Managing Crop Residue with Green Manure, Urea, and Tillage in a Rice–Wheat Rotation

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ABSTRACT

Most double-crop grain farmers in South Asia remove or burn crop residue to facilitate seedbed preparation and to avoid possible yield reductions. This results in loss of soil organic matter (SOM) and nutrients. In this study, we determined whether incorporating wheat (*Triticum aestivum* L.) residue, rice (*Oryza sativa* L.) residue, and sesbania (*Sesbania aculeta* L.) green manure with urea fertilizer N in a rice–wheat cropping system can improve grain yields, N use efficiency, and SOM. We incorporated wheat residue (6 Mg ha^{-1}, C/N = 94), rice residue (6 Mg ha^{-1}, C/N = 63), or both, with and without green manure (20 or 40 Mg fresh ha^{-1}, C/N = 19), in a field experiment with irrigated rice and wheat grown each year in rotation on a Tolewal sandy loam (Typic Ustochrept) in the Punjab of India. Rice and wheat residue did not affect grain yields of wheat and rice, but residue incorporation did result in reduced recovery efficiency of urea N and green manure N. Rice production was greater with wheat residue incorporation when an average of 86 kg N ha^{-1} of a prescribed 120 kg N ha^{-1} dose was applied as green manure N and the balance as urea N vs. 120 kg urea N ha^{-1} alone. Despite wider C/N than rice residue, wheat residue additions to flooded rice resulted in greater C sequestration in soil than with rice residue or 40 Mg green manure ha^{-1}. These results demonstrate that a green manure crop and/or incorporating crop residue in a rice–wheat system has potential to increase SOM while maintaining high grain yields.

Crop residue is a vital natural resource for conserving and sustaining soil productivity. It is the primary substrate for replenishment of soil organic matter (SOM). Upon mineralization, crop residue supplies essential plant nutrients (Walters et al., 1992). Additionally, residue incorporation can improve physical and biological conditions of the soil and prevent soil degradation (Nyborg et al., 1995).

In South and Southeast Asia, large amounts of crop residue are burned or removed after harvest (Nguyen et al., 1994; Smil, 1999). This results in loss of organic matter and nutrients and causes atmospheric pollution due to emissions of toxic and greenhouse gases such as CO, CO_2, and CH_4, which pose a threat to human and ecosystem health (Andreae, 1991; Nguyen et al., 1994). Demand for crop residue for cooking fuel and animal feed is high in South Asia (Bronson et al., 1998). Removal or burning of residue ensures farmers' quick seedbed preparation and avoids the risk of reduced crop yields associated with incorporating wide C/N ratio residue that immobilizes N during decomposition (Khera, 1993; Beri et al., 1995). The benefits of sequestering soil organic C (SOC) to sustaining crop productivity by applying organic amendments and crop residue and including legumes in crop rotations have been well documented in the temperate regions. Although many green manuring studies have been conducted with rice in Asia (Buresh et al., 1993; Yadvinder-Singh et al., 1993), few studies have looked at comparative effects of crop residue management with or without fertilizer N and legume green manure on crop yields and SOC.

Annual rice–wheat double-crop systems occupy 21 million ha in the Indo-Gangetic plains of South Asia and China (Woodhead el al., 1994). On-station data from long-term experiments in China (Byerlee, 1992), Nepal (Regmi, 1994), and India (Nambiar, 1995) indicate that productivity of rice and wheat has been declining. Inadequate or imbalanced nutrient management and decreasing SOM are probably the factors in the declining trend in this cropping system (Abrol et al., 1997). There is a need, therefore, to develop agronomic strategies for efficient utilization of crop residue while also sequestering organic C in the soil. The present field experiment was initiated in 1993 in northwest India with these objectives: (i) to test the effects of incorporating wheat and rice residue alone and in combinations with green manure on grain yields and N use efficiency and (ii) to quantify C sequestration in soil with crop residue and green manure incorporation.

MATERIALS AND METHODS

A field experiment was conducted from 1993 to 1997 on a semiarid, irrigated, Tolewal sandy loam (Typic Ustochrept) soil at Punjab Agricultural University Research Farm, Ludhiana, India. Ludhiana is situated at 30°54′ N and 75°48′ E and is 247 m above mean sea level. Mean monthly minimum air temperatures during the 4 yr of the study ranged from 5 to 8°C

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Abbreviations: AE, agronomic efficiency; FN_0, FN_{120}, or FNx, 0, 120, or variable kg urea fertilizer N ha^{-1}; GM_0, GM_{20}, or GM_{40}, 0, 20, or 40 Mg sesbania green manure ha^{-1}; PE, physiological efficiency; RE, recovery efficiency; RR_0 or RR_6, 0 or 6 Mg rice residue ha^{-1}; SOC, soil organic carbon; SOM, soil organic matter; WR_0 or WR_6, 0 or 6 Mg wheat residue ha^{-1}.

Table 1. Treatment combinations and rates of fertilizer N, dry wheat and rice residues, and fresh biomass of sesbania green manure applications.

