPE and stage-based irrigation rules, which do not take into account the effect of soil evaporation, transpiration or drainage on soil water content. However, using SMP scheduling, the time of irrigation with mulching was delayed by 5, 12 and 24 days before the first, second and third irrigations, respectively, compared with no mulch (Table 1). This is consistent with the hypothesis that the mulch reduces evaporation losses. Thus, it is to be expected that in some years, depending on the incidence and amount of rainfall, fewer irrigations will be required with mulching when using irrigation scheduling based on SMP.

In Punjab, India, the first irrigation to wheat is recommended at 3–4 weeks after sowing, at the crown root initiation stage (Prihar and Sandhu 1987). Our results suggest that, in the presence of rice straw mulch, the first irrigation to wheat can be delayed by about 1 week. Similarly, Sandhu et al. (1990) concluded that the first irrigation to mulched wheat can be delayed to 40 DAS. Whether mulching will ultimately lead to reduced irrigation applications will depend on the incidence and amount of seasonal rainfall, and this also needs to be investigated using crop models and long-term weather data. Gajri et al. (1997) reported similar grain yields of sunflower grown in the dry hot season (February–May) with

Table 3. Effect of straw mulch and irrigation scheduling on yield and yield contributing characters, input water productivity (g grain/kg irrigation water + rain) of wheat (experiment 1)

Treatment	Spike density (no./m^2)	Grains/spike	Grain weight (mg)	Grain yield (t/ha)	Input water productivity (g/kg)
A. Mulch					
No mulch	334	43	46	3.76	1.34
Straw mulch	336	43	45	3.71	1.33
LSD (0.05)	NS	NS	NS	NS	–
B. Irrigation					
Control	326	41	46	3.46	0.97
SMP	319	42	45	3.59	1.28
IW/CPE 0.75	332	45	45	3.70	1.80
IW/CPE 0.9	362	43	46	3.54	1.26
LSD (0.05)	NS	NS	NS	NS	–
LSD (0.05) for interaction	NS	NS	NS	NS	–

150 mm less irrigation water with mulch compared with no mulch.

Input water productivity (WP_{I+R}; g grain/kg irrigation water + rain) was not influenced by mulching but was strongly influenced by irrigation scheduling (Table 3). Applying irrigation based on IW/CPE 0.75 resulted in the highest WP_{I+R}, which was 86% higher than the control and 42% higher than the other two irrigation treatments.

Effect of mulch and irrigation scheduling on soil water content

Soil water content, measured before the first common irrigation at 33 DAS, and before the second and fourth irrigations, is presented in Table 4. There was a trend for higher gravimetric soil water content in the topsoil (0–15 or 30 cm) of the mulched treatment before the first and second irrigations of the IW/CPE and control treatments, but little effect by the time of the fourth irrigation. Soil water content was, however, markedly influenced by the irrigation schedule—prior to the second irrigation it was much higher in the control than in the IW/CPE and SMP treatments. Delaying the second irrigation from 95 DAS (IW/CPE 0.9) to 101 DAS (IW/CPE 0.75) forced the crop to extract water from deeper in the profile. Soil water content of the 0–150 cm profile before the first irrigation was significantly higher (by about 20 mm) with mulch than without mulch.

Experiment 2. N fertiliser management

Grain yields ranged from 1.86 t/ha in the unfertilised treatment to 4.66 t/ha in the LCC treatment (T6) (Table 5). Agronomic efficiency of N (AE, kg grain/kg N applied) ranged from 16.3 to 23.3. Recovery efficiency (RE), the difference between N uptake in the fertilised and control treatments as a percentage of the amount of fertiliser N applied, ranged from 36.7% to 51.9%.

Grain and straw yields and total N uptake were significantly increased with N application over the no N

Table 4. Effect of mulching and irrigation scheduling on gravimetric soil water content (%) immediately prior to irrigation (experiment 1)

Treatment	Soil depth (cm)						
	0–7.5	7.5–15	15–30	30–60	60–90	90–120	120–150
Before 1st irrigation							
– mulch	9.7	9.5	11.3	17.5	19.7	21.8	22.2
+ mulch	11.8	10.2	12.0	17.6	21.1	22.2	23.3
LSD (0.05) Mulch 0.51, depth 2.35, mulch × depth NS							
Before 2nd irrigation							
Control							
– mulch	12.6	11.2	12.8	15.1	21.1	22.2	22.8
+ mulch	15.9	14.2	13.6	14.9	19.5	21.1	21.5
IW/CPE 0.9							
– mulch	4.3	8.1	15.8	17.5	19.4	20.7	21.4
+ mulch	6.3	8.9	15.2	17.8	20.2	21.3	22.1
IW/CPE 0.75							
– mulch	2.2	5.6	6.3	11.3	18.8	20.7	21.8
+ mulch	5.3	5.3	8.0	14.0	19.0	21.9	22.6
LSD (0.05) Mulch 0.49, irrigation 0.59, mulch × irrigation 0.84, depth 1.32, mulch × irrigation × depth 3.23							
Before 4th irrigation							
Control							
– mulch	5.7	5.8	6.5	9.3	15.0	20.0	19.6
+ mulch	5.9	6.7	6.9	9.5	16.8	20.7	21.4
IW/CPE 0.9							
– mulch	5.8	5.6	5.9	9.1	14.7	18.5	20.2
+ mulch	7.0	5.9	5.8	11.6	16.4	20.0	21.2
LSD (0.05) Mulch NS, irrigation NS, depth 1.31, interactions NS							

