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Effect of Fertilizer and Mungbean Residue Management on Total Productivity, Soil Fertility and N-use Efficiency of Intensified Rice-wheat Systems*

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Abstract: Rice-wheat (RW) sequences are major food production systems over approximately 13 Mha in the Indo-Gangetic plain (IGP) of south Asia. A major increase in productivity and maintaining its sustainability is required to provide food security for an expanding population. Field experiments to study intensified RW systems were conducted in Bangladesh at Joydebpur, Nashipur and Ishwordi differing in soils and climate by adding a third pre-rice crop, either mungbean or maize. Experiments started with wheat in 1995 at the former two sites and in 1999 at the third site and ended with rice in 2001 at all sites. System productivity and sustainability were evaluated under two fertilizer regimes (soil-test based and farmers' rates) and for mungbean, the effect of residue retention. Yields of all crops were often adversely affected by heavy rainfall during grain filling. Mungbean residue yields were smallest at Ishwordi (range: 1.6 to 2.4 t ha^{-1}) with silty clay soils and a hotter climate and greatest at Nashipur (range: 2.3 to 5.1 t ha^{-1}) with sandy loam soils and a cooler climate. Total System Productivity (TSP) across treatments ranged from 7.1 to 17.7 t ha^{-1}, being greatest at Nashipur (8.8 to 17.7 t ha^{-1}), smallest at Joydebpur (7.1 to 13.8 t ha^{-1}) with clayey sols and a hotter climate, greatest following maize (9.0 to 17.7 t ha^{-1}) and smallest with the removal of residues (7.1 to 12.2 t ha^{-1}). TSP increased over time at Nashipur, declined at Joydebpur and remained stable at Ishwordi. The content of organic C and total N (SON) in the surface soil, measured after rice harvest in 2000, decreased at all sites, but residue retention maintained SON at Ishwordi only. Phosphorus, potassium and sulphur all increased but micronutrients decreased in sandy loam and clayey soils of Nashipur and Joydebpur. Mean agronomic efficiency of applied N ranged from 4.6 to 9.3 kg kg^{-1} across sites and treatments and was greatest at Nashipur and smallest at Joydebpur. Results reveal that while farmers may improve their diet with mungbean grain, the residual effect of the crop, even with residue retention, is not significant in short-run and that TSP is greater by inclusion of maize rather than mungbean in the RW system. Longer-term experiments are required to establish the potential benefits of legumes in increasing TSP, soil fertility and system-level N-use requirement and efficiency of intensified RW systems of the IGP.

Key words: Rice-wheat-mungbean, rice-wheat-maize, residue and fertilizer management, total system productivity, soil fertility

Introduction

Rice-wheat (RW) sequences are practiced on about 13 M ha in the Indo-Gangetic Plains (IGP) of south Asia (Timsina and Connor, 2001) and on about 3.4 M ha in China (Dawe *et al.*, 2004).

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Increasing population pressure is demanding for greater Total System Productivity (TSP) and sustainability. Grain for human consumption and crop residues for both fuel and animal fodder are required, suggesting the value of including a third crop in already intensive and diverse RW systems. Intensification must inevitably increase nutrient extraction from the soil, which may be minimized by including a N-fixing crop in the system, especially if residues with root nodules are retained. Prasad *et al.* (1999) and Sharma and Prasad (1999) have reported yield benefits from legume crops ranging from 16 to 115% to the immediate rice crop plus a residual effect of 4 to 63% to the subsequent wheat crop.

In the IGP and particularly in Bangladesh, mungbean and maize are suitable options for the short, but problematic, growing period of 70 to 100 days available after wheat and before rice. Rains during the early part of the season promote disease while late rains may seriously damage the harvest (Rahman, 1991). Both crops can establish quickly and accumulate biomass and yield potential but are susceptible to waterlogging, especially N-fixation processes in mungbean. Maize is potentially a useful crop for animal feed, especially for expanding poultry industry in the region.

An important issue in the RW systems of the IGP is the decline in partial factor productivity (i.e., the ratio of output value to a specific input, such as N) (Yadav, 1999), decline in Soil Organic Nitrogen (SON) (Yadav, 1999) and decline in Soil Organic Carbon (SOC) and nutrient-use efficiencies (Yadav, 1998; Timsina *et al.*, 2001). Fertilizers will inevitably be required to increase the TSP and legumes might have potential to revert the decline of SOC and SON and increase the nutrient-use efficiencies. Sharma and Prasad (1999) and Aulakh *et al.* (2000) reported an interactive effect of fertilizers and mungbean residues on TSP of RW systems in the semi-arid areas of the IGP, but there are no such studies for the tropical and sub-tropical areas with heavy rainfall and high temperature such as that exist in Bangladesh. Though local farmers in Bangladesh grow maize or mungbean as pre-rice crops, their widespread practice has been limited due to lack of improved management practices and other scientific information.

