Summary

Analysis of Long-Term Soil Fertility Experiments with Rice-Wheat Rotations in South Asia

J M Duxbury, I P Abrol, R K Gupta, and K F Bronson

Abstract

In eighteen long term rice-wheat experiments, initial yields ranged from 3.6 to 8.3 t ha^{-1} for rice and from 2.0 to 4.7 t ha^{-1} for wheat. Rice yields generally declined over time while wheat yields were more stable. Yield trends were reasonably well described by a linear regression model fitted to three year moving average yield data. A downward trend in rice yield, between 0.05 and 0.5 t ha^{-1} year, was observed in eight of eleven long-term experiments that had run for at least eight years. Wheat yields were stable or increased over time in eight of the eleven experiments. The rate of yield change was independent of initial yield for both rice and wheat. Without fertilization, yields of rice dropped by an average of 39% to between 0 and 2.7 t ha^{-1}, while yields of wheat dropped by an average of 17% to between 0.2 and 1.6 t ha^{-1}.

A yield plateau was reached in only half of eight experiments analyzed for crop response to N where P and K were not limiting yields, indicating that yields of both rice and wheat should be increased with higher N inputs. Over time, the yield plateau was displaced downwards in three experiments with rice and one experiment with wheat, indicating that a constraint other than N,P or K was limiting yields. Agronomic nitrogen use efficiency at 120 kg N ha^{-1} varied between 11-22 and 8-25 kg grain kg^{-1} N for rice and wheat, respectively, and changed little over time. The estimated average recovery of nitrogen in grain was low at 21% for rice and 26% for wheat.

The only consistent effects of green manuring with *Sesbania* prior to rice were substitution for N fertilizer in rice and no residual effects on wheat. However, crop yield potential was distinctly increased by addition of Lantana green manure in one experiment and by addition of farmyard manure (FYM) in another experiment. A large effect of straw as a mulch in wheat was found in one experiment. Small or no effects of organic inputs on crop yields were observed in other experiments and evidence that the impact of organic additions would increase over time was weak. Although the highest crop yields were often obtained with inputs of organic materials, there was no consistent evidence that their use improved the sustainability of crop yields.

Recommended rates of NPK generally balance or exceed nutrient removal for P but there are large deficits with K and, considering losses, likely also N. Return of straws to soil would dramatically improve K budgets and to a lesser extent, N budgets. Despite large budget deficits, response to K was observed in only two experiments. Soil P chemistry and supply differed between saline/alkali soils and other soils, but P management is well understood. Inputs of micro-nutrients were only made in a few of the experiments and deficiencies in one or more of these elements could have contributed to yield declines.

Soil organic carbon (SOC) contents declined substantially in those experiments where they were initially highest (1 and 1.5%) and levels were universally low (0.2 to 0.8%) without organic inputs. Additions of FYM at 15 or more t dry matter yr^{-1} were able to maintain SOC levels between 1.5–1.75% in silt loam and silty

clay loam soils. Although the effects of organic inputs to sandy soils can be seen, SOC levels were always < 0.5%.

Introduction

Stagnating productivity and production of rice and wheat in S. Asian countries and indications that yields are declining in rice-wheat rotation experiments have raised questions about the sustainability of this cropping system (Hobbs and Morris, 1996). The eighteen experiments reported in this publication provide a wealth of information on the relationships between soil fertility management and crop productivity in the rice-wheat rotation. They are spread across the Indo-Gangetic plain (Fig. 1), include soil types ranging in texture from sandy loam to clay loam, and three sodic soil sites in Haryana, India.

The goals of this overview paper are:

- to analyze and provide a perspective on observed yield trends;
- to identify possible causes for observed yield trends;
- to identify any generalizations that can be made about nutrient management; and
- to suggest key areas for future research.

Crop Yield Trends

Year to year fluctuations in crop yields are a common feature of field experiments. There are numerous possible causes for temporal variability in yields, including differences in planting date, weather and pressures from pests and diseases. Additionally, cultivars were changed in many of the experiments but it is assumed that the best available cultivars were always used. In order to better see temporal trends in yields, the data were smoothed by plotting as a 3-year moving average. The one exception to this is an experiment in West Bengal (chapter 13) where 5-year means were used. Only experiments that had been carried out for eight years or longer were analyzed.

Figure 2 shows yields for the highest yielding treatment in each experiment regardless of nutrient sources. In all experiments, the best treatment for rice was also the best treatment for wheat. With the exception of the experiment at Bhairahawa, Nepal, the yield trends of rice and wheat are reasonably well represented by a linear regression model. At Bhairahawa, complex yield patterns were observed for the two rice crops in the triple crop rice-rice-wheat rotation, but the linear model fitted the wheat data well. Use of the linear regression model implies that yields will eventually reach zero; this is unlikely to be the case in most situations as farmers have been practicing "one tonne" agriculture with indigenous cultivars and without fertilizer inputs for almost a century. Therefore analysis of rate changes is with the caveat that yields will drop to some low sustainable level rather than zero.

Yields of rough rice declined over time in eight of eleven experiments, were relatively stable in two experiments, and showed a modest increase in one experiment. In contrast, yields of wheat were more stable over time; they declined in only three experiments, were stable in three experiments, and increased in five experiments. Rice-wheat system yield trends were dominated by the trend in rice yields, declining in eight experiments and increasing in two experiments. The rates of yield change (Fig. 3) from the linear regression model ranged from -0.48 to +0.16 t ha^{-1} yr^{-1} for rice, from -0.09 to +0.12 t ha^{-1} yr^{-1} for wheat and from -0.56 to +0.18 t ha^{-1} yr^{-1} for the rice-wheat system. Yield changes were independent of initial yields which ranged from 3.6 to 8.3 t ha^{-1} for rice, from 2.0 to 4.7 t ha^{-1} for wheat and from 6.8 to 13.3 t ha^{-1} for the rice-wheat system (average of first three

Figure 1. Map showing location of Long-term Rice-Wheat Experiments in the Indo-Gangetic Plains of India, Nepal and Bangladesh.

