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EFFECTS OF FARMYARD MANURE, FERTILIZERS AND GREEN MANURING IN RICE-WHEAT SYSTEMS IN BHUTAN: RESULTS FROM A LONG-TERM EXPERIMENT

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SUMMARY

An experiment conducted from 1988 to 1997 to determine the effects of the timing of application and nutrient supply (particularly of phosphorus) is reported. The sources of applied nutrients that were compared were farmyard manure, pre-rice green-manuring with *Sesbania aculeata* and fertilizer application in a rice-wheat rotation on a typic ustifluvent. The application of seven tonnes farmyard manure per hectare to both the rice and the wheat crops over eight years increased organic carbon levels from 1.4 to 1.6% but had no yield effect on either crop. Phosphorus application through farmyard manure was not adequate for rice, whilst an application of 34 kg P ha^{-1} to the rotation gave an economic yield increase only in rice and then only in the first four years of the experiment. From the third year, green manuring was able to replace the effects of the recommended nitrogen, phosphorus and potassium fertilizer applications in increasing rice yield. Green manuring had no effect on the wheat yield but the recommended fertilizer application increased yield. Green manuring increased soil total nitrogen and available potassium levels and reduced base saturation. After adjusting rice yields for variation in transplanting date between years there was no statistical evidence of a yield trend in either crop over the period of the experiment. Farmers' practice of applying seven tonnes farmyard manure per hectare appears adequate to produce stable rice paddy yields of 4–6 t ha^{-1} a^{-1}.

INTRODUCTION

Traditionally, wetland soils in the Wangdue-Phodrang valley of Bhutan have been used to grow one summer crop of rice (*Oryza sativa*) per year. Increasingly, winter crops (wheat [*Triticum aestivum* var. aestivum] or mustard [*Brassica campestris* var. toria]) or, less commonly, a spring rice crop are also being grown on these soils. To meet the manuring requirements of this cropping intensification, farmers need to spread their traditional but increasingly limited farmyard manure (FYM) resources more thinly (i.e. between two crops rather than one) and are supplementing the use of FYM with the use of inorganic fertilizers, particularly urea. Farmers do not use green manures.

In a recent survey (DRDS, 2001b) in the valley, the farmers' estimate of mean yield was 3.50 (*s.e.* = 0.22) t ha^{-1} for paddy and 0.75 (*s.e.* = 0.18) t ha^{-1} for wheat. These yields are close to the recent national average estimates of 3.55 t ha^{-1} for rice and 0.93 t ha^{-1} for wheat (RGoB, 2000). Urea was applied by 52% of farmers to rice

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Table 1. Research questions and the contrasts used to answer them.

Contrasts	Treatments†	Contrast question
RQ 1. When inorganic N, P and K are not limited in a rice-wheat rotation, is the FYM better applied to the rice or the wheat crops?		
1	T5 v. T2	Is it worth applying 7 t FYM ha^{-1} to rice when N, P and K are not limited?
2	T6 v. T2	Is it worth applying 7 t FYM ha^{-1} to wheat when N, P and K are not limited?
RQ 2. When inorganic N and K are not limited either to rice or to wheat, is there a carry-over of inorganic P between the two crops?		
3	T4 v. T2	If 17 kg P ha^{-1} is applied to rice in the absence of FYM, is there any benefit to applying further P (17 kg P ha^{-1}) to the wheat crop?
4	T4 v. T3	If only 17 kg P ha^{-1} is applied, does it matter if it is applied either to rice or to wheat?
RQ 3. When inorganic N and K are not limited to rice or to wheat and no inorganic P is applied, is the phosphorus applied in the form of FYM adequate?		
5	T5+T6 v. T7+T8	When 14 t FYM ha^{-1} is applied (7 t FYM ha^{-1} to rice and 7 t FYM ha^{-1} to wheat) is there any benefit to applying 34 kg P ha^{-1} (17 kg to rice and 17 kg to wheat).
RQ 4. What is the value of *Sesbania aculeata* as a pre-rice green manure in a rice-wheat rotation?		
6	T9 v. T1	What is the effect of green manuring with *Sesbania* over no manure or fertilizer application?
7	T10 v. T9	If green manuring with *Sesbania* is used, is there a benefit to applying 35:17:17 kg N:P:K ha^{-1} to rice?
8	T9 v. T2	Can green manuring with *Sesbania* replace the application of the recommended rate of fertilizers to rice (70:17:17 kg N:P:K ha^{-1}) and to wheat (60:17:17 kg N:P:K ha^{-1})?
What is the effect of the recommended fertilizer application?		
9	T2 v. T1	What is the effect of the application of 70:17:17 kg N:P:K ha^{-1} to rice and 60:17:17 kg N:P:K ha^{-1} to wheat in the absence of FYM application or green manuring?