control, and trends in total N uptake were similar to trends in yield (Table 5). Grain yield, total N uptake and RE with the recommended practice (T9, with straw burnt and 60 kg N/ha broadcast at sowing and before the first irrigation) were significantly higher than with the same N management in the presence of residues (T8). However, drilling the 1st 60 kg N/ha at sowing in the presence of rice residues (T4) restored yield and N uptake to similar values to the control. These data suggest greater immobilisation or N losses from surface-applied N in the presence of straw than when the straw was burnt before sowing, which is consistent with the findings of others (Philips et al. 1980; Rice and Smith 1984; Patra et al. 2004). Drilling part of the fertiliser below the soil surface at sowing may have reduced these losses due to reduction in fertiliser N contact with straw (Rao and Dao 1996). Despite this, Sidhu et al. (2007) found an average 9–15% higher yield of wheat with the Happy Seeder sowing into rice residues, with the fertiliser broadcast at sowing and before the first irrigation, compared with farmer practice (conventional tillage after burning, whereas we used zero tillage in T9) in the adjacent field.

Fertiliser application with the LCC (T6) was the same as T5 with three split doses (60, 30, 30). Grain yield of T5 and T6 was usually significantly higher than all other treatments. As with grain and straw yield and N uptake, AE and RE were highest in T5 and T6 and lowest in T8. There are several possible reasons for the superior performance of the triple split with the last application delayed to the time of the second irrigation. These include greater canopy cover and reduced presence of mulch due to decomposition, and reduction of the potential for N immobilisation and ammonia volatilisation. Using the nylon bag technique, about 25% of the rice straw placed on the soil surface in wheat fields had decomposed within 60 days (Yadvinder-Singh, unpubl. data).

Drilling all the fertiliser N at sowing (T2) resulted in grain yield similar to that of the recommended practice of applying N in two equal split doses at sowing and with the first post-sowing irrigation (T4). When the amount of N drilled at sowing was reduced to 30 kg N/ha, with 30 and 60 kg N/ha before the first and second irrigations, respectively, grain yield was reduced significantly in comparison with T5 and T6. These results suggest that delaying half the N fertiliser application until the second irrigation is too late.

Conclusions

Soil water content was significantly affected by mulching, and this needs to be taken into account in developing irrigation scheduling guidelines for efficient use of irrigation water. The results showed that irrigations could be delayed by 1–3 weeks when scheduled according to soil moisture status (matric potential). Whether this will reduce the total irrigation amount, and to what degree, will depend on seasonal conditions, particularly the incidence and amount of rain. Further field experimentation and modelling studies are needed to help design optimum irrigation strategies and to quantify the potential irrigation and total water savings as a result of mulching.

Table 5. Effect of fertiliser N management on yield, total N uptake, agronomic efficiency (AE) and recovery efficiency (RE) of N in wheat in experiment 2

Treatment[a]	N management[b]	Grain yield (t/ha)	Straw yield (t/ha)	Total N uptake (kg/ha)	AE (kg grain/kg N)	RE (%)
T1	0, 0, 0	1.86	2.14	36.2	–	–
T2	0, 120, 0	4.21	5.24	91.0	19.6	45.7
T3	90, 0, 30	4.18	5.22	90.4	19.3	45.2
T4	60, 60, 0	4.12	5.28	85.7	18.8	41.3
T5	60, 30, 30	4.46	5.92	98.4	21.7	51.8
T6	60, 30, 30	4.66	6.05	98.5	23.3	51.9
T7	30, 30, 60	4.04	5.47	85.9	18.2	41.4
T8	60, 60, 0	3.82	5.08	80.2	16.3	36.7
T9 (burnt)	60, 60, 0	4.17	5.23	90.9	19.3	45.6
LSD (0.05)		0.32	0.54	8.1	2.3	3.7

[a] T1–T8 residues retained on the surface
[b] N applied at sowing, before first irrigation, before second irrigation; all N applied at sowing drilled at 5–6 cm the day before sowing except in T8 and T9; all post-sowing applications broadcast

Application of N fertiliser in three splits with 50% drilled at sowing increased yield and N use efficiency compared with the recommended practice of two equal splits at sowing and with the first post-sowing irrigation. Broadcasting half the N fertiliser at sowing was less efficient and gave lower yield than drilling the N at sowing. N fertiliser management for wheat sown into rice residues needs further field and modelling studies for a range of seasonal conditions to develop recommendations for farmers.