Research Teams	Location	Latitude	Longitude
1. Bijay Singh, Yadvinder Singh, CS Khind and OP Meelu	Ludhiana, Punjab	30° 56'N	75° 52'E
2. RS Narang and MS Gill	Ludhiana, Punjab	30° 56'N	75° 52'E
3. Yadvinder Singh, Bijay Singh, OP Meelu and CS Khind	Ludhiana, Punjab	30° 56'N	75° 52'E
4. RS Rekhi, DK Benbi and Bhajan Singh	Ludhiana, Punjab	30° 56'N	75° 52'E
5. VK Nayyar, and IM Chhibba	Ludhiana, Punjab		
6. R Chhabra and NP Thakur	Karnal, Haryana	29° 43'N	76° 57'E
7. DLN Rao and HS Gill	Karnal, Haryana		
8. KN Singh and Anand Swarup	Karnal, Haryana		
9. TS Verma and K Sharma	Palampur, Himachal Pradesh	30° 6'N	73° 3'E
10. M Badaruddin, MA Razzaque, CA Meisner and RA Razu	Dinajpur, Bangladesh	25° 38'N	88° 41'E
11. Nand Ram	Pantnagar, UP	29° N	79.3°E
12. Y Singh, SP Singh and AK Bhardwarj	Pantnagar, UP	30° 56'N	79.3°E
13. B Prasad and S K Sinha	Samastipur, Bihar	20° 56'N	85° 50'E
14. R Sakal	Pusa, Bihar	25° 50'N	85° 50'E
15. MN Saha, AR Saha, BC Mandal and PK Ray	Barrackpore, West Bengal	22° 45'N	88° 26'E
16. AP Regmi, SP Pandey and D Joshy	Bhairawaha Nepal	27° 23'N	83° 28'E
17. P Singh and RA Khan	Jabalpur, *MP	40° 30'N	81°15'E
18. AL Kundu and RC Samui	Mohanpur Nadia, West Bengal	32° 5'N	88° 5'E

*Research site outside the Indo-Gangetic Plains.

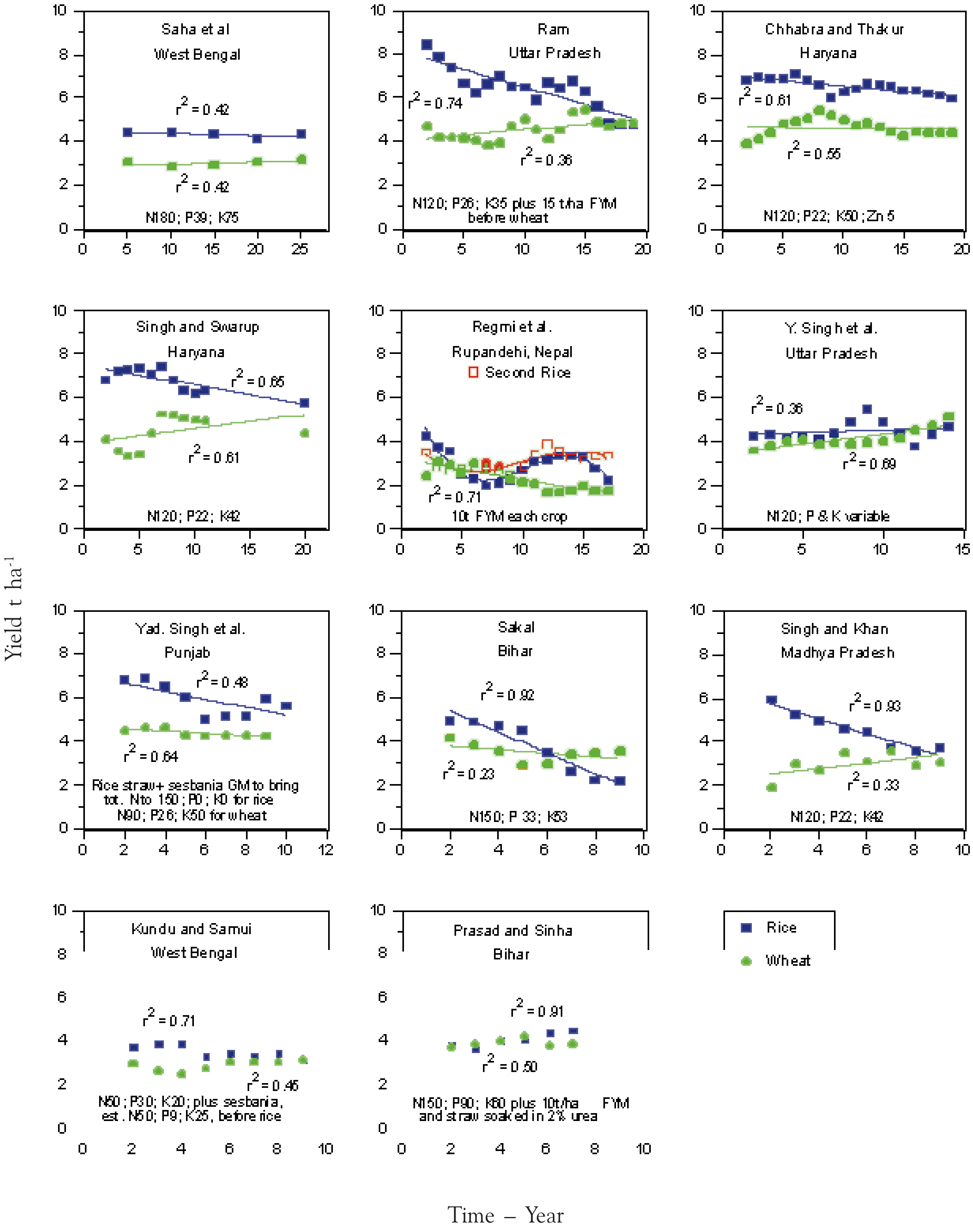

Figure 2. Yield trends for highest yielding treatment (shown at bottom of each panel) in long-term rice-wheat experiments. Data are 3-yr moving average, except for Saha et al where 5 year averages are used.

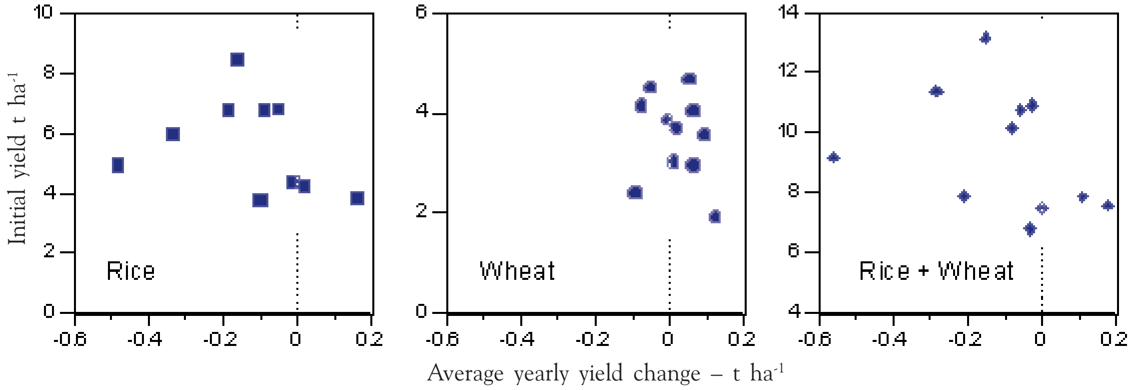

Figure 3. Relationship between initial crop yields and average yearly yield change.

years). The variation in initial yields of rice and wheat most probably reflects a combination of differences in site fertility, biotic stresses and crop yield potential.