The experiments reported here were carried out at three sites over periods of 4 to 6 years in Bangladesh to measure the medium-term performance of TSP and evaluate trends in soil fertility and agronomic N-use efficiency across sites. Agronomic results for component crops for each site are presented in Quayyum *et al.* (2002a, b) while the plant nutrient concentrations and uptake and soil nutrient balances are presented in Panaullah *et al.* (2006), Saleque *et al.* (2006) and Timsina *et al.* (2006). Yields of individual crops are stated only briefly here because the focus of this paper is on TSP rather than on the productivity of individual crops.

Materials and Methods

Experimental Sites

Three experimental sites were established at the Bangladesh Agricultural Research Institute (BARI) experimental farms at Head Quarters at Joydebpur (24°N, 90° 3' E, 8 m elev.), the Wheat Research Center at Nashipur (25°48' N, 88°4' E, 30 m elev.) and the Regional Agricultural Research Station at Ishwordi (24° N, 89°E, 45 m elev.). Joydebpur has a tropical climate and is within Agro-ecological Zone (AEZ) 9 (Old Brahmaputra Floodplain), on flood-free, flat, medium highland, with fine-textured clayey and low permeability soil. Nashipur and Ishwordi both have a sub-tropical climate; the former is in AEZ 1 (Old Himalayan Piedmont Plains), on flood-free high land, with coarse-textured (sandy loam) and high permeability soil, while the latter is in AEZ 11 (High Ganges River Floodplain), on flood-free high land, with fine-textured (silty clay loam) and medium permeability soil (BARC, 1997).

Experimental Design and Treatments

At each site, the experiments compared the inclusion of either maize or mungbean as an additional pre-rice crop. The sequences commenced with wheat, in 1995 at Joydebpur and Nashipur and in 1997 at Ishwordi and ended with rice in 2001 at all sites. There were two main treatments-pre-rice treatment (3 levels) and fertilizer treatment (2 levels)-in a randomized complete block design with four replicates. The plots were 16.5×10 m and were separated by earthen banks lined with plastic to a depth of about 20 cm to avoid nutrient transfer between adjacent plots by lateral seepage. Pre-rice treatments included mungbean with or without residue removal and maize with residues removed. Mungbean residues were removed by uprooting the plants, thereby removing much root and nodule materials, but in residue retention, above-ground biomass as well as roots and nodules were incorporated. In maize, above ground residues were removed, because though maize residues could increase SOC and SON, they are needed for animal feed and for use as fuel in Bangladesh. Fertilizer treatments included Soil Test-based (STB) - recommended dose to achieve high yield and Farmers' Practice (FP) - the typical regime used by farmers in each location. Soil-test based fertilizer for all years was based on the analysis done prior to start of experiments in 1995 for Joydebpur and Nashipur and in 1997 for Ishwordi. Farmers' practice based fertilizer was determined based on interactions with representative local farmers in each location prior to start of experiments. The results thus will have limitations because farmers' practices as well as the soil nutrient status are dynamic in nature and so the soil-test based fertilizer recommendations.

Crop Management

All rice and wheat residues were removed prior to land preparation for the succeeding crop. Rice was transplanted by hand into well-pulverised puddled soil, but wheat, mungbean and maize were sown into cultivated soil. Planting and harvest dates of crops across years slightly varied. Wheat (cv. Kanchan), mungbean (cv. Kanti), maize (cv. Barnali) and rice (cv. BR32) were planted with 20×5 cm, 25×10 cm, 75×25 cm and 25×15 cm row spacing, respectively. Wheat was planted in November/December, maize/mungbean in April/May and rice in July/August and were, respectively harvested in March/April, June/July and October/November. For all crops, fertilizer other than N was broadcast and incorporated at sowing. For rice, N was broadcast in three splits at 15, 30 and 45 days after transplanting, while for wheat, two-thirds of N was broadcast and incorporated at sowing and the remainder top dressed at Crown Root Initiation (CRI). For maize, one-third N was applied at sowing and then a third more at each of 21 and 42 days after sowing (DAS). Fertilizer rates for each site and crop are given in Table 1.

At each site, wheat received three irrigations, each of approximately 100 mm, at CRI, Maximum Tillering (MT) and Grain Filling (GF). For rice at Nashipur, 5 irrigations, each of approximately 150 mm, were applied following rainless periods of 5 to 7 days duration. At the other two sites rice was irrigated twice after the grain-filling stage in 1997, but in other years it was not irrigated. Mungbean and maize received only a small irrigation (about 50 mm) for germination, while in dry years a supplementary irrigation was applied during the early vegetative stage.

Grain Yield and Total System Productivity

Grain yields of all crops were determined from a 10 m^2 area in each plot. Grain yields of rice and maize were adjusted to 14% moisture content and those of wheat and mungbean to 12%. Mungbean pods were picked twice, at 60 and 70 DAS, respectively. Mungbean formed nodules in their roots but the nodules were neither counted nor their biomass recorded. Mungbean residue yield was determined as oven-dry weight of above- and below-ground parts.