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A financial assessment of the Happy Seeder for rice–wheat systems in Punjab, India

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Abstract

Burning of rice stubbles is widely practised in Punjab, India, due to a lack of suitable machinery to direct drill wheat into combine-harvested rice residues. Although direct drilling into burnt stubbles is a rapid and cheap option, and allows for a quick turnaround between crops, it is causing serious problems for human and animal health due to air pollution, and a decline in soil fertility due to loss of nutrients and organic matter. The recent development of the Happy Seeder (HS) overcomes the technical problems associated with direct drilling into rice residues. The aim of the present study was to conduct a preliminary evaluation of the direct financial benefits and costs to farmers of use of the Happy Seeder in comparison with the current practices of straw burning followed by direct drilling or conventional tillage prior to sowing. The analysis was conducted for a 20-year period, assuming a 20-year life of the machine, with discounting back to 2006 values using a real discount rate of 7%.

The results of the financial evaluation suggest that the HS technology is more profitable than 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—a 5% increase in yield doubles 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. To encourage widespread adoption of the HS technology, a range of potential mechanical, technical, social, institutional and policy constraints need to be considered and addressed. A detailed economic assessment of the technology will also help to estimate its potential significant economic, community and environmental benefits to society.

Introduction

Rice–wheat (RW) cropping is the predominant and most profitable farming system in north-western India, especially in Punjab state, where it accounts for more than 2.6 million hectares (Mha) or 60% of the total net sown area (Government of Punjab 2005). Timeliness of field operations for both rice and wheat is a key element in accommodating both crops each year and achieving high yields. The majority of the rice and wheat in Punjab is combine harvested, leaving anchored straw 0.3–0.6 m high and loose straw in windrows (Gajri et al. 2002). Management of the rice stubble (more than 6 t/ha) is a major problem in the system. Burning is widely practised due to the lack of suitable machinery to direct drill into the combine-harvested rice residues. This is a rapid and cheap option, and allows for a quick turnaround between crops. More than 90% of the 17 Mt of rice

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stubble in Punjab is burnt each year. However, air pollution from stubble burning is a serious threat to human and animal health (Gupta and Sahai 2005). Burning also results in large loss of nutrients and organic matter (Table 1). After burning, the seedbed for wheat is typically prepared by two discings, two tine harrowings and one planking. Wheat is then sown using a tractor-operated seed-fertiliser drill. Zero tillage after stubble burning is now being adopted by many farmers; however, in 2005–06 less than 10% of the total area sown to wheat was sown using zero-till machines (Department of Agriculture, Punjab, 2005). Less than 1% of farmers incorporate the rice straw, which requires more tillage operations than after burning.

To overcome the problem of direct drilling into rice residues, research engineers from Australia and India involved in ACIAR Project LWR/2000/089 'Permanent beds for irrigated rice–wheat and alternative cropping systems in north-west India and south-east Australia' developed the Happy Seeder (HS). The HS is a tractor-powered machine that cuts and lifts the rice straw, sows into the bare soil, and deposits the straw over the sown area as a mulch (Sidhu et al. 2007, 2008). It combines the stubble mulching and seed and fertiliser drilling operations into one machine in a single pass. The HS approach has considerable potential agronomic benefits, in addition to reducing air pollution and retention of nutrients and organic matter, by avoiding stubble burning. The mulch suppresses weeds and may reduce the need for weed control measures, and also reduces soil evaporation. Wheat can be sown immediately after rice harvest while the straw is still too green to burn. Traditionally, a pre-sowing irrigation is applied prior to sowing wheat after rice. This irrigation is usually not required with the HS because there is a quick turnaround before the residual surface soil moisture from the rice crop is lost through soil evaporation.

Adoption of the HS will involve significant initial capital investment, replacement and maintenance costs. Therefore, before recommending the HS to farmers, it is important to compare the potential benefits of the HS with the costs of purchase and its potential use. This information will also help to identify the total benefits to industry, develop policies for successful adoption and estimate returns to R&D investment.

The main aims of the study presented here were:

- to estimate the potential financial benefits to farmers of use of the HS compared with other current practices of soil and stubble management for sowing wheat after rice
- to estimate the costs of adoption of the HS
- to identify constraints to adoption of the HS
- to compare the overall benefits and costs of adoption of the HS to farmers.