The finding that rice yields are less stable than wheat yields is suprising given that the paddy environment is considered to be optimal for rice but leads to a poor soil physical condition for growth of wheat, especially in heavier textured soils. Although wheat yields are more stable, they probably are still lower than potential yields.

Yield changes in rice and wheat without nutrient inputs are shown in (Fig. 4). Initial

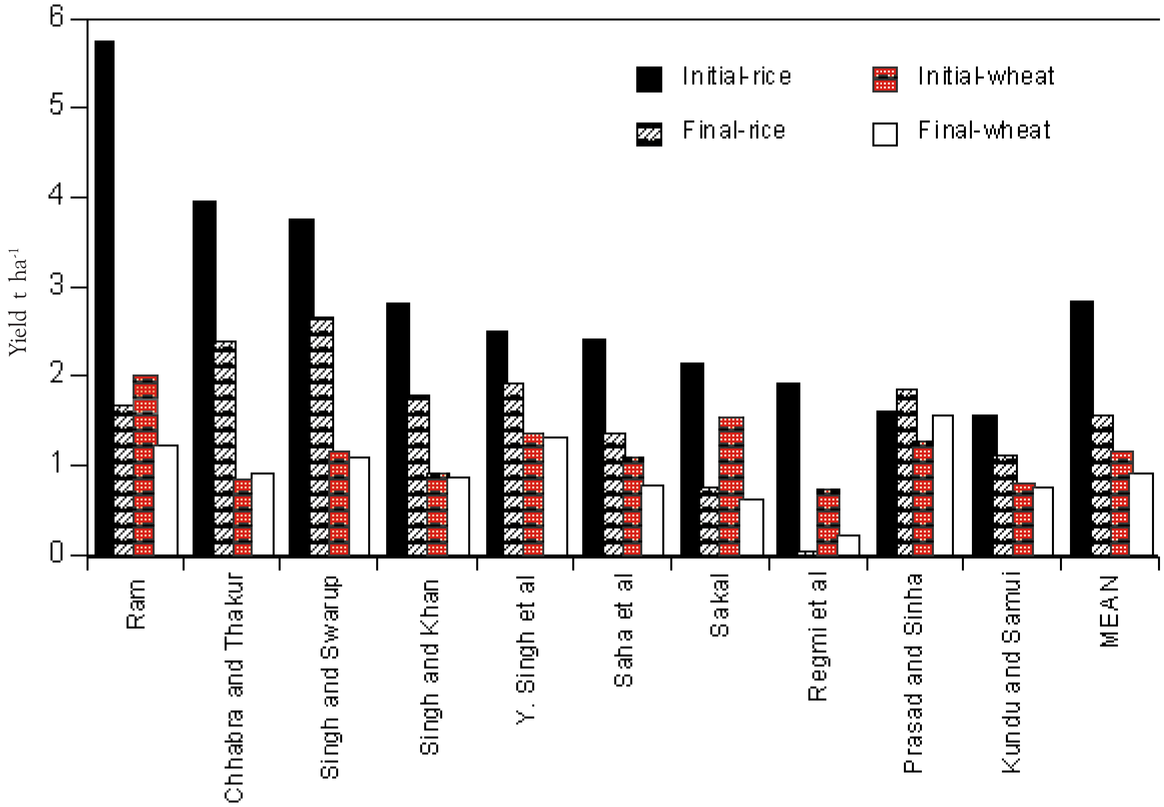

Figure 4. Average yields of rice and wheat without fertilizer addition for the initial and final three years of the experiments.

yields for rice ranged from 1.6 to 5.8 t ha^{-1}, suggesting that soil fertility levels and/or other constraints to crop productivity varied considerably across sites at the beginning of the experiments. With the exception of one study in Bihar (chapter 14), the final yields of rice were much lower, ranging from zero to 2.7 t ha^{-1}. The mean yield of rice dropped from 2.8 to 1.6 t ha^{-1}, a 45% decrease. Wheat yields were again more stable and lower than rice yields. Initial yields ranged from 0.7 to 2.0 t ha^{-1} and final yields ranged from 0.2 to 1.6 t ha^{-1}. The mean yield for wheat dropped from 1.2 to 0.9 t ha^{-1}, a 21% decrease. The most dramatic change in control yields occurred at Bhairahawa, in the Nepal terai, where the yield of rice dropped to zero and the yield of wheat to 0.2 t ha^{-1} due to severe P deficiency.

Decreases in yields of rice and wheat over time are expected in unfertilized treatments as nutrient deficiencies intensify due to crop removal of nutrients without replenishment. Similarly, if soil fertility is not maintained with intensive cropping, nutrient inputs needed to sustain high crop yields will also eventually increase. This scenario may apply to these long-term experiments because nutrient inputs were held constant over time. Yield response patterns to nutrient inputs provide a means of evaluating this possible cause for yield declines.

Crop Yield Response to Nutrient Inputs

Crop yield response patterns to nitrogen inputs for the initial and final phases of the eight experiments where treatment combinations allow this assessment are shown in (Fig. 5). In four of the eight experiments (chapter 13, 7, 3, 2) the yield response has been isolated to a response to N by using data from treatments where P and K were not limiting yields. Treatments in three experiments (chapter 11, 9, 14) were based on increasing additions of N, P and K and responses cannot be definitively associated with particular nutrients. In the final experiment (chapter 18), N levels were varied while P and K inputs were held constant.

For rice, a yield plateau is being approached in only half of the eight experiments (chapter 13, 7, 3, 14). In the remaining experiments, the response patterns clearly show that insufficient nutrients were added to reach maximum yield. Control yields were generally higher at the beginning than at the end of the experiments and consequently yield response curves for the initial and final phases of the experiments are separated. Higher N inputs were needed to sustain productivity in the two experiments where yields were relatively stable over time (chapter 13, 3). In three experiments (chapter 7, 2, 11), the yield plateau has shifted substantially downwards. This could be due to a nutrient deficiency other than N, P or K, or to some other cause. In only one experiment (chapter 14) did the response to nutrient inputs increase with time.

In contrast to rice, wheat yields in control treatments were unchanged over time in six of the eight experiments, and yield response curves in the initial and final phases were essentially identical in four of the six experiments. In the other two experiments (chapter 3, 2), there was a greater response to nutrient additions and higher yields (increase of 0.6 and 1 t ha^{-1}, respectively) in the last three years of the experiment. Similar to the result with rice, the response of wheat to nutrient inputs was linear in the experiments of Kundu and Samui and of Verma and Sharma, indicating that wheat yields could be increased with further nutrient inputs. The yield potential was reduced over time in only one experiment (chapter 11).