Table 1: Fertilizer treatments (kg ha^{-1}) by individual crops at three sites

	Fertilizer treatment									
	STB[*]					FP[†]				
Crop	N	P	K	S	B	Zn	N	P	K	S
Joydebpur										
Mungbean	20	20	20	0	0	0	0	0	0	0
Maize	120	26	33	20	0	0	60	13	17	0
Rice	90	26	33	20	0	0	60	9	17	10
Wheat	120	22	66	20	2	0	60	11	25	0
Nashipur										
Mungbean	20	20	20	0	0	0	0	0	0	0
Maize	120	18	33	20	0	0	60	9	17	0
Rice	120	18	50	10	0	0	60	13	17	0
Wheat	140	15	50	20	2	0	60	11	25	0
Ishwordi										
Mungbean	15	15	0	10	0	0	0	0	0	0
Maize	80	30	0	20	0	0	80	26	33	0
Rice	87	26	0	12	0	0.5	80	26	17	0
Wheat	120	26	33	25	1	4	60	18	25	0

[*]STB and FP are complete fertilizer treatments based on recommendations from soil tests and farmers' practice, respectively, [†]Boron (B) and Zinc (Zn) applications is not a common practice among farmers

Total System Productivity (TSP), expressed as total annual productivity of equivalent yields, was calculated following Tanaka (1983). Harvested organs of crops vary widely in chemical composition. The percentages of proteins, lipids and carbohydrates in rice grain are 8.8, 2.7 and 87%, respectively, in wheat grain are 12.1, 2.3 and 83.7%, in maize grain are 9.5, 5.3 and 83.7% and in fababeans are 24.1, 2.6 and 69%, respectively. The conversion efficiencies (the process of conversion from primary photosynthetic products, such as glucose, to biosynthesis of harvested organs or grains) for proteins, lipids and starch are 0.38, 0.31, 0.84, respectively. The glucose equivalent yields for the various crops were thus calculated according to their composition (proteins, lipids and carbohydrates) of harvested organs (values for fababeans used for mungbean) and the conversion efficiencies. Using the given composition and the conversion efficiency, for example, the equivalent yield for rice is 1.35 (0.088/0.38+0.027/0.31+0.87/0.84). Finally, TSP, based on three sequence years, for each treatment was calculated as the average total annual productivity (or the average annual total of economic yield of the individual crops) based on the equivalent yields (1.35, 1.39, 1.42 and 1.54, respectively, for rice, wheat, maize and mungbean) as follows:

TSP (rice-wheat-mungbean/maize) = (rice grain yield*1.35)+ (wheat grain yield*1.39)+(mungbean grain yield*1.54) or (maize grain yield*1.42)

Plant and Soil Analyses

Soil samples ('initial", 0 to 15 cm depth) were collected before the experiments were established and again ("final") after rice harvest in 2000 and analysed for major nutrients. Grain and residues were analyzed for N concentrations at harvest of each crop in each year and were used in calculations of N-use efficiency. N concentrations in irrigation and rainwater were also determined.

System-level N-use Efficiency

Agronomic efficiency (AE, grain yield/kg N applied, kg kg^{-1}) of TSP was calculated for each site in each year following Novoa and Loomis (1981). AE reflects the recovery and utility of fertilizer N to crop productivity under the conditions of other nutrients and existing N.

Weather Data

Maximum and minimum temperatures, rainfall and solar radiation were recorded daily at each site over the experimental period.

Statistical Analysis

Statistical analysis of grain yields of all crops, residue yield of mungbean, TSP and agronomic efficiency were performed using IRRISTAT (IRRI, 2000) using combined analyses over sites and years. In the analyses of variance (ANOVA), the degrees of freedom (d.f.) were partitioned as: Year (Y), Site (S), Pre-rice (P), Fertilizer (F), Y*P, Y*F, Y*P*F, S*P, S*F, S*P*F, Y*S*P, Y*S*F, Y*S*P*F. Such partitioning is necessary and useful for the analysis of long-term experiments over sites, seasons, or years (Gomez and Gomez, 1984).

Results

Weather Description

The climate is essentially similar at all sites, hot wet summers (April to October) and mild dry winters (November to March). The important issues from the perspective of cropping practices and management relate to site-to-site and year-to-year variability in rainfall and, to a lesser extent, temperature and solar radiation. The overall climatic pattern is described here by the data for Nashipur presented in Fig. 1. The annual rainfall at this site (long term mean = 1970 mm) was 1384, 2448, 2815 and 1787 mm in the four years. Comparable long-term means at Joydebpur and Ishwordi are 2069 and 1585 mm, respectively. At all sites, most rain fell during June to September, with a peak in July when rainfall across sites in that month ranged from 560 to 900 mm. Despite the large differences in annual rainfall the duration of the rainless period was relatively constant from year to year across sites. Temperatures over the years reflect that Nashipur has relatively lower maximum and minimum temperatures during winter, with also the onset of winter starting earlier than at the other two sites. Solar radiation is low considering the latitudinal position of the sites, being depleted by cloud cover in summer and by persistent haze in winter.