† For treatment details see Table 2.

(mean 35 [*s.e.* = 3] kg N ha^{-1} when applied) and by 41% of farmers to wheat (mean 38 [*s.e.* = 5] kg N ha^{-1} when applied). Other fertilizers are rarely used.

The fertilizer recommendations available in Bhutan for rice and wheat are derived from single-season fertilizer experiments on the individual crops. These do not take into account the possible carry-over, cumulative effects from one crop to another in the rotation, or the complementary effects of different manures. Given these possibilities, the use of an integrated plant nutrient systems (IPNS) approach for rice-wheat systems offers the possibility of making better use of scarce manuring resources.

Against this background, a long-term experiment on IPNS in rice-wheat systems was begun in 1988 with the objective of providing improved soil fertility management options for rice-wheat cropping systems in the Punakha-Wangdue valley.

The experiment was conducted at the RNR-RC Bajo, Bajothang, Wangdue-Phodrang, Bhutan, and was designed to answer the four research questions (RQ) given in Table 1.

METHODS

Experimental treatments and management

The experimental treatments summarized in Table 2 were applied to each crop in each year.

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Table 2. Experimental treatments for the long-term rice-wheat integrated plant nutrient systems experiment at RNR-RC Bajo.

T	Pre-rice green manure[§]	Rice (summer)				Wheat (winter)			
		N kg ha^{-1}	P kg ha^{-1}	K kg ha^{-1}	FYM t ha^{-1}	N kg ha^{-1}	P kg ha^{-1}	K kg ha^{-1}	FYM t ha^{-1}
1	No	0	0	0	0	0	0	0	0
2	No	70	17	17	0	60	17	17	0
3	No	70	0	17	0	60	17	17	0
4	No	70	17	17	0	60	0	17	0
5	No	70	17	17	7	60	17	17	0
6	No	70	17	17	0	60	17	17	7
7	No	70	0	17	7	60	0	17	0
8	No	70	0	17	0	60	0	17	7
9	Yes	0	0	0	0	0	0	0	0
10	Yes	35	17	17	0	0	0	0	0

[§] *Sesbania aculeata* grown as a pre-rice green manure.

The experiment commenced with the winter wheat crop of 1988/89, and the last crop to which experimental treatments were applied was the 1996/97 winter wheat crop. In total nine wheat and eight rice crops were grown although the results from the first wheat crop are not presented in this paper. In 1997, a rice crop was grown without any treatment application to test for residual effects.

Treatments were laid out in a complete randomized blocks design with three replicates. Plot size was 21 m^2. The fertilizer application rates used for the individual nutrients (Table 2) were those recommended for the Punakha-Wangdue valley and were based on earlier on-station and on-farm research (FAO, 1990). Fertilizer nutrient sources were urea, single super-phosphate and muriate of potash. Basal N, P and K applications were made during final cultivation: before puddling to rice and before sowing to wheat. In both crops, half of the N was applied as a top dressing after weeding: 30–35 days after transplanting into standing water in the case of rice and 30–35 days after sowing for wheat. The rice variety was IR 64 in all years except in 1989 when Milyang 54 was grown. For wheat, the variety used was Sonalika in all years except in 1991 when Bajoka 1 was grown.