Treatment applied to		Amount added				
		Rice			Wheat	
Rice	Wheat	Wheat residue	Fertilizer N	Green manure	Rice residue	Fertilizer N
		Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
WR_0 FN_0 GM_0†	RR_0 FN_{120}‡	0	0	0	0	120
WR_0 FN_{120} GM_0	RR_0 FN_{120}	0	120	0	0	120
WR_0 FNx GM_{20}§	RR_0 FN_{120}	0	34§	20	0	120
WR_0 FN_0 GM_{40}	RR_0 FN_{120}	0	0	40	0	120
WR_6 FN_0 GM_0	RR_0 FN_{120}	6	0	0	0	120
WR_6 FN_{120} GM_0	RR_0 FN_{120}	6	120	0	0	120
WR_6 FN_x GM_{20}§	RR_0 FN_{120}	6	34§	20	0	120
WR_0 FN_0 GM_0	RR_0 FN_0¶	0	120	0	0	0
WR_0 FN_{120} GM_0	RR_6 FN_0¶	0	120	0	6	0
WR_0 FN_{120} GM_0	RR_6 FN_{120}¶	0	120	0	6	120

† WR = wheat residue (subscript is Mg ha^{-1}); FN = fertilizer N (subscript is kg ha^{-1}, X is varied); GM = green manure (subscript is Mg ha^{-1}).
‡ RR = rice residue (subscript is Mg ha^{-1}); FN = fertilizer N (subscript is kg ha^{-1}).
§ Amount of 120 kg N ha^{-1} applied through 20 Mg green manure ha^{-1} and the balance (averaged 34 kg N ha^{-1}) through fertilizer N.
¶ Treatment was not included in Year 1.

in January to 26 to 27°C in June, while maximum temperatures ranged from 8 to 19°C in January to 35 to 40°C in June. Annual rainfall ranged from 590 to 1230 mm with 74 to 85% occurring from July to September. Characteristics of the Tolewal sandy loam soil (0–15 cm), determined by standard methods (Westerman, 1990): pH 7.9 (1:2 soil-to-solution ratio); electrical conductivity 0.21 dS m^{-1} (1:2 soil-to-solution ratio); organic carbon 3.8 g kg^{-1}; and total N 0.4 g kg^{-1}. The soil contained 780 g kg^{-1} sand, 110 g kg^{-1} silt, and 110 g kg^{-1} clay. The infiltration rate of the unpuddled soil averaged 1.0 cm h^{-1} and the puddled soil rate was 0.2 cm h^{-1}. The groundwater table was below 8 m.

Rice Treatments and Management

Treatments for rice consisted of two levels of wheat residue (0 and 6 Mg ha^{-1} on dry weight basis) without or with 120 kg urea N ha^{-1}, which is the recommended rate for optimum rice production (Gill, 1995; Aulakh et al., 2000), and three levels of green manure (0, 20, and 40 Mg ha^{-1} of fresh biomass containing about 800 g water kg^{-1}) that were arranged in a randomized complete block design with three replications. The total numbers of treatment combinations were 7 in 1993 and 10 from 1994 to 1997 (Table 1).

Within 7 d of harvesting the preceding wheat crop, dry wheat residue was uniformly distributed in allocated plots and disked into the soil in the third or fourth week of April each year (Table 2). One week later, sesbania was seeded as green manure crop in green manure treatment plots. Sesbania seed was drilled in rows 20 cm apart at the rate of 50 kg seed ha^{-1} in good soil moisture. After 51 to 60 d, the green manure crop was harvested and fresh biomass of green manure (20 or 40 Mg ha^{-1}) was uniformly distributed in respective treatment plots and incorporated into the soil in June, 2 d before transplanting rice seedlings. Nitrogen added through aboveground portion of green manure (20 Mg ha^{-1}), 6 Mg wheat residue ha^{-1}, and 6 Mg rice residue ha^{-1} was determined by micro-Kjeldahl analysis (Westerman, 1990) (Table 3), and the total dose of 120 kg N ha^{-1} in WR_0 (0 Mg wheat residue ha^{-1}) FNx (variable kg urea fertilizer N ha^{-1}) GM_{20} (20 Mg sesbania green manure ha^{-1}) and WR_6 (6 Mg wheat residue ha^{-1}) FNx GM_{20} treatments was given through 20 Mg green manure ha^{-1} with the balance through urea N. Plots designated not to receive green manure were maintained weed-free during the fallow period.

Rice (cv. PR 106) was seeded in a separate field adjoining the experimental plots in the second or third week of May and fertilized with 15 kg N ha^{-1} and 18 kg P ha^{-1} as diammonium phosphate, and 10 kg zinc sulfate ha^{-1}. Two weeks later, 25 kg N ha^{-1} as urea was top-dressed before irrigation. Healthy 45-d-old seedlings were transplanted (2 hill^{-1}) in the third or fourth week of June or first week of July (Table 2). Hill spacing was 20 by 15 cm and individual plots measured 3 by 7.5 m. As recommended (Gill, 1995), 120 kg urea N ha^{-1} was applied in three equal amounts at about 0, 3, and 6 wk after transplanting rice seedlings to synchronize N supply with crop de-

Table 2. Calendar of different field operations, incorporation of crop residue, and fertilizer application in rice–wheat rotation.