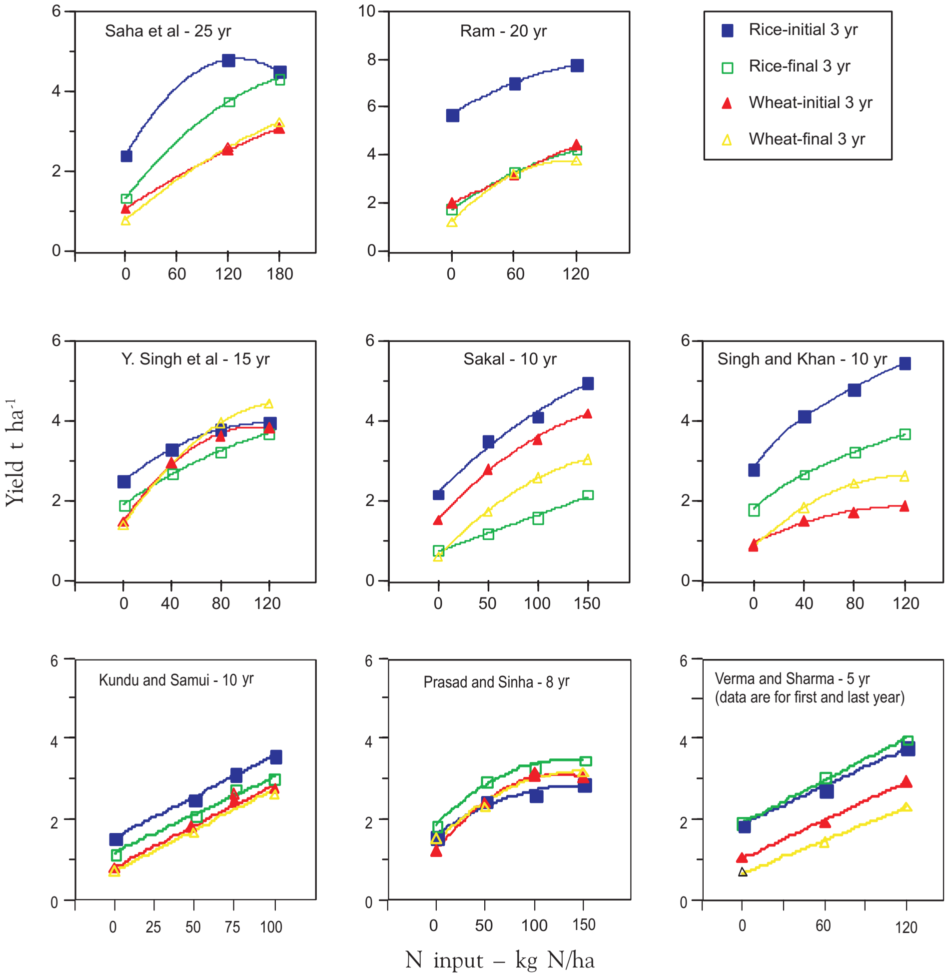

Figure 5. Yield response to nitrogen inputs for the initial and final three years of the experiments.

The hypothesis that greater inputs of N, P and K may be needed to sustain crop yields in long-term experiments is supported in only two cases for rice (both requiring greater N inputs) and not at all for wheat. The nutrient response patterns also indicate that recommended levels of nutrient inputs, probably mostly N, are often insufficient to obtain maximum yields. This may reflect researcher knowledge that lodging, rather than genetic potential becomes a yield limiting factor at high nutrient input levels.

Nitrogen Use Efficiency

The agronomic efficiency of nitrogen fertilizer (change in grain yield per unit of N input) at the 120 kg N ha input level ranges from 11-22 kg grain kg N for rice and 8-25 kg grain kg N for wheat for the eight experiments included in Figure 5. The range in agronomic efficiency for rice is similar to values reported with prilled urea in long-term rice-rice experiments (Cassman et al, 1996), while the values for wheat are lower than normally obtained in experiments where the protein content of wheat is 10%. Averaging over all experiments, the agronomic efficiency is the same for rice and wheat (16-17 kg grain kg N) and does not change between the initial and final three years of the experiments.

As expected, agronomic efficiency decreases as N input levels increase; for both crops it averages between 19 and 22 kg grain kg N for the first 60 kg N ha increment and this drops to 13 kg grain kg N for the second 60 kg N ha increment. Overall, there is little change over time, indicating that some other factor is responsible for the general trend of declining rice yields.

Nitrogen recovery in grain cannot be calculated for each experiment because data on grain N content is only available for a few of the experiments (see Table 1). However, if grain N is assumed to be 1.3% (7% protein) for rice and 1.6 % (10% protein for wheat), the average recovery of N at the 120 kg N ha input level is 21% for rice and 26% for wheat. These values are towards the low end of the range generally reported for rice (20-40%) and are low for wheat, where recoveries of 50% or more are common in upland cropping systems. This would suggest that the environment of the rice-wheat system is sub-optimal for wheat production.

Table 1. Agronomic efficiency for nitrogen between 0-60 and 60-120 kg N ha input levels

	Response to N - kg grain/kg N			
Study	Rice[1]		Wheat[1]	
	0-60 I - F	60-120 I - F	0-60 I - F	60-120 I - F
Saha et al	23-24	15-17	14-19	12-12
Ram	21-27	12-15	19-33	22-9
Y. Singh et al	18-18	7-12	31-34	9-17
Sakal	23-9	17-9	23-23	17-14
Singh & Khan	27-20	17-12	12-22	4-12
Kundu and Samui	15-15	15-15	15-15	15-15
Prasad & Sinha	15-21	6-8	22-18	8-8
Verma & Sharma	16-17	16-17	16-14	16-14
Mean	**20-19**	**13-13**	**19-22**	**13-14**

1. I and F are for the initial and final three years, respectively, except for Verma and Sharma where they are for the initial and final year, respectively.

Effects of Organic Inputs on Crop Yields

Seven of the eighteen experiments included a legume green manure (LGM) between wheat and rice; this was *Sesbania aculeata* in six of the experiments and *Lantana*, a weed species, in one experiment. Nine experiments included a farmyard manure treatment (FYM), and five experiments had both LGM and FYM treatments. Four experiments included crop residue management as a variable. In five of the eleven experiments shown in Figure 2, the best yields of rice and wheat were obtained with an organic input in addition to NPK fertilizer, indicating that organic inputs play an important role in maximizing crop yields in the rice-wheat system.