The rate of FYM applied (7 t ha^{-1}) was based on farmers' practice in the valley but its nutrient content was not recorded in the experiment. However, in a follow-up comparable long-term experiment starting in 1998 (DRDS, 2001a) using FYM from the same source farmers, and using the same heap-storage methods, the FYM dry matter content was reported to be 68% with dry matter nutrient contents of 1.6% N, 0.8% P and 2.9% K. These values have been confirmed by a wider household survey (DRDS, 2001b). On this basis, the application of 7 t FYM ha^{-1} was estimated to have supplied 76 kg N ha^{-1}, 38 kg P ha^{-1} and 138 kg K ha^{-1}.

Analysis of the irrigation water sources found that nutrient contents are low, 0.01–0.02 mg N l^{-1}, 0.01 mg P l^{-1} and 0.16–0.47 mg K l^{-1}. Standard station rice irrigation methods maintain standing water levels between 50–100 mm, and water management

Table 3. Mean values for pre-1989[1] wheat crop soil samples.

Variable*	Unit	Mean	*s.e.*	Nutrient status**
pH (H_2O)		5.98	0.05	Slightly acid
Organic C[2]	%	1.22	0.02	Moderate
Total N[1]	%	0.08	0.01	Very low
Available P[3]	mg kg^{-1}	4.49	1.12	Low
Available K[4]	mg kg^{-1}	123	8	Moderate
Zinc	ppm	1.17	0.12	Low
Iron	ppm	186	6	Low
Copper	ppm	4.06	0.18	Optimum
Manganese	ppm	9.62	1.53	Optimum

* Analysis conducted at Hindustan Fertilizer Company Laboratory, Siliguri.
** RGoB/DASA (1995).
1. Total N was not determined in 1989, data given are from pre-1996 wheat samples. 2. Walkley Black. 3. Bray. 4. Ammonium acetate extraction.

research on an adjacent experiment site has shown that mean annual irrigation water use for rice is about 1000 mm per crop. These data suggest that nutrient additions to the rice crop from the irrigation water would have been negligible except for K (1.6–4.8 kg K ha^{-1}).

Sesbania aculeata was planted in early May, following irrigation and cultivation. The vegetative material was incorporated during the pre-transplanting land cultivation after the fresh weight yield of the *Sesbania* had been recorded. The nutrient content of the incorporated *Sesbania* was not determined. However, as for the FYM, in a subsequent comparable experiment the mean nutrient contents of a pre-rice green manuring *Sesbania* crop were estimated to be 3% N, 0.3% P and 2.5% K (of the dry matter) with a dry matter content of 16%. *Sesbania* biomass yields are given below.

Butachlor was used to control weeds in rice and no other plant protection measures were taken in any crop. No weed, pest or disease incidences of any consequence occurred.

Experiment site

The experiment site at RNR-RC Bajo (27°29.40′N 89°53.84′E) had a mean annual rainfall during the period of the experiment of 768 mm with 73% of this falling in the summer monsoon months of June to September. In the summer months, the range of mean maximum and mean minimum temperatures were 26.3–28.6 °C and 13.6–19.5 °C respectively. In the winter months, mean maximum temperatures fell to 16.5 °C and mean minima to 5 °C.

The site was on a terrace soil at 1200 m asl, described by BSSP (1998) as a typic ustifluvent and ustorthent (USDA Soil Taxonomy, 1975; 1992). This fine sandy clay loam/silty clay soil is characteristic of the Wangdue-Phodrang valley rice-growing soils. The nutrient status of the soil of the experiment, as determined in 1989, is given in Table 3.

Composite soil samples were taken from each plot on four occasions; before the 1988 wheat crop, before the 1996 rice crop; before the 1996 wheat crop and after the 1996 wheat crop. The samples from the pre-1988 wheat crop were sent to the Hindustan Fertilizer Company, Soil Testing Laboratory, Siliguri, India for analysis of pH (H_2O), organic carbon (Walkley Black), available P (Bray), available K (ammonium acetate extraction) and micronutrients (zinc, iron, copper and manganese). All the other samples were analysed at the Soil and Plant Analytical Laboratory (SPAL), Semtokha, Bhutan, for pH (H_2O), organic carbon (Walkley Black), total N (Kjeldhal), available P (Bray), available K (calcium chloride extraction). The post-1996 wheat crop samples were also analysed for exchangeable bases (ammonium acetate extraction) and cation exchange capacity (potassium chloride).