The methodology for the financial analysis is outlined below, followed by an estimation of the potential benefits and costs of adoption of the technology. The results of the analysis and their implications, as well as the main constraints to adoption of the technology, are then discussed, followed by the conclusions.

Methodology

The financial analysis involved a partial budgeting approach in which the additional and foregone annual financial costs and benefits associated with the HS were compared to estimate net gains from adoption of the new technology. In undertaking a

Table 1. Nutrient losses due to burning of rice residues in Punjab in 2001–02

Nutrient	Nutrient loss			
	Concentration in straw (g/kg)	Percentage lost in burning	Loss (kg/ha)	Total loss from 10.7 Mt (kt)
C	400	100	2,400	4,280
N	6.5	90	35	63
P	2.1	25	3.2	6
K	17.5	20	21	37
S	0.75	60	2.7	5

Note: The data are calculated from estimates of 10.7 Mt of rice straw burning in 2001–02 (Gajri. et al. 2002), straw yield of 6 t/ha (Humphreys et al. 2006) and nutrient composition of straw and percentage lost in burning (Dobermann and Fairhurst 2002).

financial evaluation, it is appropriate to use financial values for all relevant inputs and outputs. 'Financial values' refer to the prices/benefits actually received by farmers for outputs, and the actual costs paid by them for inputs used or losses suffered. In an economic analysis (as opposed to the financial analysis presented here) inputs and outputs would be priced at the value placed on them by society, but an economic analysis is beyond the scope of this study.

The criterion used in assessing the financial merit of adoption of the HS was the net present value (NPV) of the investment. NPV is the difference between the present value of benefits from the technology and the present value of costs associated with the investment. The proposal is deemed to have a positive impact if its NPV exceeds zero.

Estimation of farm-level benefits

The study used a range of techniques to measure on-farm benefits from the adoption of the HS technology on a typical RW farm in Punjab. The benefits to farmers from adoption of the technology were estimated based on the Combo Happy Seeder (Sidhu et al. 2008).

Gross margin analysis

The gross margin (GM) is the gross return from a crop (yield times price) less the variable costs of production such as tillage, seed, fertiliser, irrigation water, plant protection, fuel, harvesting, crop insurance and marketing. Overhead and operating costs that do not vary with the level of production, such as rent, wages to permanent labour, interest and depreciation, are not considered in a GM analysis. Crops and rotations can be compared using GMs as long as there is no significant change in overhead costs between the alternative options in the comparison.

The cost of some inputs or operations such as irrigation water, fertiliser, weedicide and machinery operations are different under different stubble management regimes. An increase in yield or price also leads to an increase in the cost of some variable inputs and operations such as harvesting, threshing and marketing. Therefore, the variable costs and returns of growing wheat and other crops after rice with different tillage and/or stubble management techniques were calculated separately.

Crop sequence gross margin analysis

GM analysis deals with only one crop at a time, whereas farmers grow a sequence of crops on the same field according to a particular rotation. Furthermore, selection of an enterprise by a farmer is not always done only on the basis of its profitability as an independent enterprise, but also by its contribution to other enterprises and the total cropping system. To improve soil fertility, farmers can grow nitrogen (N) fixing crops like pulses or crops grown solely for green manuring. While GMs of such crops may be low or negative, they may reduce input costs and/or increase yield of other crops in the rotation. These crops may also act as a break crop to help reduce input costs or yield losses from weeds and diseases. However, for RW farmers in Punjab, the typical rotation is puddled transplanted rice planted in June and harvested in October, followed by wheat sown in November and harvested in April, with no legumes or green manure crops during the long fallow (~10 weeks) between wheat harvest and rice transplanting.

Straw retention (by mulching or incorporation) saves considerable amounts of nitrogen and some phosphorus, potassium and sulphur that would otherwise be lost by burning (Table 1), and also affects soil fertility in other ways. Straw retention also influences biotic factors such as weed diversity and the weed seedbank, and the incidence of other pests and diseases. The effects vary depending on the method of stubble retention. With a carbon:nitrogen (C:N) ratio in rice straw of around 100:1, incorporation results in temporary immobilisation of inorganic N. To avoid adverse impacts on the crop, more N fertiliser is required or sowing needs to be delayed for at least 2 weeks after incorporation is completed. However, delaying sowing beyond the optimum date of 25 October in Punjab, India, (Ortiz-Monasterio et al. 1994) reduces yield.

Estimation of the long-term benefits and costs of such changes in straw management and crop sequence requires analysis of the total crop sequence. Therefore, we compared the benefits and costs of the adoption of the HS with those of other current practices of wheat establishment after rice harvest over a 20-year period.

The NPV of the crop GM was calculated as the sum of the discounted annual GMs from the crops in the rotation, using equation 1:

$$\text{NPV} = \sum_{t=1}^{n} GM_t \,/\, (1 + rate)^t \qquad \text{equation 1}$$

where *rate* is the discount rate (7%) and GM_1, GM_2, …, GM_t are the GMs for years 1 to *n* (n=20 in this study).