Changes in Soil Fertility

The data in Table 2 compare, for each site, the range of nutrient concentrations found in the surface soil (0 to 15 cm) in the three treatments at the end of the experimental period with the initial

Table 2: Initial and final chemical characteristics of surface soil (0-15 cm depth) at the three experimental sites

	Joydebpur		Nashipur		Ishwordi*
Characteristics	Initial	Final[†]	Initial	Final	Initial
Texture	Clayey	-	Sandy loam	-	Silty-clay loam
pH (1:2.5 in water)	6.0	-	5.5	-	7.3
Organic C (g kg^{-1})	10.8	6.6-9.3	7.1	3.5-7.2	10.1
Total N (g kg^{-1})	0.8	0.72-0.90	0.7	0.52-0.69	1.0
Exch. K (cmol kg^{-1})	0.13	0.11-0.18	0.07	0.08-0.11	0.44
Avail. P (mg kg^{-1})	9	5.3-12	19	9.6-36.1	5
Avail. S (mg kg^{-1})	9	9.3-20.7	12	15.8-33.9	10
Avail. Zn (mg kg^{-1})	3.4	0.8-2.2	1.7	0.53-0.94	2
Avail. Fe (mg kg^{-1})	145	58-84	71	80-167	2
Avail. Cu (mg kg^{-1})	3.2	2.2-3.0	1.6	0.9-1.7	0.5
Avail. Mn (mg kg^{-1})	-	18.8-34.1	-	14.4-44.3	-

*only initial analyses available, except final analysis for total N (range: 0.63-1.0 g kg^{-1})

[†] Values for final analyses (measure after rice harvest in 2000) represent ranges for various treatments

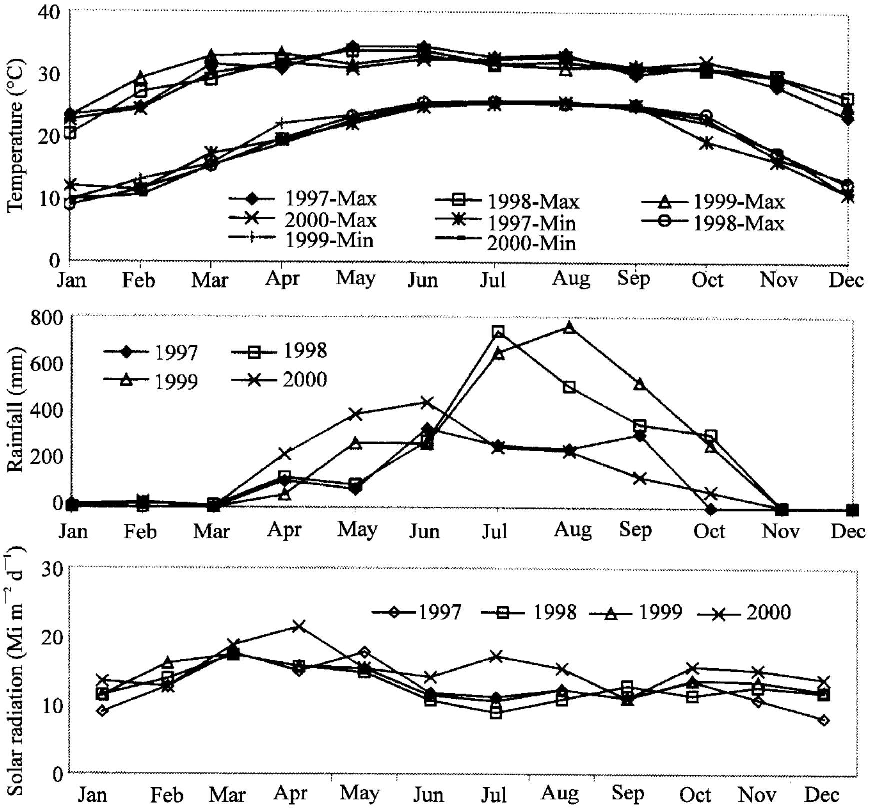

Fig. 1: Mean monthly maximum and minimum temperatures, cumulative monthly rainfall and mean daily solar radiation during 1997-2000, Nashipur

values recorded across the site at the start of the experiment. After five years of cropping at Nashipur (sandy loam) and Joydebpur (clayey), organic C decreased substantially at those sites, but total N decreased to a greater extent at Nashipur than at Joydebpur. The exchangeable K and available P and S increased while available Zn, Fe and Cu decreased at both sites. At Ishwordi (silty clay loam), the total N in the mungbean residue retained treatment remained unchanged but in other treatments it decreased from 1 to 0.63-0.86 g kg^{-1} (Timsina *et al.*, 2006).