Operation	Year 1	Year 2	Year 3	Year 4
Incorporation of wheat residue	21 Apr. 93	16 Apr. 94	17 Apr. 95	22 Apr. 96
Green manure				
Seedling	28 Apr. 93	22 Apr. 94	24 Apr. 95	29 Apr. 96
Harvest, incorporation, and flooding	20 June 93	14 June 94	22 June 95	29 June 96
Rice				
Transplanting	22 June 93	16 June 94	24 June 95	01 July 96
First fertilizer N	23 June 93	20 June 94	25 June 95	03 July 96
Second fertilizer N	16 July 93	08 July 94	14 July 95	04 Aug. 96
Third fertilizer N	05 Aug. 93	29 Aug. 94	02 Aug. 95	26 Aug. 96
Harvest	09 Oct. 93	08 Oct. 94	14 Oct. 95	14 Oct. 96
Incorporation of rice residue	†	14 Oct. 94	21 Oct. 95	17 Oct. 96
Wheat				
Seeding	07 Nov. 93	09 Nov. 94	11 Nov. 95	05 Nov. 96
First fertilizer N	07 Nov. 93	09 Nov. 94	11 Nov. 95	05 Nov. 96
Second fertilizer N	02 Dec. 93	13 Dec. 94	13 Dec. 95	10 Dec. 96
Harvest	09 Apr. 94	15 Apr. 95	14 Apr. 96	21 Apr. 97

† Treatment was not included in Year 1.

Table 3. Mean (across years) N and C additions and characteristics of sesbania green manure, wheat residue, and rice residue.

	n	Dry matter	N content	C/N ratio	N addition	C addition
		$Mg\ ha^{-1}$	$g\ kg^{-1}$		$kg\ ha^{-1}$	$Mg\ ha^{-1}$
GM_{20}†	24	3.3 ± 0.2§	26.2 ± 2.4	19 ± 2.0	86 ± 7.0	1.6 ± 0.1
GM_{40}‡	12	6.6 ± 0.4	26.2 ± 2.4	19 ± 2.0	172 ± 14	3.2 ± 0.2
Wheat residue	36	6.0 ± 0.1	4.3 ± 0.1	94 ± 3.0	26 ± 1.0	2.5 ± 0.1
Rice residue	18	6.0 ± 0.1	6.5 ± 0.3	63 ± 3.0	39 ± 2.0	2.5 ± 0.1

† 20 Mg fresh biomass ha^{-1} of sesbania green manure.
‡ 40 Mg fresh biomass ha^{-1} of sesbania green manure.
§ Mean ± standard deviation.

mand. The experimental area was bordered with five rows of nonexperimental rice plants on all sides of the field. The crop was irrigated daily during the first month and thereafter as needed to prevent the soil surface from being without overlying water for more than 2 d. This practice of intermittent irrigation saves water without reducing rice yields (Sandhu et al., 1980). Irrigation water was used either from canal or tubewell and contained no N. Rice was harvested from a 10-m^2 area (330 hills) of each plot at physiological maturity in the first or second week of October. Grain and straw yields are expressed on the basis of 140 g kg^{-1} water and dry weight, respectively.

Wheat Treatments and Management

Rice residue treatments were imposed within a week after harvesting rice crop to provide a 3- to 4-wk period for decomposition before seeding wheat. In the third or fourth week of October each year (except in 1993), dry rice residue was uniformly distributed in respective rice residue-treatment plots at 6 Mg ha^{-1} and disked into the moist soil (Table 2). One week later, the plots were re-disked followed by preseeding irrigation. Wheat (cv. HD 2329) was drilled at 40 kg seed ha^{-1} in early November in the same permanent plots as rice in rows 20 cm apart. A uniform application of 26 kg P ha^{-1} as single superphosphate was drilled in all plots at the time of seeding. Two rates of fertilizer N (0 or 120 kg urea N ha^{-1}) were broadcast in two equal splits: at seeding and 4 to 5 wk later (1 d after the first irrigation) (Table 2). Three more flood irrigations of about 7 cm were applied during the season. The center 10 m^2 of each plot was harvested in the second or third week of April. Grain and straw yields are expressed on the basis of 140 g kg^{-1} water and dry weight, respectively.

Plant and Soil Analyses

Concentration of N in representative grain and straw samples of both rice and wheat was determined by the micro-Kjeldahl method (Westerman, 1990) at harvest. Dynamics of soil mineral N (NH_4–N + NO_3–N) were monitored in the third year, during pre-rice fallow (17 Apr. to 23 June 1995) and rice growing season (24 June to 13 Oct. 1995), and in fourth year during after-rice fallow period (15 Oct. to 4 Nov. 1996) and wheat growing season (5 Nov. 1996 to 20 Apr. 1997). Soil cores (5-cm diam. × 15-cm length) from each of three replications of selected treatments were collected at 1- to 2-wk intervals. Field moist soil samples were thoroughly mixed and representative subsamples were extracted by shaking with 2 *M* KCl solution (1:6 soil-to-solution ratio) for 1 h on a mechanical shaker followed by filtration. Extracts were analyzed for mineral N using a micro-distillation procedure (Mulvaney, 1996).