Data and assumptions used in the analysis

The key data and assumptions used in the GM analysis of the potential financial benefits from the adoption of the HS are given below.

Output and input prices

Output prices used in the GM analysis were the government procurement prices for wheat and paddy during 2005–06. Various government agencies purchased more than 90% of the wheat and paddy, paying these prices to the farmers. The input costs were also estimated using 2005–06 market prices.

Machinery costs

The HS has only been developed and tested, on a limited acreage each year, over the past 3 years. Furthermore, there is no information in general on the machinery costs involved in managing stubbles and sowing wheat and other crops after rice on a typical rice farm in Punjab. Therefore, the cost of use of the HS was based on the contract rate for a Roto-broadcaster, which has similar power requirements, capacity and working width as the HS. For consistency, contract rates during 2005–06 for all tillage and sowing operations were also used in the GM and crop sequence analysis.

Benefits and costs of methods of wheat establishment after rice

Establishment of wheat by sowing into rice residues with the HS was compared with the current practices of conventional and zero tillage after stubble burning. The value of the potential benefits and costs of the HS were estimated using the results of research to date (Sidhu et al. 2007, 2008; Yadvinder-Singh et al. 2008), together with estimates by PAU research and extension staff to fill data gaps.

The potential benefits to farmers of using the HS are:

- reduced cost of machinery operations for crop establishment in comparison with conventional tillage (but not in comparison with zero tillage after straw burning) through reduced diesel consumption, machinery repairs and maintenance, and labour
- increased yield through improved soil physical, chemical and biological properties
- reduced fertiliser inputs through improved soil fertility
- reduced weed control costs through suppression of weeds by mulching
- irrigation water savings through suppression of soil evaporation
- labour savings through fewer tillage operations and reduced irrigation time
- electricity savings through reduced pumping time.

Estimating the value of the benefits of the HS

Yield increase

The analysis assumes the same yield of wheat sown by all methods. Long-term experiments of Sidhu and Beri (2005) found no significant increase in yield of wheat from incorporation of rice stubbles compared with wheat sown after burning of stubbles. However, in farmers' fields Sidhu et al. (2007) found an average yield increase of about 10% from sowing with the HS compared with farmer practice.

Both the HS and the zero-till drill allow sowing of wheat shortly after rice harvest, although turnaround can be faster with the HS because of the time taken for the straw to dry before burning prior to use of the zero-till drill. This could be particularly important for basmati rice, which is harvested much later than other types, in terms of achieving wheat sowing close to the optimum time for maximum yield. Therefore, a sensitivity analysis for increases in wheat yield of 5% and 10% was included.

Fertiliser saved

Retention of rice stubble would add nutrients to the soil (Table 1). However, there is little information on the effect of mulching on the impact on fertiliser requirements over time. In the high-yielding rice systems in California (>10 t/ha rice straw, one crop per year), N fertiliser rates were able to be reduced by 20% (27 kg N/ha, equivalent to 59 kg/ha of urea) after 5 years of rice straw retention (Bird et al. 2002). In our analysis we assumed that mulching of rice stubble would reduce N fertiliser requirement of wheat by 10% (26.5 kg/ha of urea) in the 5th year and by 15% (40 kg/ha urea) from year 10. We considered that the low soil organic C, subtropical climate promoting rapid mineralisation, and high soil permeability of Punjab soils would reduce the nutrient benefit of straw retention in comparison with the Californian situation. These fertiliser savings result in a financial benefit of 133 Rs/ha/year from years 5 to 10 and 199 Rs/ha/year from years 11 to 20.

The analysis assumed no carry-over effect of retaining rice straw on N fertiliser requirement for rice.

Herbicides saved

Mulching suppresses establishment and growth of weeds, and many studies have shown very large effects of mulching with rice straw on weeds in wheat (e.g. Rahman et al. 2005; Sidhu et al. 2007, 2008). Due to the consequent lower population of weeds, farmers may then be able to use weedicide in alternative years. Therefore, we assumed that mulching would reduce the cost of herbicide by 50%, thus saving 908 Rs/ha/year.

Diesel saved

Direct drilling wheat using the HS or zero-till drill would reduce tractor time by 3 hours compared with conventional tillage (after burning) and sowing wheat, and using the HS would take a little longer than the zero-till drill. However, we have costed the use of machinery based on contract rates, which already take into account the diesel savings (and the machinery repair and maintenance and labour savings) through the reduced time taken for field operations.