Residue Yield of Mungbean

Mungbean dry residue yield ranged from 1.6 to 5.1 t ha^{-1} (Table 3) and in individual years there were differences between sites. Year x site interaction was also significant ($p<0.05$; LSD = 0.13 t ha^{-1}). Residue yield was smallest at Ishwordi (1.6 to 2.4 t ha^{-1}) and greatest at Nashipur (2.3 to 5.1 t ha^{-1}) and responded significantly ($p<0.05$; LSD = 0.13 t ha^{-1}) to fertilizer. At Joydebpur and Nashipur, there were no significant trends in residue yield of mungbean over time, but at Ishwordi it tended to increase in all treatments.

Table 3: Grain yield of maize and mungbean and residue yield of mungbean (t ha^{-1}) as influenced by residue retention and fertilizer during 1998 to 2001 at three sites in Bangladesh*

		Joydebpur				Nashipur				Ishwordi			
Pre rice	Fertilizer	1998	1999	2000	2001	1998	1999	2000	2001	1998	1999	2000	2001
Mungbean grain yield													
Residue removed	STB*	0.3	0.6	0.2	0.5	0.4	0.5	0.4	0.8	0.5	0.7	1.0	1.6
	FP	0.3	0.5	0.2	0.5	0.4	0.4	0.4	0.8	0.5	0.6	1.0	1.4
Residue retained	STB	0.5	0.5	0.2	0.6	0.4	0.5	0.5	0.8	0.4	0.6	0.9	1.0
	FP	0.3	0.5	0.2	0.4	0.3	0.5	0.4	0.6	0.4	0.6	0.8	1.3
Mean		0.4	0.5	0.2	0.5	0.4	0.5	0.4	0.6	0.4	0.6	0.9	1.3
Mungbean residue yield[†]													
Residue removed	STB*	3.4		2.3	3.8	3.7		4.3	2.9	1.7		1.6	1.9
	FP	3.0		2.4	3.0	2.9		4.1	2.8	1.8		1.6	1.6
Residue retained	STB	3.8		2.6	3.6	3.4		5.1	2.9	2.2		1.7	2.0
	FP	3.2		2.2	2.1	2.3		4.9	2.8	2.4		1.6	1.6
Mean		3.4		2.4	3.1	3.1		4.6	2.9	2.0		1.6	1.8
Maize yield													
Maize	STB	3.1	2.5	1.9	2.7	2.8	2.7	3.9	2.9	2.9	3.5	3.9	5.1
Maize	FP	2.4	1.9	1.5	1.8	1.6	1.9	2.8	1.8	2.9	3.3	2.6	4.3

*LSD (mungbean residue), t ha^{-1} ($p<0.05$): Year*site 0.13; Year*site*pre-rice 0.16

LSD (mungbean grain), t ha^{-1} ($p<0.05$): Year*site 0.03; Year*site*pre-rice 0.03

LSD (maize grain), t ha^{-1} ($p<0.05$): Year*site 0.13; Year*site*fertilizer 0.20

[*] STB and FP are fertilizer levels based on soil-test and farmers' practices

[†] samples were damaged and hence not included for analyses for 1999

Table 4: Grain yield (t ha^{-1}) of rice as influenced by pre-rice crop and fertilizer during 1997 to 2000 in Bangladesh

		Joydebpur					Nashipur					Ishwordi			
Pre rice	Fertilizer	1997	1998	1999	2000	Mean	1997	1998	1999	2000	Mean	1998	1999	2000	Mean
Mungbean residue removed	STB	4.6	4.1	4.4	3.0	4.0	3.7	4.0	3.8	5.2	4.2	4.5	3.6	4.2	4.1
	FP	4.1	4.0	3.9	3.1	3.8	3.4	4.0	3.9	5.4	4.2	4.3	3.3	3.7	3.9
	Mean	4.0	3.5	3.8	2.9	3.5	3.2	4.0	3.5	4.3	3.8	3.7	3.1	2.7	3.3
Mungbean residue retained	STB	4.5	4.0	3.9	3.2	3.9	2.9	3.7	3.8	5.9	4.1	4.5	3.8	4.3	
	FP	4.3	4.0	3.8	3.3	3.8	2.8	3.8	4.1	5.6	4.1	4.2	3.3	3.7	3.8
	Mean	4.0	3.5	3.6	3.0	3.5	2.7	3.8	3.8	4.7	3.7	3.7	3.2	2.7	3.3
Maize cropping	STB	4.6	3.8	4.1	3.0	3.9	3.0	4.2	4.0	5.8	4.3	4.5	3.5	4.2	4.1
	FP	4.3	3.8	3.8	3.1	3.7	3.0	4.0	3.9	4.9	4.0	4.3	3.3	3.6	3.8
	Mean	4.0	3.4	3.6	3.0	3.5	2.4	4.1	3.6	4.4	3.6	3.6	3.1	2.7	3.3