In many of the experiments, LGM's and FYM were added as substitutes for commercial fertilizers making it difficult to determine whether organic inputs altered crop yield potential. Moreover, the nutrient content of the organic inputs was measured in only one experiment, which severely limits interpretation of results and precludes accurate assessment of nutrient budgets.

The only consistent effect of using *Sesbania* LGM was substitution for N fertilizer; a 60 day *Sesbania* crop usually provided the equivalent of about 60 kg urea-N/ha for rice. In only two of the experiments (chapter 12, 1) was it demonstrated that N was not limiting yield of rice and neither found any additional effect of the LGM beyond its N supplying capacity. There were no residual effects of the LGM on wheat yield.

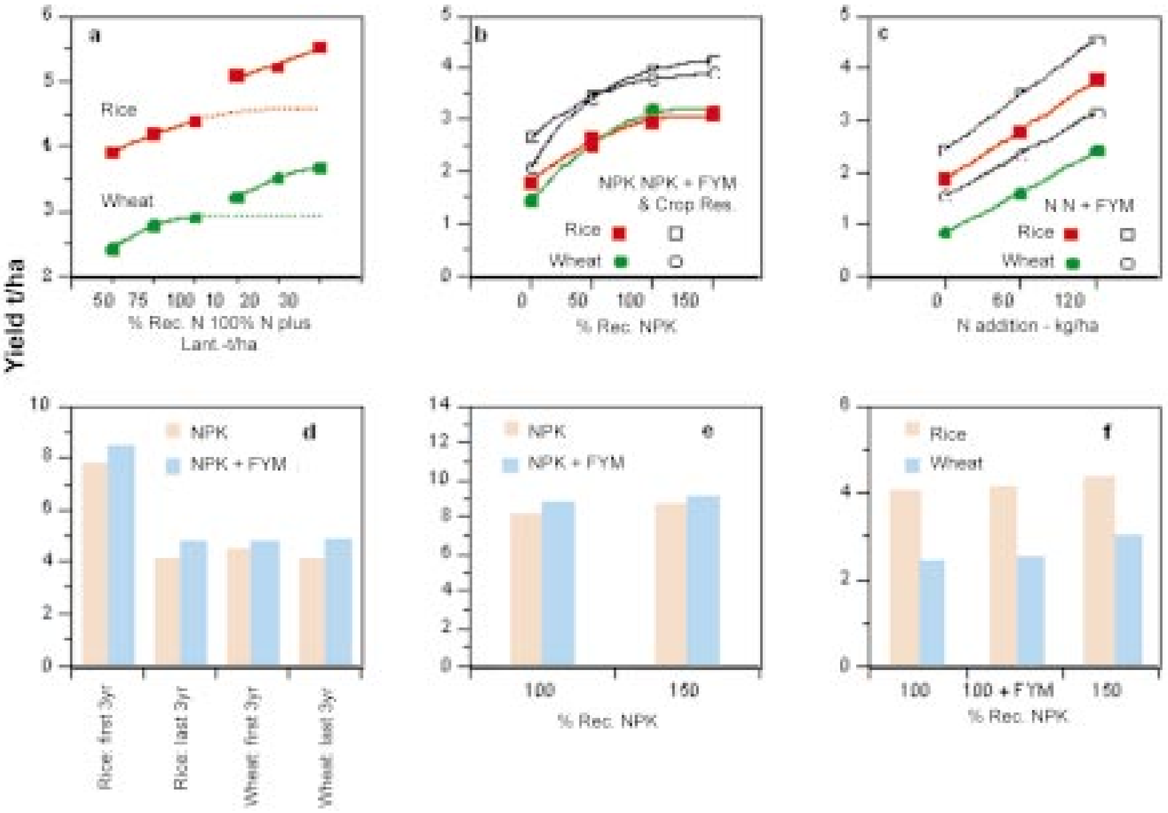

Figure 6. Effects of organic inputs on crop yields: a) and c) Verma and Sharma; b) Prasad and Sinha; d) Ram; e) Badaruddin et al; and f) Saha et al.

In contrast to the results with *Sesbania*, the yield potential of both rice and wheat was increased in an eight year experiment in Himachal Pradesh when *Lantana* was incorporated prior to rice (Fig. 6a; chapter 18). Addition of 30 t ha^{-1} (fresh weight) of *Lantana* in addition to the recommended N fertilizer (90 kg N ha for rice and 120 kg N ha for wheat) increased the average yields of rice and wheat by 1.05 t ha^{-1} (24%) and 0.76 t ha^{-1} (26%), respectively.

A clear effect of both FYM and crop residue return on crop yields was found in an eight year experiment in Bihar (chapter 14), with the combination of the two being the most effective. The response curves for the FYM + crop residue treatment (Fig. 6b) show that addition of the organic materials increased the yield potential of both rice and wheat. At the highest nutrient input level, the organic additions increased the yield of rice by 1.1 t ha^{-1} (35%) and the yield of wheat by 0.74 t ha^{-1} (24%). The shape of the response curves in this experiment and that with *Lantana* demonstrate that the yield increases observed with the organic additions were not simply due to increased N addition; they may have been due to correction of an unrecognized nutrient deficiency, to an indirect effect of nutrient addition such as the effect of K on increasing resistance to lodging, or to some effect unrelated to nutrients such as control of soil borne pathogens.

The addition of FYM together with fertilizer increased yields of both rice and wheat compared to fertilizer alone in a residue management experiment carried out for five years in Himachal Pradesh (Fig. 6c; chapter 18).

However, linear yield responses to N in all treatments indicated that insufficient N was used in this experiment. A more dramatic result was that adding rice straw (5 t ha^{-1}) as a mulch to wheat gave yields comparable to FYM addition. Further, an increasing yield trend was found for mulch and FYM treatments, whereas yields declined with fertilizer alone. After 5 years, wheat yield in the mulch treatment was 3.6 t ha^{-1} compared to 2.4 t ha^{-1} with fertilizer alone. In contrast to the mulch treatment, straw incorporation showed the classical N immobilization depression of wheat yields in the first three years of the experiment, but yields were comparable to or higher than the no straw treatment thereafter. The straw incorporation plus FYM treatment tended to give the highest yields of both rice and wheat, suggesting that straw addition contributed to nutrient supply after the initial years where its addition caused net immobilization of N.

Small positive effects of additions of organic materials on yields of rice and wheat were observed in other experiments. Addition of 15 t ha^{-1} of FYM prior to wheat in conjunction with NPK fertilizer consistently increased yields of rice compared to fertilizer alone in a twenty year experiment in Uttar Pradesh even though the yields of rice declined over time (Fig. 6d; Ram). The effect of FYM additions on wheat yield increased over time, suggesting that FYM was supplying a nutrient that was becoming limiting. Only small effects of FYM addition were observed in experiments at Dinajpur, Bangladesh (Fig. 6e; chapter 8) and in West Bengal (Fig. 6f; chapter 13), In the latter case mean yields with FYM + recommended NPK were less than those achieved at 150% recommended NPK.