Water saved

Sowing wheat immediately after rice harvest could reduce the need for pre-irrigation. Farmer and researcher experience with direct drilling of wheat into burnt or partially burnt rice straw with the zero-till drill indicates irrigation water savings of 20–35% or 70–100 mm compared with conventional tillage, with the largest savings in the first irrigation (Humphreys et al. 2007). Both the HS and the zero-till drill allow sowing shortly after rice harvest, although turnaround can be faster with the HS. Mulching of stubble also helps reduce soil evaporation. In addition to saving the pre-irrigation water, we assumed a farmer also saves 15% from the first and 10% from the second irrigation, with an overall saving of 30% of water applied to the wheat crop using both the HS (with full straw retention) and the zero-till drill (with partial or complete burning) in comparison with conventional tillage (Table 2).

Electricity saved

Reduced irrigation water use also helps save electricity use by tube-well pumps. Currently, the farm sector gets an unlimited supply of free electricity for irrigation. Therefore, there is no financial benefit to farmers from any saving of electricity used for irrigation. There are likely to be considerable economic benefits to society from the electricity saved but these have not been considered in the financial analysis.

Labour saved from reduced irrigation

A typical RW farmer in Punjab employs casual labour to meet the peak demand during both the winter and summer seasons. Farm labour is readily available from the local market for 10 Rs/hour.

In Punjab about 28% of the net sown area is under the canal command area, ranging from less than less than 1% in central districts to 80–90% in some of the south-western districts of the state (Government of Punjab, 2005 and Appendix 2). The use of canal water for irrigation is much cheaper than the costs and time involved in pumping groundwater. Due to lack of information on the amount of channel water used and the charges, the value of labour saved from irrigation operations was based on the time required to irrigate using groundwater (15 hours to apply one irrigation of 7.5 cm to 1 ha or 0.5 hour/cm of irrigation). A 30% irrigation water saving (11.9 cm) thus saves 23.8 hours or 238 Rs/ha of human labour involved in irrigation operations.

Table 2. Total water use and value of water saved from sowing wheat using the HS in the rice–wheat farming system in Punjab

Irrigation	Conventional sown wheat (cm/irrigation)	Wheat sown using zero tillage (cm/irrigation)	Wheat sown using the HS (cm/irrigation)	Water savings from wheat sown using the HS (%)
Pre-sowing	10	0	0	100
First	7.5	6.38	6.38	15
Second	7.5	6.75	6.75	10
Third	7.5	7.5	7.5	0
Fourth	7.5	7.5	7.5	0
Total	40.0	28.1	28.1	30

Note: It was assumed that there were no water savings from wheat sown using the HS over stubble-burnt zero-till wheat in the baseline analysis.

The HS also helps save labour required for operating machinery compared with conventional tillage; however, these benefits are captured in the costs of custom hire for all machinery operations, as for fuel and other machinery costs.

Value of total benefits

The total annual financial benefits from using the HS compared with sowing wheat following conventional tillage and zero tillage after burning rice stubbles were estimated taking into account the benefits from reduced input costs, human labour and machinery costs. The total value of the annual financial benefit from using the HS was 2,445–2,642 Rs/ha over wheat sown following conventional tillage and 370–566 Rs/ha over zero tillage after burning rice stubbles.

Estimating the costs of methods of wheat establishment after rice

We used contract rates to estimate the costs of using the HS and other machinery for different options of managing stubbles and sowing wheat. It is assumed that tractors and other machinery are readily available for different agricultural operations on a contract basis. Full details of the operations involved and their costs are provided in Appendix 1. A summary of total costs is: mulching of stubbles and direct drilling wheat using the HS costs 2,163 Rs/ha; sowing wheat with the seed-fertiliser drill after incorporation and burning of stubbles costs 3,600 Rs/ha and 3,500 Rs/ha, respectively; and sowing wheat with zero tillage machines after burning rice stubble is the cheapest method, costing 1,688 Rs/ha.

Benefit–cost analysis

Over the 20-year period the NPV of the total financial benefits from adoption of the HS was 6,150 Rs/ha compared with stubble burnt / zero tillage wheat, and 31,910 Rs/ha compared with the stubble burnt / conventional tillage option. Sensitivity analysis was used to demonstrate the effects on returns of changes in yield, savings of key inputs and changes in discount rate used in the analysis (Table 3).

The NPV of the total financial benefits of the HS was most sensitive to changes in yield, followed by weedicide use and discount rate, and less sensitive to irrigation water and nitrogen use or number of discings (Table 3). For example, the net benefits almost doubled over conventional tillage and increased by five times over zero tillage with a yield increase of only 5% using the HS. With no reduction in weedicide use with the HS, zero tillage after burning is slightly more profitable than the HS at the same yield.