At the beginning and at the completion of the study, soil bulk density was determined to a 15-cm depth using 5-cm i.d. by 15-cm-long steel cores with open ends by collecting and combining four cores for each of the 30 plots (10 treatments × 3 replications). Soil samples were air-dried, crushed to pass a 2-mm sieve, and analyzed for SOC by Walkley and Black's method (Westerman, 1990). Mean bulk density values for each treatment were used for converting SOC concentrations (mg C kg^{-1} soil) to units of kg C ha^{-1}.

Calculations and Statistics

Recovery efficiency (RE) of added N was calculated (Dilz, 1988):

$$\mathrm{RE} = \left(\frac{\text{Total N uptake (kg N ha}^{-1}\text{) Treatment} - \text{Total N uptake (kg N ha}^{-1}\text{) Control}}{\text{Applied N (kg N ha}^{-1}\text{) Treatment}}\right)100 \quad [1]$$

Physiological efficiency (PE) of N was calculated (Isfan, 1990):

$$\text{PE (kg grain kg N uptake}^{-1}\text{)} = \frac{\text{Grain yield (kg ha}^{-1}\text{) Treatment} - \text{Grain yield (kg ha}^{-1}\text{) Control}}{\text{Total N uptake (kg N ha}^{-1}\text{) Treatment} - \text{Total N uptake (kg N ha}-1\text{) Control}} \quad [2]$$

Agronomic efficiency (AE) of added N was calculated (Novoa and Loomis, 1981):

$$\text{AE (kg grain kg N applied}^{-1}\text{)} = \frac{\text{Grain yield (kg ha}^{-1}\text{) Treatment} - \text{Grain yield (kg ha}^{-1}\text{) Control}}{\text{Applied N (kg N ha}^{-1}\text{)Treatment}} \quad [3]$$

Sequestration of added organic C, and proportion of C added through green manure, wheat residue, or rice residue stored in soil as organic C were calculated as follows:

$$\text{Organic C Sequestration} = \left(\frac{\text{SOC (Mg C ha}^{-1}\text{) Treatment} - \text{SOC (Mg C ha}^{-1}\text{) Control}}{\text{SOC (Mg C ha}^{-1}\text{) Control}}\right)100 \quad [4]$$

We accounted for the fact that rice residue was not added in 1993, that is, only 3 yr of rice residue additions compared with the 4 yr of wheat residue additions.

$$\text{C added in SOC} = \left(\frac{\text{SOC (Mg C ha}^{-1}\text{) Treatment} - \text{Organic C (Mg C ha}^{-1}\text{) Control}}{\text{Added C (Mg C ha}^{-1}\text{) Treatment}}\right)100 \quad [5]$$

Analysis of variance of grain yields from the second to forth years was done using a repeated measures analysis with "year" in the "sub-plot" (SAS, 1982). Data from 1993 were excluded from the analysis since 3 of the 10 treatments were not imposed that year. Duncan's Multiple Range Test was used to compare treatment means at the 0.05 level of probability.

RESULTS AND DISCUSSION

Grain Yields

Three-year means of rice grain yield are shown because the treatment × year interaction was not significant (Table 4). Rice grain yields were significantly greater in plots treated with 120 kg urea N ha^{-1} (WR_0 FN_{120} GM_0) compared with zero-N control (WR_0 FN_0 GM_0) plots (5.6 vs. 3.4 Mg ha^{-1}).

Rice grain yields were similar when all of the N was applied as urea N (WR_0 FN_{120} GM_0), when green manure N made up most of a 120 kg N ha^{-1} dose (WR_0 FN_{120} GM_0), and when 172 kg N ha^{-1} was applied in 40 Mg green manure ha^{-1} (WR_0 FNx GM_{40}) (Table 4). Aulakh et al. (2000) also observed that green manuring can result in the same rice yields as a 120 kg N ha^{-1} dose of urea. Forty megagrams green manure per hectare, however, is probably more biomass than most farmers can raise in the short period between the start of monsoon rain and transplanting of rice. This amount of green manure was excessive since straw yields increased compared with other treatments but not grain yield (data not shown).

Wheat residue incorporation, with or without urea N, had no significant effect on rice yields, unlike in other studies where yield reductions were reported (Verma and Bhagat, 1992; Beri et al., 1995). Rice straw yield, however, was depressed by wheat residue addition in the presence of 120 kg urea N ha^{-1} (data not shown). In the presence of incorporated wheat residue, providing some N as green manure (WR_6 FN_x GM_{20}) resulted in greater rice yields than without green manure (WR_6 FN_{120} GM_0). Adoption of green manuring in Asia has unfortunately been low. Ali and Narciso (1994) stated that farmers perceive a green manure crop as a lost economic opportunity compared with a food or cash crop.

Wheat grain yields did show significant year × treatment interaction, therefore the interaction means are shown (Table 4). Nitrogen fertilizer response in wheat yield was observed each year. The wheat residue and green manure integrated treatment to rice (WR_6 FN_x GM_{20}) had a significant residual effect on wheat yield in 1997, compared with WR_0 FN_{120} GM_0. Small residual benefits of green manure to the following crop have been reported in rice–rice (Becker et al., 1994) and in rice–wheat (Aulakh et al., 2000). Incorporating rice residue had no effect on wheat yields in the presence of urea N, but rice residue depressed wheat yields without urea N in 1997 (Table 4).