Data analysis

A series of single degree of freedom contrasts amongst the treatments (Pearce, 1992) were used to best answer the original four research questions and to examine the effects of fertilizer application (Table 1). The treatments did not appear to permit contrasts to be developed that could easily be used to answer research question 2 so alternative contrasts that provide related information were used. A contrast (9) was used to examine the effect of fertilizer application although this effect was not included in the original research questions.

GENSTAT 4.1 was used for all statistical analyses. An analysis of variance for yields was conducted for each of the crop-by-year combinations as a preliminary analysis to examine the pattern of the results and the reliability of the data. As a result of this preliminary analysis, all yield data were transformed ($\log_{10} X + 1$) for further analysis in which the contrasts were calculated in the individual analyses of variance at each date. This transformation reduced the mean coefficient of variation for each crop-by-year analysis in the rice crops from 12.0 (*s.e.* = 1.1)% to 5.9 (*s.e.* = 0.6)% and in the wheat crops from 20.6 (*s.e.* = 3.4)% to 13.9 (*s.e.* = 2.3)%. There was significant ($p = 0.03$) heterogeneity of variance amongst the variances of the individual crop-by-year combination analyses of variances ($\log_{10}$ transformed data). Accordingly, a repeated measures analysis was conducted and interpreted cautiously only to examine evidence that any experimental treatment effects were likely to have been missed in the individual crop-by-year combination analyses of variance. There was no evidence that effects had been missed. Thus results are given here as $\log_{10}$ transformed values based on the separate analyses of variance for each crop-by-year combination as these provide the most reliable basis for interpretation.

RESULTS

Crop yields

The significance and the size of the effects of the contrasts for crop grain yields using log-transformed data were summarized across crops and years to determine where the main experimental effects lay. Only those contrasts (namely 5, 6, 7, 8 and 9) that showed consistent and significant effects (i.e. $p < 0.10$) during the period of the

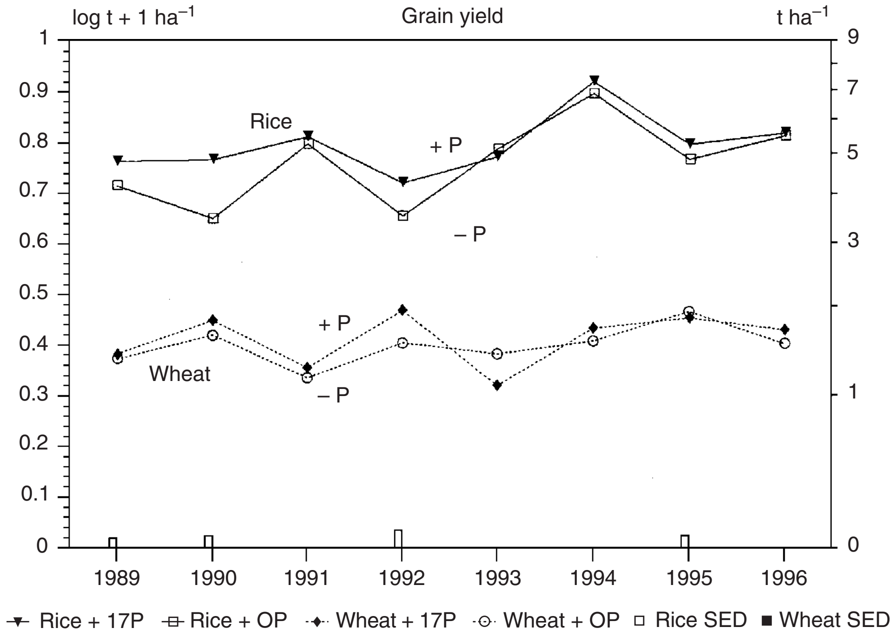

Figure 1. Effect of applying 17 kg fertilizer P ha^{-1} to both the rice and wheat crops on grain yields in a rice-wheat rotation (1988–1996). Standard errors of differences for comparing two means (*s.e.d.*) are given for either crop only when the contrast effect is significant at $p < 0.10$.

experiment are presented in detail here. The complete report is given in Chettri *et al.* (2000).