Small positive effects of LGM's and/or straws on system productivity were observed in two other experiments. Supplying half of the N via a LGM or rice straw increased the mean productivity of the rice-wheat system (about 6 t ha yr^{-1} over 10 years) by 0.59 and 0.47 t ha^{-1}, respectively, compared to supplying all of the N via urea in an experiment in West Bengal (chapter 13). A similar effect of rice straw, used in combination with LGM and urea N, was found in another ten year experiment in the Punjab (chapter 17); in this case mean system productivity (about 10 t ha yr^{-1}) was increased by 0.41 t ha^{-1}. Possible explanations for the straw/LGM effect are an increasing supply of N from the soil as a larger pool of active soil organic N builds up, and/or, for rice, reduced N losses by NH_3 volatilization due to lowering of floodwater pH as mineralizing organic materials release CO_2. System productivity should gradually increase over time if the soil N supply explanation is correct. Such was the case in West Bengal where the organic additions increased system productivity by an average of 0.28 to 0.43 t ha yr^{-1} (4 to 7%), in the initial three years of the experiment, then by 0.63 to 0.85 t ha yr^{-1} (11 to 16%) in the final three years of the experiment. However, the reverse result was found in the Punjab, where the LGM plus rice straw treatment increased system productivity by 0.80 t ha yr^{-1} (8%) in the initial three years of the experiment, then was the same as the urea N treatment in the final three years of the experiment.

Nayyar and Chibba suggested that continued use of LGM's could help to overcome (or prevent) micronutrient deficiencies and this may well be the case with all organic inputs. Nayyar and Chibba found that Sesbania GM increased mean rice yield from 3.4 to 4.3 t ha^{-1} (26%) over a six year period by overcoming Fe deficiency in a sandy loam soil in the Punjab. The LGM was more effective than foliar sprays of Fe and the authors suggested that it increased reducing intensity in this coarse textured soil

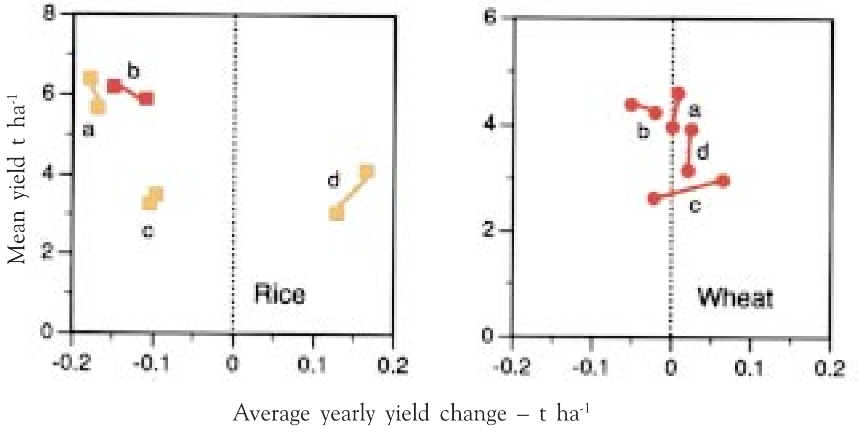

Figure 7. Effects of organic inputs on sustainability of crop yields: a) Ram; b) Yadvinder Singh et al; c) Kundu and Samui; and d) Prasad and Sinha. Paired points represent ± organic inputs for a given experiment and the higher yield value is always + organic inputs.

which did not retain water well. There was no effect of Sesbania on wheat yields (3.8 t ha^{-1}).

Effects of Organic Inputs on the Sustainability of Crop Yields

The effects of organic inputs on the sustainability of rice and wheat productivity can be assessed by comparing the average yearly yield change for treatments with and without organic additions. The paired points in (Fig. 7) represent the latter combinations using mean yield data. In all cases the higher yield is associated with organic additions. If productivity were more sustainable with organic additions the yearly yield change would be less negative (or more positive if yield increases were found) than without organic additions, i.e. the upper point of each pair would be to the right of the lower point. However, no consistent effect of organic additions on yield change is found for either rice or wheat. While organic additions increased crop productivity in these experiments, there is no compelling evidence from the few data sets available for this analysis that they generally improve the sustainability of crop yields.

Nutrient Budgets and Constraints

A. Macronutrients

The approximate uptakes of N,P and K per ton of grain and straw shown in Table 2 were calculated from data collected in several of the experiments (chapter 5, 12, 13, 6). These values would vary somewhat with varieties and growing environments. Actual nutrient removal rates in any given experiment will also depend on crop yields, harvest indices and residue management practices. Nevertheless, the values in Table 2 can be used to illustrate some generalities with respect to nutrient removal and nutrient budgets in the rice-wheat cropping system.

To evaluate how nutrient removal compares with current recommendations for nutrient inputs, a grain yield of 5t ha^{-1} for both rice and wheat can be used with no return of straw. At the yield level of 5 t ha^{-1} for each crop, and assuming that equal amounts of grain and straw are produced, removal of N, P and K will be 85, 20 and 100 kg ha, respectively, for rice and 105, 20 and 93 kg ha, respectively, for wheat. Removal of N is generally less than the typically recommended levels of 100-120 kg N ha for

Table 2. Approximate nutrient uptake by rice and wheat.[1]

Nutrient	Rice		Wheat		Approx. Ratio	Nutrient Removal at 10 t/ha system yield[2]
	Nutr. Uptake-kg/Mg product					
	Grain	Straw	Grain	Straw	Grain : Straw	kg N/ha/yr
N	13	4	16	5	3:1	190
P	3.5	0.4	3.5	0.4	9:1	39
K	4	16	3.5	15	1:4	193

1. Based on data in Chabbra and Thakur; Narang and Gill; Saha et al; and Singh and Swarup.
2. Assuming 5 t/ha grain yields of rice and wheat, equal production of grain and straw (harvest index of 50%) and removal of straw.

each crop. However, N losses by a variety of volatilization processes and leaching usually limit the recovery of fertilizer N in grain to between 20-40% for rice and around 50% for wheat. At these efficiency levels an additional source of N is needed to achieve a 5 t ha^{-1} yield level and, in the absence of any organic inputs, the only other source is mineralization of soil organic N. The ability of soil to supply N, assessed from unfertilized treatments, dropped over the course of all experiments indicating that progressively higher N fertilizer additions would be required over time to sustain a 5 t ha^{-1} yield level. It is worth noting that 25% of the N removed by rice and wheat is contained in the straw and that its return will have a positive impact on N availability after an initial period of 1-2 years where net immobilization of N may occur (chapter 18).