Table 3. Net present value of total financial benefits of the HS with different levels of crop yield, input savings and discount rate

Financial benefits of the HS in comparison with:	NPV of benefits (Rs/ha)	
	Conventional	Zero tillage
1. Wheat yield increase		
No increase	31,910	6,150
5% increase	59,500	33,945
10% increase	87,250	61,524
2. Weedicide use		
50% reduction	31,910	6,150
No reduction	21,415	–5,097
3. N fertiliser use		
With reduction	31,910	6,150
No reduction	30,325	4,576
4. Irrigation water saving		
With 30% reduction	31,910	6,150
No reduction	28,640	6,150
5. Discount rate		
4%	44,785	9,267
7%	31,910	6,150
10%	24,190	4,783
6. Machinery operations (conventional tillage)		
1 discing	31,910	
2 discings	38,115	

The findings of the initial financial evaluations of the HS technology suggest that its use is financially viable for farmers and more profitable than conventional alternatives, especially conventional tillage. However, these evaluations assume contract provision of HS sowing services for an 'average' farm. The implications of uncertainty about some of the key variables in the analysis need further investigation for a range of soils and farm sizes in different agroclimatic regions in Punjab, India, before firm conclusions are drawn about the financial viability of the technology (Pagan and Singh 2006).

Due to the current institutional arrangements surrounding the RW production system of Punjab, the current costs of many of the inputs, e.g. irrigation water, electricity used for pumping groundwater, diesel, fertiliser and interest on agricultural loans, are not fully borne by farmers. Hence, in addition to the financial benefits to farmers, the adoption of the HS technology may deliver benefits to the rest of the community. For example, there would be significant economic benefits from any reduction in the costs involved in the use of electricity (supplied free to agriculture) as a result of reduced groundwater pumping due to improved water use efficiency. Reduced demand for water may also lead to a reduction in the huge investment required to convert to submersible pumps as groundwater depth declines. Similarly, savings of fertiliser and fuel would lead to reductions in the cost to government of subsidies for fertiliser and fuel used in agriculture. There will also be considerable benefits to society through the reduction in air pollution from stubble burning. A detailed economic analysis is required to estimate the full potential economic benefits from reductions in a range of inputs and from the reduced adverse environmental impacts.

Major constraints to adoption of the HS

Some of the mechanical, technical and social constraints to adoption of the HS technology may include:

- Limited use due to the small size of holdings—there is a large capital cost involved to buy an HS and 45 hp tractor, currently the minimum power required to operate the HS. More than 66% of the RW farms in Punjab are less than 4 ha in size (Appendix 3). Therefore, machinery purchased by small farmers would be underused due to its limited use on-farm. Farm size affects the financial viability of individual farmers owning and using the HS on their farm, in comparison with contractor- and cooperative-based approaches to making the technology available.
- Capacity of the machine—with a capacity of the current model of the HS of 5 acres/day and a narrow sowing window for wheat, even the professional machinery contractors may not be able to operate the HS for more than about 30 days each year.
- Less efficient contract arrangement—most of the custom work in growing and harvesting crops is done by full-time farmers. Due to stiff competition, most farmers tend to use their machines for custom work even at very low rates. A professional machinery contractor may not be able to afford to provide machinery at the prevailing market rates, and this may increase the cost of managing stubbles followed by direct drilling wheat compared with the other current practice of direct drilling wheat after burning stubbles.
- Lack of information on potential benefits—the HS was developed recently and farmers have not yet adopted this technology. There is a general lack of information on its long-term impacts on soil fertility, crop yields, and saving of machinery, labour, herbicide, water and other input costs.
- Limited capacity of the industry to meet demand—at present Dasmesh Mechanical Works, Amargarh, Punjab, who have developed this machine in collaboration with the Punjab Agricultural University (PAU), and National Agro Industry, Ludhiana, Punjab, are the only manufacturers of the HS in Punjab, India. The maximum capacity of Dasmesh and National is 200–250 HSs per year each, which may not meet the potential demand for the machine. The level of manufacturing capacity is a highly relevant parameter for policymakers when they are determining a feasible timetable for enforcement of the ban on residue burning.
- Lack of straw spreaders on combine harvesters in Punjab—the loose straw needs to be spread uniformly prior to using the HS. This can be done manually but it is tedious, time consuming and incurs labour costs, and spreading will be less even than can be achieved by mechanical straw spreaders.
- Lack of machinery to form bunds in the presence of rice straw—a typical 1-acre rice field is normally divided into quarters after wheat sowing by forming small bunds to enable more even and efficient irrigation of wheat. The current machines used to form bunds do not work well in the presence of straw.

Conclusions

The results of this preliminary benefit–cost analysis suggest that the NPV of the total financial benefits from adoption of the HS was 6,150 Rs/ha over 20 years compared with stubble burnt / zero tillage wheat, and 31,910 Rs/ha compared with the stubble burnt / conventional tillage option. This is based on the conservative assumption that there were no yield increases associated with the HS, in contrast to findings to date of average yield increases of around 10% (Sidhu et al. 2008).