LSD ($p<0.05$) Year*site 0.12; Year*site*pre-rice 0.17; Year*site*pre-rice*fertilizer 0.33

STB and FP are fertilizer nutrients supplied according to soil-test based recommendations and farmers' practices

Grain Yield of Component Crops

Mungbean grain yield across sites, years and treatments ranged from 0.2 to 1.6 t ha^{-1}, with smallest at Joydebpur (0.2-0.6 t ha^{-1}) and greatest at Ishwordi (0.3-1.6 t ha^{-1}) and significant year x site interaction ($p<0.05$; LSD = 0.23 t ha^{-1}) (Table 3). Grain yield at each site and in each year also responded significantly ($p<0.05$; LSD = 0.03 t ha^{-1}) to fertilizer, however those increases were generally small (around 0.05-0.1 t ha^{-1}). At Joydebpur and Nashipur, there were no significant trends in grain yield over time, but at Ishwordi it tended to increase in all treatments.

Maize grain yields across sites, years and treatments ranged from 1.5 to 5.1 t ha^{-1} with greatest at Ishwordi (1.3 to 5.1 t ha^{-1}) and smallest at Joydebpur (0.2 to 3.1 t ha^{-1}) (Table 3). There were large and significant ($p<0.05$) yield responses to STB fertilizer at all sites, with significant year and site interaction means ($p<0.05$; LSD = 0.13). Mean yields at Joydebpur decreased from 1997 to 2000, while at Nashipur and Ishwordi, they increased over the years.

Mean rice yields were significantly different between various treatments and sites ($p<0.05$; LSD = 0.33 t ha^{-1}), ranging from 2.1 to 3.4 t ha^{-1} at Ishwordi, 1.3 to 1.9 t ha^{-1} at Joydebpur and 1.4 to 1.5 t ha^{-1} at Nashipur (Table 4). Yields in the individual treatments were generally greater at Nashipur (1.5-5.9 t ha^{-1}) and almost similar at the other two sites (1.3-4.6 t ha^{-}). Surprisingly, there was almost no significant response to STB fertilizer and a trend for greater yields with STB was observed only at Ishwordi. Interaction means for year and site, for pre-rice crop management, fertilizer and for year, site and pre-rice crop management were also significant (LSD = 0.12; 0.11 and 0.17 t ha^{-1}, respectively).

Wheat yields were significantly different across sites and treatments ($p<0.05$; LSD = 0.25 t ha^{-1}), ranging from 1.8 to 4.2 t ha^{-1}, with almost always a significant response to STB fertilizer at all sites (Table 5). Wheat yields following removal of mungbean residues ranged from 0.6 to 4.0 t ha^{-1}, those following their retention ranged from 0.7 to 4.2 and after maize from 0.6 to 4.2 t ha^{-1}. Interaction means for year and site, pre-rice crop management and fertilizer for grain yield were significant ($p = 0.05$; LSD = 0.12, 0.11 and 0.17 t ha^{-1}, respectively).

Total System Productivity

Mean TSP across treatments and years was significantly different, ranging from 7.1 to 13.8 t ha^{-1} at Joydebpur, 8.8 to 17.7 t ha^{-1} at Nashipur and 9.3 to 14.6 t ha^{-1} at Ishwordi ($p<0.05$; LSD = 0.62 t ha^{-1}) (Table 6). With removal of mungbean residues, TSP ranged from 7.1 to 12.2 t ha^{-1} across sites, while with its retention it ranged from 7.4 to 13.5 t ha^{-1} and following maize from 9.0 to 17.7 t ha^{-1}. TSP was greater with the inclusion of maize rather than mungbean and was greatest at Nashipur and smallest at Joydebpur, irrespective of pre-rice crop treatments. Interaction means for year and site and for year, site and pre-rice crops were significant (LSD = 0.20 and 0.31 t ha^{-1}, respectively). TSP declined for all treatments at Joydebpur, increased at Nashipur, but either slightly declined or remained stable at Ishwordi.

Table 5: Grain yield (t ha^{-1}) of wheat as influenced by pre-rice crop and fertilizer 1998 to 2001 in Bangladesh

		Joydebpur					Nashipur					Ishwordi				
Pre rice	Fertilizer	1998	1999	2000	2001	Mean	1998	1999	2000	2001	Mean	1998	1999	2000	2001	Mean
Mungbean	STB	3.0	2.4	2.7	3.3	2.8	2.8	2.7	3.3	4.0	3.2	2.9	3.4	2.4	2.9	2.9
residue removed	FP	2.9	2.0	1.9	2.4	2.3	2.4	2.1	1.8	2.8	2.2	2.6	2.8	2.0	2.5	2.5
	Mean	2.1	1.5	1.6	2.0		1.7	1.6	1.7	2.4		2.1	2.2	1.5	2.1	
Mungbean	STB	3.1	2.4	2.7	3.5	2.9	2.4	2.7	3.5	4.2	3.2	2.5	3.5	2.4	3.2	2.9
residue retained	FP	2.6	2.0	2.0	2.3	2.2	2.4	2.3	2.2	3.4	2.6	2.7	3.0	2.1	2.6	2.6
	Mean	2.0	1.5	1.6	2.1		1.7	1.7	1.9	2.7		2.1	2.3	1.6	2.2	
Maize cropping	STB	3.1	2.3	2.7	3.2	2.8	2.5	2.6	3.1	4.2	3.1	2.7	3.4	2.4	3.1	2.9
	FP	2.6	2.0	2.0	2.2	2.2	2.4	2.2	1.9	2.7	2.3	2.7	2.9	2.2	2.5	2.6
	Mean	2.0	1.5	1.6	1.9		1.6	1.5	1.8	2.4		2.1	2.2	1.5	2.1	