Several workers have reported in earlier studies from the Philippines (Ponnamperuma, 1984), India (Verma and Bhagat, 1992; Beri et al., 1995), China (Wen, 1989), and Korea (Oh, 1984) that incorporating wide C/N ratio residue just before transplanting rice or seeding wheat could immobilize N and reduce crop yields. Our finding that incorporating residue shortly after harvest did not negatively affect grain yields of N-fertilized rice or

Table 4. Grain yield as affected by incorporating crop residue with or without fertilizer N and green manure.

Treatment applied to: Rice	Treatment applied to: Wheat	Rice 1994-1996	Wheat 1995	Wheat 1996	Wheat 1997
		Mg ha^{-1}			
WR_0 FN_0 GM_0†	RR_0 FN_{120}‡	3.4 d§	4.9 bcdefg¶	4.5 j	4.8 efgh
WR_0 FN_{120} GM_0	RR_0 FN_{120}	5.6 bc	5.0 abcdef	4.5 hij	4.8 efghi
WR_0 FNx GM_{20}#	RR_0 FN_{120}	5.9 ab	5.1 abcde	4.9 defgh	5.1 abcde
WR_0 FN_0 GM_{40}	RR_0 FN_{120}	5.8 ab	5.2 ab	4.7 fghij	5.1 abcde
WR_6 FN_0 GM_0	RR_0 FN_{120}	3.2 d	4.9 cdefg	4.5 ij	4.9 bcdefg
WR_6 FN_{120} GM_0	RR_0 FN_{120}	5.5 c	5.2 abc	4.5 j	4.9 defgh
WR_6 FNx GM_{20}	RR_0 FN_{120}	5.9 a	5.2 a	4.6 ghij	5.2 abcd
WR_0 FN_0 GM_0	RR_0 FN_0	3.4 d	2.2 k	2.3 k	2.2 k
WR_0 FN_{120} GM_0	RR_6 FN_0	5.6 bc	2.1 kl	2.3 k	1.9 l
WR_0 FN_{120} GM_0	RR_6 FN_{120}	5.6 bc	5.2 abcd	4.8 efgh	5.0 abcde

Analysis of variance

Source of variation	Rice df	Rice F value	Wheat df	Wheat F value
Replicate	2	3.3ns	2	0.8ns††
Treatment	9	235**	9	4.7**
Replicate × treatment	18	1.7ns	18	2.1*
Year	2	19.6**	2	31.9*
Year × treatment	18	1.0ns	18	3.6**
Residual	40		40	
CV (treatment), %	4.5		5.4	
CV (year), %	3.4		3.7	

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† WR = wheat residue (subscript is Mg ha^{-1}); FN = fertilizer N (subscript is kg ha^{-1}, X is varied); GM = green manure (subscript is Mg ha^{-1}).
‡ RR = rice residue (subscript is Mg ha^{-1}); FN = fertilizer N (subscript is kg ha^{-1}).
§ Values within this column followed by same letter do not differ significantly ($P \geq 0.05$) by Duncan's Multiple Range Test.
¶ Values within the next three columns followed by same letter do not differ significantly ($P \geq 0.05$) by Duncan's Multiple Range Test.
\# Amount of 120 kg N ha^{-1} applied through 20 Mg green manure ha^{-1} (average 86 kg N ha^{-1}) and the balance through fertilizer N (average 34 kg N ha^{-1}).
†† ns, not significant.

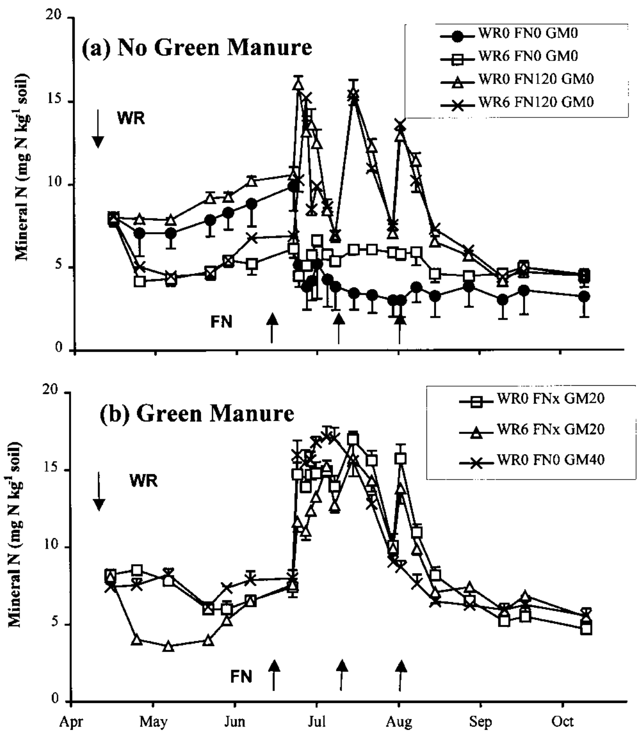

Fig. 1. Mineral N in soil (0 to 15 cm) during pre-rice fallow and rice growing season of 1995 as affected by incorporating wheat residue and fertilizer N (a) without green manure and (b) with green manure. Time of wheat residue (WR) incorporation. Time of green manure (GM) incorporation and flooding. Time of fertilizer N (FN) application. All treatments had no rice residue and 120 kg FN ha^{-1} in the wheat seasons. Bars represent SE, shown in only one direction for clarity.

wheat is a significant result. Triple-cropping, however, may not allow sufficient time between crops for residue decomposition. Hopefully our results in rice–wheat will encourage residue incorporation as a means of disposal instead of burning or removal.