A response to P was observed in many of the experiments and was generally well predicted by the Olsen soil test for P with a critical value of about 11 kg P ha. Without P inputs, soil test P dropped below the critical level in most of the experiments (Figure 8, N only treatment). The P fertilization rate required to maintain soil test P level above the critical value may, however, vary with soil chemistry. An annual addition rate between 22-33 kg P ha (40-60 kg P_2O_5) appears sufficient to maintain soil test P levels above the critical value in non-alkali soils (Fig. 8). However, these input levels are less than the 39 kg P ha removed at a system productivity level of 10 t ha^{-1}. The lower inputs of P are probably effective because flooding of soil increases P availability for rice, possibly due to the formation of more soluble phosphate species as Fe is reduced to the divalent form. As noted by Singh, B. et al, it is likely that higher rates of P addition will eventually be needed to sustain yields.

Different susceptibilities of rice and wheat to P deficiency were found in alkali and non-alkali soils. In non-alkali soils in the Punjab, wheat required P fertilization while rice did not (chapter 4,2). In contrast, rice was more susceptible than wheat to P deficiency in two experiments on alkali soils in Haryana that had received gypsum additions (chapter 5,6). Use of gypsum to ameliorate sodic soils should reduce P availability as calcium phosphate species are formed. Such species will also not be directly affected by flooding/redox potential. The soil chemistry changes created by gypsum addition would initially occur in the surface soil, so crops that root deeply, such as wheat, will still have access to more available P lower in the profile. In contrast, the restricted rooting of rice reduces its access to P lower in the profile. Other factors may also be involved as soil chemistry in these systems is complex and dynamic.

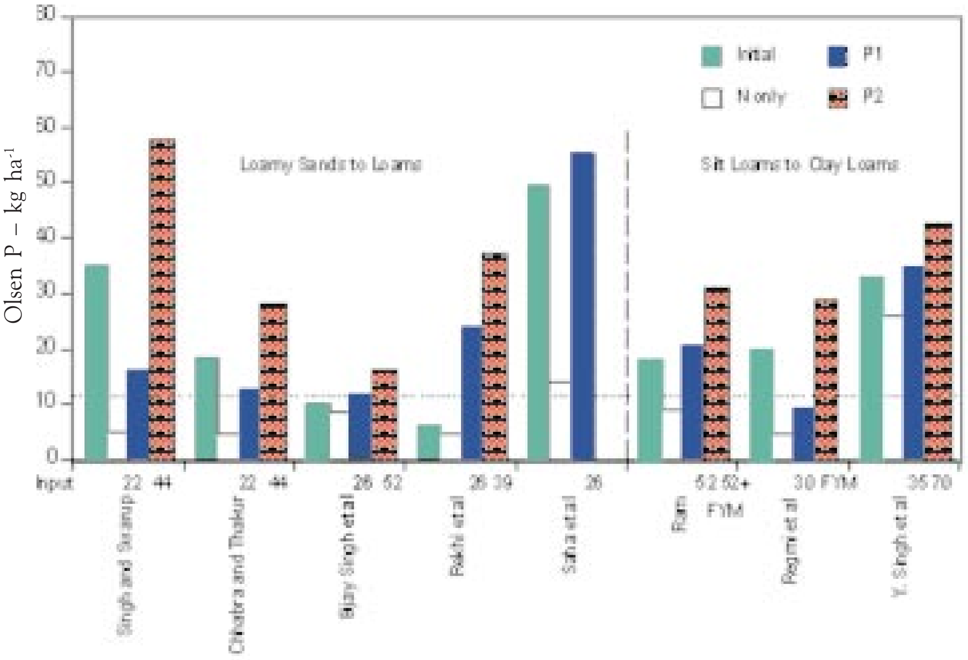

Figure 8. Changes in available P at different P input levels.

Current recommendations for P inputs, which range from 39 to 52 kg P ha year, are adequate. The return of straw will not influence P budgets because of the low P content of straw (Table 2). However FYM, which is enriched with P relative to N, is a good source of this nutrient.

A 5 t ha^{-1} crop contains 90-100 kg K. Recommended K fertilization rates for the experiments in this publication range from 25 to 50 kg K ha so K balance is routinely negative. Despite this situation, a response to K is rarely observed because the soils of the IGP generally have high K supplying capacity. A response to K was observed only in the terai of Nepal (chapter 15) and with a sandy soil in the Punjab (chapter 1). The negative K balance would be overcome with the return of straws because roughly 80% of the K assimilated by the crop is in straw.

B. Secondary and Micronutrients

A 28% yield response to S was observed for rice in West Bengal (chapter 13). Additions of S through fertilizers such as ammonium sulfate and single super phosphate have stopped with the use of urea as the N source and triple super phosphate as the P source so S deficiency would be expected to become more widespread in the future.

Similarly, widespread micronutrient deficiencies are recognized in the IGP where soils are mostly calcareous. Most experiments did not include micronutrient treatments and deficiencies in one or more of these elements could have contributed to the observed yield declines and changes in response to NPK inputs. As expected, levels of available micronutrients (DTPA extractable) generally declined with simple NPK treatments but were always higher where green manures (chapter 10, 18), FYM (chapter 14,7,18), or crop residues (chapter 14) were added to soils. Organic materials increase the availability of micronutrients by recycling and by increasing soil organic matter levels. Measurements of available Fe and Mn were shown to be affected by the redox status of soil (chapter 10) and this may also affect available Cu, indicating that care must be taken in interpreting measurements of these elements.

Changes in Soil Organic Matter

SOC or carbon content and the use of organic manures are traditionally linked with soil fertility maintenance. The "potential" organic carbon content of soils varies with soil texture, which regulates the possibility of forming aggregates, and with soil mineralogy, which affects the strength of aggregates. The formation of aggregates protects soil organic matter by a a soil initially high in SOC is the mollisol at Pantnagar, where 20 years of cropping reduced SOC from 1.48% to 0.49% and 0.84% in unfertilized and recommended NPK treatments, respectively (Table 3; chapter 7). High losses of SOC in the rice-wheat system contrast with results from double and triple cropped long-term rice experiments where SOC levels are maintained or even increased (Cassman et al, 1996) due to differences in decomposition patterns and products under more continuous maintenance of anaerobic conditions.