LSD ($P<0.05$) Year*site 0.09; Year*site*pre-rice 0.13; Year*site*pre-rice*fertilizer 0.25

STB and FP are fertilizer nutrients supplied according to soil-test based recommendations and farmers' practices

Table 6: Total system productivity (t ha^{-1}) as influenced by pre-rice crop and fertilizer during 1997-98 to 1999-2000 at three sites in Bangladesh*

		Joydebpur				Nashipur				Ishwordi			
Pre rice	Fertilizer†	1998	1999	2000	Mean	1998	1999	2000	Mean	1998	1999	2000	Mean
Mungbean residue removed	STB	10.0	10.2	8.1	9.4	9.9	9.6	12.2	10.6	10.8	10.6	10.6	10.7
	FP	9.8	8.7	7.1	8.5	9.3	8.8	10.4	9.5	10.2	9.3	9.3	9.6
Mungbean residue retained	STB	10.4	9.5	8.3	9.4	8.9	9.6	13.5	10.7	10.1	10.9	10.8	10.6
	FP	9.3	8.7	7.4	8.5	9.0	9.5	11.3	9.9	10.0	9.5	9.1	9.6
Maize cropping	STB	13.8	12.2	10.5	12.2	13.0	12.8	17.7	14.5	13.9	14.4	14.6	14.3
	FP	12.2	10.7	9.0	10.6	11.1	11.0	13.2	11.8	13.6	13.3	11.5	12.8
	Mean	10.9	10.0	8.4	9.8	10.2	10.2	13.1	11.2	11.4	11.3	11.0	11.3

*LSD, t ha^{-1} ($P<0.05$): Year*site 0.20; Year*site*pre-rice 0.31; Year*site*pre-rice*fertilizer 0.62

†STB and FP are fertilizer nutrients supplied according to soil-test based recommendations and farmers' practices

Table 7: System-level responses to nitrogen presented as agronomic efficiency (AE, kg kg^{-1}) for various treatments at three sites in Bangladesh*

Treatment	Fertilizer	Joydebpur	Nashipur	Ishwordi
Mungbean residue removed	STB	4.8	4.6	5.2
	FP	6.8	7.6	5.7
Mungbean residue retained	STB	4.8	4.7	5.1
	FP	6.7	8.8	5.6
Maize cropping	STB	6.1	6.8	8.2
	FP	8.4	9.3	8.5

*Data are means of 3 years

System-level N-use Efficiency

Average AE ranged from 4.6 to 9.3 kg grain/kg N applied, at the three sites, with greatest at Nashipur (4.6 to 9.3 kg kg^{-1} N) and smallest at Joydebpur (4.8 to 8.4 kg kg^{-1} N) (Table 7). Across sites, average AE ranged from 4.6 to 7.6 kg kg^{-1} N for the residue removal, 4.7 to 8.8 kg kg^{-1} N for the residue retention and 6.1 to 9.3 kg kg^{-1} N after maize cropping.

Discussion

The actual yields of the crops are discussed in detail for the individual sites in Quayyum *et al.* (2002a, b) and are stated only briefly here because the focus here is on TSP and not on the yields of individual crops. The maximum yields achieved were comparable, rice (5.9 t ha^{-1}), wheat (4.2 t ha^{-1}), maize (5.1 t ha^{-1}) and mungbean (1.6 t ha^{-1}), although mostly smaller than those reported in other studies in the region, rice and wheat (Timsina *et al.*, 1998, 2001), maize (Quayyum and Hoque 1995) and mungbean (Hossain *et al.*, 1990; Pannu and Singh, 1993; AVRDC, 1999). Especially, mungbean and maize yields were comparatively low due to waterlogging and heavy rainfall events in early as well as late growth stages. Crop yields are highly variable in this region, mostly in response to strong winds and heavy rainfall that cause lodging and waterlogging of maize and mungbean both at the start of the monsoon or during grain filling and also cause lodging of rice, especially during grain filling. Variability in wheat yield is mostly a result of high temperatures that can occur during the reproductive phase, especially for the late-sown crops (Midmore *et al.*, 1984).