Soil Mineral Nitrogen

The lack of yield depressions with straw incorporation right after harvest suggests rapid decomposition of residue. Soil mineral N data support this hypothesis. The amount of mineral N ($NO_3 + NH_4$) at the beginning of the fallow period of 1995 (16 Apr.) was 8 mg N kg^{-1} in all treatments (Fig. 1a and 1b). Soil mineral N concentrations in the unamended control (WR_0 FN_0 GM_0) increased slightly as a result of mineralization of soil organic N during the aerobic fallow. During the flooded rice season, mineral N declined and remained low in control plots (Fig. 1a). Wheat residue incorporation immobilized mineral N during the fallow period, evidenced by a sharp decline during the fallow period (Fig. 1a and b). Mineral N increased rapidly at the start of the flooded rice season in all treatments that received green manure and/or urea N, including the wheat residue plots. Green-manured plots showed longer periods of high mineral N levels (Fig. 1b) compared with plots with urea N or urea N and wheat residue only (Fig. 1a), which had a more up-and-down trend, apparently since N from urea was taken up by rice and then urea N was re-applied.

Rice residue incorporation also depressed levels of mineral N, initially, followed by sharp increases as urea N was applied at sowing of wheat (Fig. 2). In a trend more pronounced than in rice, mineral N in RR_6 (6 Mg

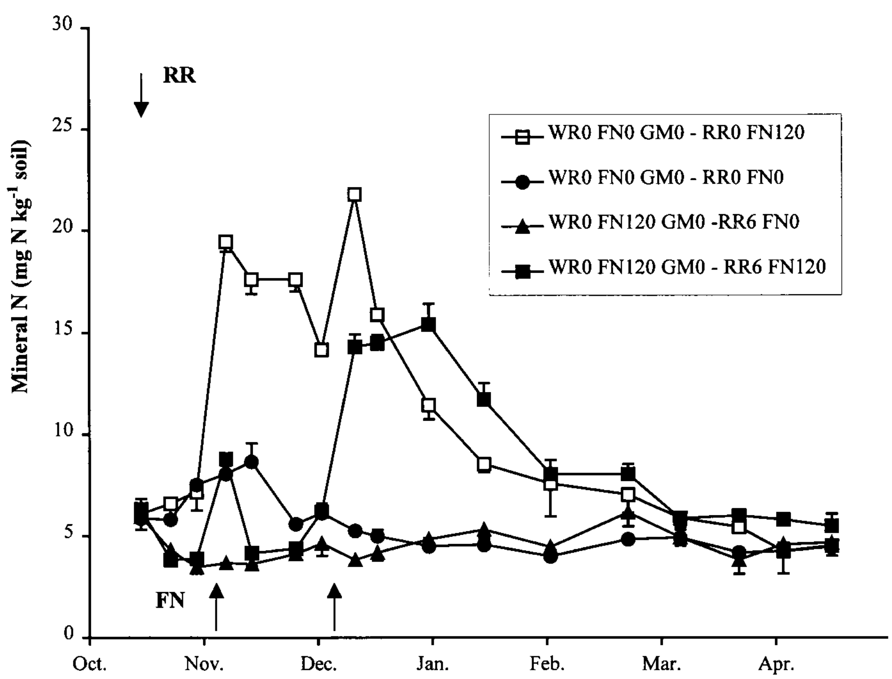

Fig. 2. Mineral N in soil (0 to 15 cm) during post-rice fallow and wheat growing season of 1996 to 1997 as affected by incorporating rice residue, fertilizer N, and residual green manure. Time of rice residue (RR) incorporation. Time of fertilizer N (FN) application. Bars represent SE, shown in only one direction for clarity.

rice residue ha^{-1}) FN_0 was much lower than RR_6 FN_{120} for more than 1 mo in the early wheat season, before the mineral N levels became similar. This trend indicates early immobilization of straw N and later season mineralization in the rice residue and urea-N treatment. Previous ^{15}N-labeled growth chamber and laboratory studies have shown that "recently immobilized N" during the initial 2- to 3-wk period in residue-amended soil starts re-mineralizing after 5 to 7 wk (Aulakh, 1988; Norman et al., 1990).

Fertilizer Nitrogen, Green Manure Nitrogen, and Residue Nitrogen Use Efficiency

Recovery efficiency (RE) and agronomic efficiency (AE) of added N (all sources) in rice was higher when most of the applied N was green manure N (WR_0 FN_x GM_{20}) compared with WR_0 FN_{120} GM_0 (Table 5). This was also true in the presence of wheat residue, although RE and AE were lower with wheat residue. In most field studies, contribution of residue N toward N recovery by the crop has been ignored, assuming that crop residue N is not mineralized during one crop growth period. Norman et al. (1990) showed that rice recovered 3 to 37% of added crop residue N.