The level of SOC is increased with inputs of organic materials to soil, including crop residues, green manures and FYM. Inputs of organic materials via roots and root exudates increase with crop yield so that SOC levels are higher in fertilized than unfertilized treatments (Table 3). Fresh residues, such as straws and green manures, are generally less effective than composted materials or FYM at increasing SOC levels as they are more rapidly mineralized. However, this expected trend is weak in the data from these experiments (Table 3). SOC levels can be maintained with high inputs of organic materials; addition of 15 t ha^{-1} dry weight FYM yr maintained the original level of SOC (1.48%) at Pantanagar, India (chapter 7) and additions of 30 t ha^{-1} dry weight FYM yr increased the SOC level from 1.03 to 1.78% at

Table 3. Effect of the rice-wheat system on soil organic carbon levels.

	Soil Organic Carbon - % C						
Treatment	Ram[1]	Regmi et al[2]	Verma & Sharma[3]	Saha et al[4]	Rekhi et al[5]	Yd. Singh et al[6]	Nyyar & Chhibba[7]
Initial level	1.48	1.03	–	0.71	0.18	0.36	–
Unfertilized	0.49	0.73	1.09	0.40	0.20	0.34	–
Rec. NPK	0.84	0.88	–	0.43	0.37	–	0.19
NPK + FYM	1.49	1.75	1.3	0.45	–	0.45	–
NPK + Straw	–	–	1.25	–	–	0.47	–
NPK + LGM	–	–	1.24-1.39	–	0.41	0.41	0.34
Soil Texture	silty clay	silt loam	silty clay loam	sandy loam	loamy loam	loamy loam	sandy loam
Length of Expt (yr)	20	18	5-8	25	13	7	6

1. FYM added at 15 t dry wt/ha/yr
2. FYM added at 30 t dry wt/ha/yr
3. FYM, and straw added at 5 t dry wt/ha/yr and lantana LGM at 10 and 30 t fresh wt/yr
4. FYM added at 10 t dry wt/ha/yr
5. LGM added at 2.3 t dry wt/ha/yr
6. FYM, straw and LGM added at 6.3, 6.3, and 3.6 t dry wt/ha/yr, respectively
7. LGM was 60 day sesbania crop

Bhairahawa, Nepal (chapter 15).

Conclusions and Recommendations

1. Rice yields in the rice-wheat system declined in most experiments, whereas wheat yields were more stable. The greater stability of wheat yields does not necessarily mean that conditions are favorable for wheat, rather it is likely a reflection of the fact that yields are generally (much?) lower than the yield potential. The low agronomic efficiency of N with wheat supports the contention of a sub-optimal environment for wheat in the rice-wheat system compared to upland cropping systems.

   Reasons for the decline in rice yields probably vary amongst experiments. Patterns of crop response to N suggested that N inputs may be generally sub-optimal with the caveat that resistance to lodging may need to be improved before yield increases can be realized. The yield of rice achievable with nutrient inputs was shown to drop over time in some experiments, suggesting that constraints other than macro-nutrients contribute to yield declines. Micro-nutrient deficiencies and the build up of pest and pathogen pressures are possible additional constraints that can only be evaluated through the collection of additional information. It is recommended that diagnostic studies be undertaken to evaluate the importance of these constraints in the present experiments.

2. It is recommended that a minimum data set be identified specifically for long-term experiments. Assessments of pest and disease pressures and interactions of these with nutrient management should be included in this data set.

3. Various measurements indicated that the addition of organic materials was beneficial to soil fertility and to crop productivity. However, results from these experiments did not support the concept that the use of organic materials increases the sustainability of crop yields in the rice-wheat system. In most cases, it was difficult to evaluate effects of organic additions beyond nutrient substitution because of the tendency to design experiments for this latter purpose. It is recommended that greater attention be given to this issue in future experiments.

4. New experiments to assess long-term effects of zero- and reduced tillage practices should be initiated. Such practices have the potential to improve soil structure and increase soil organic matter levels through structure through re-formation of macroaggregates. They would be expected to benefit wheat productivity but abandonment of puddling could lead to tradeoffs between rice and wheat productivity. However, new approaches to rice culture, including direct seeding and production without flooding should be investigated.

5. Accurate assessments of nutrient budgets were precluded in many experiments because the dry mass and nutrient content of organic inputs were not routinely determined. Nevertheless, amongst the macro-nutrients, it is clear that P is well managed and that there are large deficits with K that could be overcome through return of straw. Although K deficiency was the exception in these experiments, on-going work in the region indicates that it is becoming more prevalent on farms. Greater attention should also be given to the non-nutritional benefits of K, such as reduction of lodging and bipolaris leaf blight. Known and emerging deficiencies

of S and micro-nutrients indicate that more attention should be given to budgets of these elements.

6. Results from one experiment demonstrated that net immobilization of N with straw incorporation is overcome within two to three years and an overall benefit is seen thereafter. Straw mulch (on wheat only) increased yields of wheat in the one experiment with this treatment. More experiments with residue management are needed in the rice-wheat system to elucidate potential benefits to nutrient supply, agronomic efficiency of nutrients, water use efficiency, soil structure and soil biology.

References

Cassman, K. G., DeDatta, S.K., Amarante, S.T., Liboon, S.P., Samson, M.I. and **Dizon, M.A.** 1996. Long-term comparison of the agronomic efficiency and residual benefits of organic and inorganic nitrogen sources for tropical lowland rice. Expl. Agric, 32: 427-444.

Cassman, K. G., Dobermann, A., Sta. Cruz, P.C., Gines, G.C., Samson, M.I., Descalsota, J.P., Alcantara, J.M., Dizon, M.A. and **Olk., D.C.** 1996. Soil organic matter and indigenous nitrogen supply of intensive irrigated rice systems in the tropics. Plant and Soil 32:427-444.

Fjell, D. L., Paulsen, G.M., Walter, T.L. and **Lawless, J.R.** 1984. Nitrogen and phosphorus requirements of different wheat types under dryland and irrigated conditions. J. Plant Nutr. 7:1289-1302.

Gajri, P.R., Arora, V.K. and **Prihar, S.S.** 1992. Tillage management for efficient water and nitrogen use in wheat following rice. Soil and Tillage Res. 24:167-182.

Hobbs, P and **Morris, M.** 1996. Meeting South Asia's future food requirements from rice-wheat cropping systems; Priority issues facing researchers in the post-green revolution era. NRG paper 96-01. CIMMYT, Mexico, D.F.

Ortiz-Monasterio, R.J.I., Sayre, K.D., Rajaram, S. and **McMahon, M.** 1997. Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. Crop Sci. 37:898-904.

Widdowson, F.V., Penny, A., Gutteridge, R.J., Darby, R.J. and **Hewitt, M.W.** 1985. Tests of amounts and times of application of nitrogen and sequential sprays of aphicide and fungicides on winter wheat following either beans or wheat, and the effects of take-all on two varieties at Saxmundham, Suffolk 1980-83. J. Agric. Sci. 105:97-122.