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

Figure 4. Happy Seeder 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

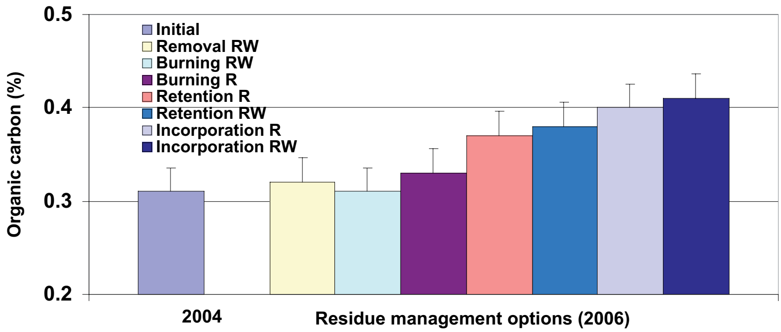

Figure 7. Effect of residue management on soil organic C (at 0–15 cm) after 2 years (four crops). Vertical bars on each column represent the LSD (0.05).

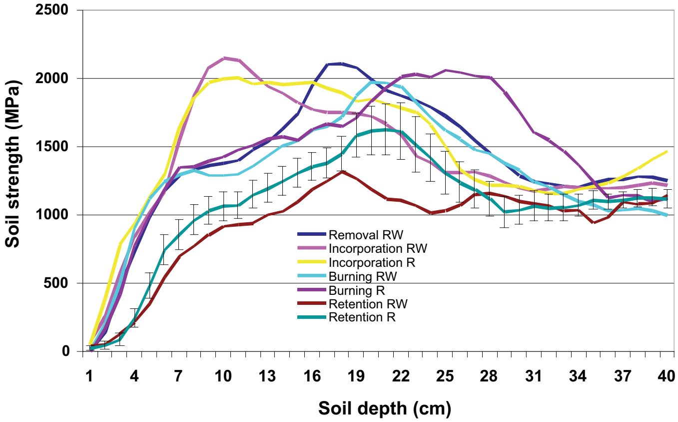

Figure 8. Effect of residue management options on soil strength (data are means of 27 determinations, vertical bars are standard error of the mean for one treatment)

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.

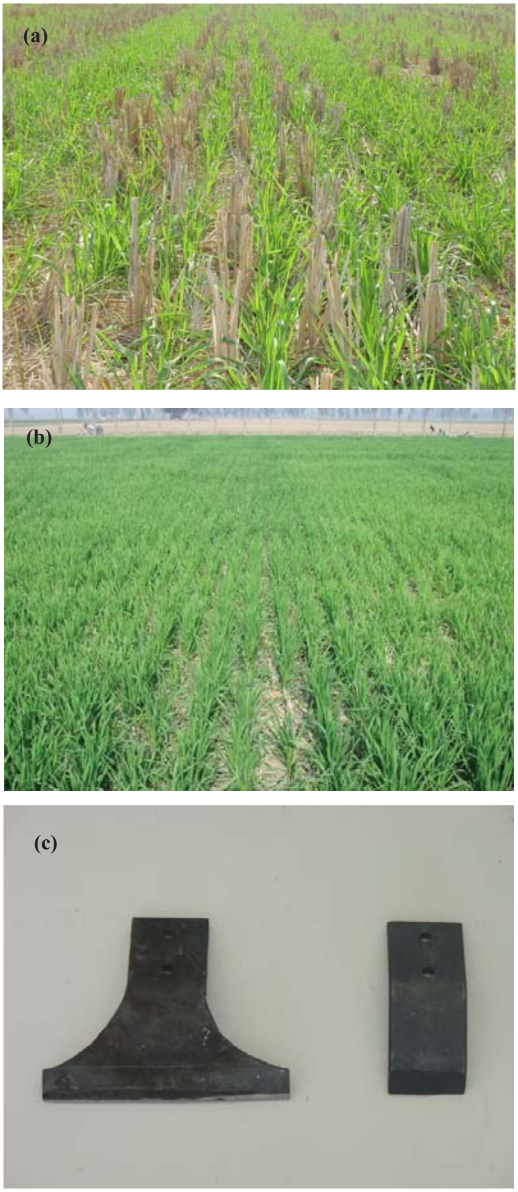
Wheat cultural practices

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 agroecological 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).

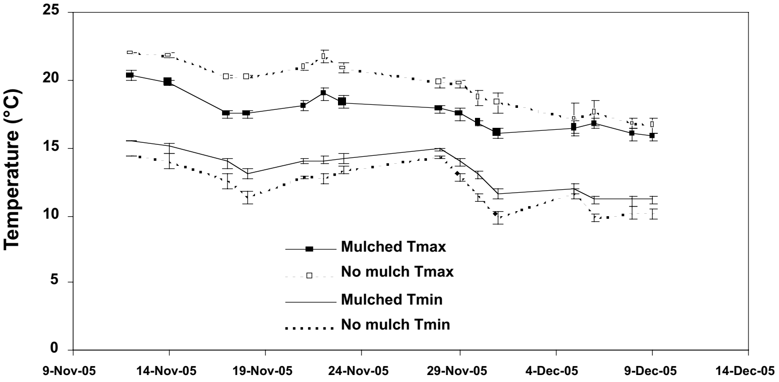

Figure 2. Minimum and maximum soil temperature at 7 cm depth with and without mulching (experiment 1); vertical bars are standard errors

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:

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

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