Green manure N was probably taken up by rice more efficiently than urea N due to the slow release nature of mineralization and to lower gaseous N losses. Recovery efficiency of 60% obtained in WR_6 FN_x GM_{20} compared with 47% in WR_6 FN_{120} GM_0 suggests that the mineralization of residue N was accelerated by incorporated green manure, and/or that some of the urea N in WR_6 FN_{120} GM_0 was immobilized by microbes involved in decomposition of the wheat residue. Physiological efficiency was reduced with 40 Mg green manure ha^{-1} compared with all of the other treatments, providing evidence that this rate of green manure was excessive and that luxury uptake of N occurred (data not shown).

Agronomic efficiency of added N by rice was improved by incorporating 20 Mg green manure ha^{-1}, but not with 40 Mg green manure ha^{-1}. Improved AE with green manure reflected the greater RE compared with urea N alone or urea N with wheat residue (Table 5).

Recovery efficiency of N by wheat was greater in 1997 when N was applied to the previous rice crop as urea and green manure rather than as urea alone (Table 5). Forty megagrams fresh green manure per hectare resulted in higher RE in wheat in 1996 and 1997 than when 120 kg urea N ha^{-1} was applied to rice without green manure.

Similar to rice, residue incorporation reduced RE in wheat (Table 5). Bijay-Singh et al. (2001), using ^{15}N dilution, also reported lower RE in wheat following rice residue incorporation, compared with rice residue

Table 5. Recovery and agronomic efficiencies of fertilizer N, green manure N and straw N additions in rice and wheat.

Treatment applied to		Rice		Wheat			
Rice	Wheat	1994–1996 RE‡	1994–1996 AE‡	1995 RE	1996 RE	1997 RE	1995–1997 AE
		%	kg grain kg N applied^{-1}	%	%	%	kg grain kg N applied^{-1}
WR_0 FN_0 GM_0§	RR_0 FN_{120}¶	–	–	5.8 cd‡‡	42 fg	54 d	21 b#
WR_0 FN_{120} GM_0	RR_0 FN_{120}	61 b#	19 b#	56 d	46 ef	56 d	21 ab
WR_0 FNx GM_{20}††	RR_0 FN_{120}	71 a	21 a	59 cd	52 de	66 ab	23 a
WR_0 FN_0 GM_{40}	RR_0 FN_{120}	56 c	14 c	54 d	55 d	72 a	23 a
WR_6 FN_0 GM_0	RR_0 FN_{120}	–§§	–§§	55 d	42 fg	58 cd	21 ab
WR_6 FN_{120} GM_0	RR_0 FN_{120}	47 d	14 c	64 bc	42 fg	58 cd	22 ab
WR_6 FNx GM_{20}	RR_0 FN_{120}	60 bc	17 b	68 ab	52 de	70 ab	23 a
WR_0 FN_0 GM_0	RR_0 FN_0	–	–	–	–	–	–
WR_0 FN_{120} GM_0	RR_6 FN_0	61 b	19 b	–§§	–§§	–§§	–§§
WR_0 FN_{120} GM_0	RR_6 FN_{120}	62 b	19 b	44 fg	38 g	47 ef	17 c

Analysis of variance

Source of variation	Rice df	Rice RE F value	Rice AE F value	Wheat df	Wheat RE F value	Wheat AE F value
Replicate	2	1.2 ns	2.1 ns	2	4.5*	1.9 ns¶¶
Treatment	6	25.4**	1.95**	7	37.0**	9.6**
Replicate × treatment	12	1.0 ns	1.5 ns	14	0.7 ns	1.9 ns
Year	2	21.3**	12.7**	2	87.7**	69.7**
Year × treatment	12	1.7 ns	0.7 ns	14	4.1**	1.1 ns
Residual	28			32		
CV (treatment), %		7.3	9.7		5.8	8.6
CV (year), %		7.2	8.0		6.9	6.5

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Recovery efficiency of added fertilizer N, green manure N, and residue N, Eq [1] in text.
‡ Agronomic efficiency of added fertilizer N, green manure N, and residue N, Eq [3] in text.
§ WR = wheat residue (subscript is Mg ha^{-1}); FN = fertilizer N (subscript is kg ha^{-1}, X is varied); GM = green manure (subscript is Mg ha^{-1}).
¶ RR = rice residue (subscript is Mg ha^{-1}).
\# Values within this column followed by same letter do not differ significantly ($P \geq 0.05$) by Duncan's Multiple Range Test.
†† 120 kg N ha^{-1} applied through 20 Mg green manure ha^{-1} (average 86 kg Nha^{-1}) and the balance through fertilizer N (average 34 kg N ha^{-1}).
‡‡ Values within the next three columns followed by same letter do not differ significantly ($P \geq 0.05$) by Duncan's Multiple Range Test.
§§ RE and AE could not be calculated as grain yields and N uptake with 6 Mg RR and WR ha^{-1} were less than the control plots.
¶¶ ns means not significant.

Table 6. Soil bulk density, and concentration and amount of organic C† in surface soil (0–15 cm) in 1997 as affected by crop residue management without or with fertilizer N and green manure in a rice–wheat rotation.