Nevertheless, despite the problems of heavy pre-monsoon rain and storms making the pre-rice crops vulnerable and risky to grow, a further increase in TSP and sustainability of RW systems is required to meet the increasing food demand. This can only be achieved by inclusion of a third crop, either maize or mungbean, after wheat and before rice. These experiments evaluated two options at three sites. Mungbean was included because of its direct value in the human diet and its potential to add nitrogen to the cropping system, especially if its residues with nodules incorporated into the soil. Maize was included because it offers an increasingly valuable commodity for an expanding poultry industry in the region as well as of its use as fuel. However, under the highly variable climatic conditions, crops in the RW systems can not exhibit their full yield potential and can result in generally smaller yields than expected. The analysis revealed that smaller yields of all crops ultimately resulted in smaller TSP from all treatments and particularly those with mungbean in sequences. The TSP, adjusted to glucose equivalent, were greater for maize and also less variable than for mungbean. The greater TSP with maize in the sequences, suggests that it may be necessary to include and promote maize in RW systems to meet the increasing food demand in the IGP, but more research may be required.

However for the maize or mungbean to be successful crops in RW sequences tolerances of the cultivars to waterlogging is essential during germination, emergence and grain filling stages. In the IGP and particularly in Bangladesh, unpredictable heavy early rains (ca. 20% of years) damage germinating seed and reduce establishment, while more frequent later rains (ca. 80% of years) abort mungbean flower buds and pods and damage maize cobs and reduce grain yield and quality. Improved management, such as planting of crops on raised beds, would also help alleviate waterlogging problems as has already shown some promise for maize and mungbean in rice-wheat sequences in northern Bangladesh (Hossain *et al*., 2004; Talukdar *et al*., 2004).

In the RW systems, there has often been concern of yield declines and of slower rates of yield gains than achieved previously and thus of their viability and sustainability. This is mostly because these crops extract a lot of nutrients, especially at high levels of productivity. If a legume or maize crop were included in those systems, the extraction would increase substantially. If extraction is continued year-after-year without replenishment, then there will be nutrient mining from the soil. Analyses of N, P and K extractions and balances for our experiments, presented in other papers (Panaullah *et al*., 2006; Saleque *et al*., 2006; Timsina *et al*., 2006), show large extractions and negative balances of N, P and K from the 3-crop systems with no N or farmers' levels of fertilizer applications, compared to fairly stable or positive balances despite large extractions for soil test based fertilizer applications.

The analysis herein reveals that both Soil Organic Carbon (SOC) and Soil Organic Nitrogen (SON) decreased at Nashipur (sandy loam) and Joydebpur (clayey) sites and residue retention helped maintain the SON at Ishwordi (silty clay loam) only. Potassium, P and S all increased but micronutrients decreased in the sandy loam and the clayey soils of Nashipur and Joydebpur. Yadav (1998) reported the decrease in SOC and SON in RW systems of India and Timsina *et al*. (2001) decrease in SOC in RW systems of Bangladesh, both with fairly similar soils and climate. Likewise, Nayyar *et al*. (2001) reported the decline of micronutrients in RW systems of NW India, corroborating our results.

Our data suggest consistently greatest AE for Nashipur and smallest for Joydebpur and greater for the farmer's practice than for the soil-test based treatment. AE was also greater for the sequences with maize compared with mungbean due to greater maize yield. The system-level agronomic efficiencies are generally lower than reported previously for irrigated RW systems in Bangladesh (Timsina *et al*., 2001). High levels of extractions from 3-crop systems and low system-level N-use efficiencies suggest that management should aim to apply fertilizer adequate for crop demand and apply in ways that minimize loss, maximize the efficiency of use and maintain nutrient balances.

Results further suggest that though farmers receive considerable grain from mungbean to meet their nutritional requirements, the retention or incorporation of its residues may not have significant residual effects to the ensuing rice and wheat as previously thought and that such advantages may differ across sites and years. Legumes can benefit succeeding crops only if they nodulate and their N concentration in plants is large during incorporation into the soil, none of which was really significant across the treatments and sites in our experiments. It is quite possible that mungbean residues tied up N (Yadvinder-Singh *et al*., 2005), implying that they may need to be retained as mulch and not incorporated. We propose that long-term experiments may be required to further explore and confirm the potential benefits of a legume for increasing the TSP and in improving soil fertility and system-level N-use efficiency in RW systems.

Finally, it must be stressed that adequate application and improved management of fertilizers and improved management of rain and irrigation and drainage water are essential for increasing the TSP and sustainability of the highly intensified RW systems and for meeting the increasing food demand of the growing population of the IGP in South Asia. For proper understanding of the nutrient demands of the component crops and to devise N fertilizer recommendations for these intensified systems, continuing analyses of nutrient-use efficiencies and their thorough balance sheets are essential. Such issues are the scope of our other papers (Panaullah *et al.*, 2006; Saleque *et al.*, 2006; Timsina *et al.*, 2006).

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