Sensitivity analysis indicates that the returns from the HS are highly sensitive to yield, and more sensitive to weedicide savings than to discount rate or water and fertiliser savings. The net benefits were almost doubled for a 5% increase in wheat yield with the HS compared with the stubble burnt conventional tillage. The assumption of a 50% herbicide saving with the HS made a difference between the HS being more or less profitable than use of the zero-till drill after stubble burning.

Although the adoption of the technology has numerous benefits as discussed above, lack of information on the long-term impacts of use of the HS on soil fertility, crop yields, and savings of machinery, labour, water and other input costs may slow its adoption. Some other key constraints that may adversely affect the rate of adoption of the technology include the capital cost of farmers buying and operating their own machinery with limited use on small holdings, and the relatively poor returns on investment for machinery contractors due to limited use in a relatively narrow wheat sowing window and low capacity of the machine. However, there may be other potential applications of the machine, which has been shown to be capable of sowing a range of crops into a range of stubbles.

This financial evaluation of the HS technology indicates that the technology is financially viable for farmers and is more profitable than conventional alternatives. However, as the technology is new and data availability is limited, more comprehensive financial evaluation is needed because of the preliminary nature of the estimates of benefits of many of the inputs. Furthermore, there are price distortion issues and impacts from the significant potential additional value of externalities associated with the HS technology. All these factors suggest that there is a strong case for undertaking an economic evaluation to determine a more complete assessment of the net benefits of the Happy Seeder technology to society as well as to farmers.

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Appendix 1. Comparison of operations and costs of methods of wheat establishment after rice

Particulars	Happy Seeder			Seed–fertiliser drill with straw incorporation			Seed–fertiliser drill after burning			Zero-till drill after burning		
	Qty/no.	Cost per operation (Rs/ac)	Total cost (Rs/ac)	Qty/no.	Cost per operation (Rs/ac)	Total cost (Rs/ac)	Qty/no.	Cost per operation (Rs/ac)	Total cost (Rs/ac)	Qty/no.	Cost per operation (Rs/ac)	Total cost (Rs/ac)
Stubble Shaver incl. 1 hour labour	–	–	–	–	–	–	1	210	210	1	210	210
Cost of burning straw (labour)	–	–	–	–	–	–	1	15	15	1	15	15
Pre-sowing irrigation[a]	–	–	–	1	25	25	1	25	25	1	25	25
Preparatory tillage:												
– first discing	–	–	–	1	300	300	1	300	300	–	–	–
– second discing	–	–	–	1	200	200	–	–	–	–	–	–
– tine harrows	–	–	–	2	200	400	2	200	400	–	–	–
– planking	–	–	–	2	100	200	2	100	200	–	–	–
Straw spreading	2	10	20	2	10	20	–	–	–	–	–	–
Sowing	1	750	750	1	200	200	1	200	200	1	300	300
Extra seed (kg/acre)	–	–	–	–	–	–	–	–	–	5	12	60
Bund making[b]	1	75	75	1	75	75	1	50	50	1	50	50
Rodent control	1	20	2	1	20	20	–	–	–	1	15	15
TOTAL			865			1,440			1,400			675

[a] Electricity is 100% subsidised
[b] Differences in cost of bund making are due to presence of rice straw.

Appendix 2. Area (ha × 10^3) irrigated by canal and tube-wells in Punjab

Year	Govt. canals	Private canals	Tube-wells	Other sources	Total	Percentage of net sown area
1960–61	1,173 (58%)	7 (0.35%)	829 (41%)	11 (0.54%)	2,020 (100%)	54
1970–71	1,286 (44%)	6 (0.21%)	1,591 (55%)	5 (0.17%)	2,888 (100%)	71
1980–81	1,430 (42%)	–	1,939 (57%)	13 (0.38%)	3,382 (100%)	81
1990–91	1660 (42%)	9 (0.23%)	2,233 (57%)	7 (0.18%)	3,909 (100%)	93
2000–01	1,002 (25%)	–	3,017 (75%)	2 (0.05%)	4,021 (100%)	94
2002–03	1,148 (28%)	–	2,880 (71%)	7 (0.17%)	4,035 (100%)	95

Appendix 3. Number and percentage of operational landholdings in Punjab (2000–01)

Size classes (ha)	Average (ha)	Number (‘000)	Percentage of total number	Area (‘000 ha)	Percentage of total area
Below 1	0.6	123	12	77	2
1–2	1.4	173	17	242	6
2–4	2.7	328	33	876	22
4–10	5.8	301	30	1,731	43
10 and above	15.2	72	7	1,096	27
Total	4.0	997	100	4,022	100

Source: Statistical abstract, Chandigarh, Punjab, 2005