Treatment applied to			Soil organic C			
Rice	Wheat	Soil bulk density	Concentration	Amount	Sequestration‡	Percentage of added residue C sequestered§
		Mg m^{-3}	g kg^{-1} soil	Mg ha^{-1}	%	%
WR_0 FN_0 GM_0¶	RR_0 FN_{120}#	1.60 a††	3.74 e	9.0 de	3.0 ed	–
WR_0 FN_{120} GM_0	RR_0 FN_{120}	1.60 a	3.71 e	8.9 de	2.2 ed	–
WR_0 FNx GM_{20}‡‡	RR_0 FN_{120}	1.54 b	4.05 d	9.4 cd	7.2 cd	10 bc
WR_0 FN_0 GM_{40}	RR_0 FN_{120}	1.50 b	4.23 cd	9.5 bc	9.4 bc	6 c
WR_6 FN_0 GM_0	RR_0 FN_{120}	1.54 b	4.69 b	10.8 a	24 a	21 a
WR_6 FN_{120} GM_0	RR_0 FN_{120}	1.54 b	4.62 b	10.7 a	22 a	20 a
WR_6 FNx GM_{20}	RR_0 FN_{120}	1.50 b	4.92 a	11.1 a	27 a	15 a
WR_0 FN_0 GM_0	RR_0 FN_0	1.60 a	3.63 e	8.7 e	0 e	–
WR_0 FN_{120} GM_0	RR_6 RN_0	1.54 b	4.25 cd	9.8 bc	13 bc	15 ab
WR_0 FN_{120} GM_0	RR_6 FN_{120}	1.545 b	4.33 c	10.0 b	14 b	17 ab
CV, %		1.5	3.0	3.1	28.2	26.5

† Bulk density and soil organic C concentration at the beginning of experiment was 1.60 Mg m^{-3}, and 3.8 g C kg^{-1}, respectively.
‡ Sequestration of soil organic C, Eq [4] in text.
§ Percentage of added residue C sequestered, Eq [5] in text.
¶ WR = wheat residue (subscript is Mg ha^{-1}); FN = fertilizer N (subscript is kg ha^{-1}, X is varied); GM = green manure (subscript is Mg ha^{-1}).
# RR = rice residue (subscript is Mg ha^{-1}); FN = fertilizer N (subscript is kg ha^{-1}).
†† Values within each column followed by same letter do not differ significantly ($P \geq 0.05$) by Duncan's Multiple Range Test.
‡‡ Amount of 120 kg N ha^{-1} applied through 20 Mg green manure ha^{-1} and the balance through fertilizer N.

removal in the Indian Punjab, with no effect on grain yields. Straw incorporation in that study also did affect loss of added ^{15}N from the plant–soil system, indicating the importance of immobilization and re-mineralization of added urea N in the presence of incorporated residue.

Agronomic efficiency of added N by wheat was not affected by any of the green manure treatments before rice. Rice residue reduced AE in wheat fertilized with 120 kg urea N ha^{-1}, a result of the depressed recovery of urea N.

Carbon Sequestration

Bulk density was significantly reduced with crop residue and/or green manure amendments compared with treatments with urea N only or untreated controls (Table 6). Green manuring enhanced SOC concentrations at both rates when no wheat residue was added (Table 6). The effect of wheat residue on SOC was much larger than that of green manure and masked effects of the latter. Among the green manure treatments without added residue, only the 40 Mg green manure ha^{-1} rate resulted in significant C sequestration on a mass area basis. Soil organic C concentrations remained unchanged from the start of the experiment in plots that did not receive residue or green manure. This was not expected as a decline in SOC in a rice–wheat system when residue was removed on a silty clay loam soil was reported by Verma and Bhagat (1992). Residue removal was the long-term practice at this site before 1993. Therefore, an equilibrium may have been established between soil C fractions and fresh residue-C, resulting in low and stable SOC concentrations.

Incorporating wheat residue resulted in more C sequestered into SOM than with rice residue (Table 6). Although comparing the total amounts favors wheat residue that was added for four seasons vs. three seasons of rice residue, as a percentage of added C, wheat residue still resulted in greater C sequestration (Table 6). This was due to the wider C/N ratio, which Aulakh et al. (1991) reported was negatively correlated to C mineralization and positively related to immobilization. Additionally, wheat residue was applied before the flooded rice crop, which Bronson et al. (1998) reported in a review of the literature results in greater SOC build-up than residue applied to an upland crop. The low C/N ratio of green manure resulted in lower amounts of C sequestration of green manure C than with rice residue or wheat residue due to more rapid mineralization, that is, CO_2 loss of green manure C. Improvement in soil physical conditions such as decreased bulk density, improved water infiltration rate, improved soil structure, and increased SOC play a more important role in the wheat phase of the rice–wheat cropping system than the rice phase. This is because the soil structure is destroyed during the puddling process in rice and because wheat is a deep-rooted crop and rice is not (Bronson et al., 1998).

CONCLUSIONS

The results of our field study in a subtropical, semiarid soil indicated that wide C/N ratio rice and wheat residue can be incorporated shortly after crop harvest without affecting yields of the following crop. Recovery efficiency and AE of N, however, were reduced in both rice and wheat with straw incorporation. Incorporating green manure crops and/or crop residue in addition to urea-N applications in a rice–wheat system can result in high grain yields and have the long-term benefit of C sequestration. These findings will hopefully discourage the common practice of burning rice and wheat straw in northwest India.

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