Research question 1. There was no consistent and significant effect of either contrast 1 or 2 on the yield of either crop.

Research question 2. The results from contrasts 3 and 4 show no benefit from applying 17 kg P ha^{-1} to wheat as well as to rice on either crop's grain yield. When only 17 kg ha^{-1} is applied to a crop, application to either rice or wheat is equally effective.

Research question 3. In three of the first four years of the experiment, application of 17 kg P ha^{-1} to both the rice and the wheat crops (i.e. a total of 34 kg P ha^{-1} to the rice-wheat rotation (in contrast 5) had a significant effect in increasing rice yields but effects on wheat yield were not significant. The average yield increase of paddy due to the P application in the first four years of the experiment was 0.74 t ha^{-1}. These effects are illustrated in Figure 1.

Research question 4. Pre-rice green manuring with *Sesbania* consistently increased the yield of rice over no manuring or fertilizer application (i.e. contrast 6) in all years (on average by 35% from 3.47 t ha^{-1} to 4.68 t ha^{-1}), although the effect was only

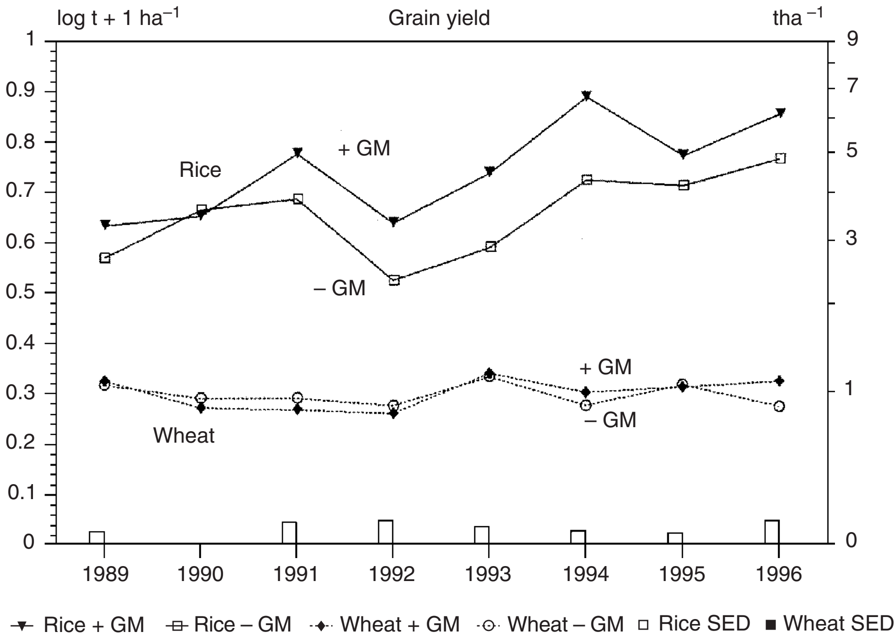

Figure 2. Effect of pre-rice green manuring (GM) with *Sesbania aculeata* on grain yields in a rice-wheat rotation (1988–1996). Standard errors of differences for comparing two means (*s.e.d.*) are given for either crop only when the contrast effect is significant at $p < 0.10$.

significant ($p < 0.05$) in five of the eight years (Figure 2). Green manuring did not have a significant effect on wheat yield.

The supplementary fertilizer application to rice following green manuring (i.e. contrast 7) increased rice yield in every year. The effect on rice yield was significant in the first two years of application (1989) and again in 1992, and the effect of the fertilizer decreased consistently with time (Figure 3). There were no significant effects of the supplementary fertilizer application on the yield of the wheat crop yield in any year.

Although green manuring resulted in a significantly lower rice yield (1.45 t ha^{-1}) than the application of fertilizer (i.e. contrast 8) in the first year (1989), from the third year (1991) differences in the yield of rice between the two treatments were small and non significant (Figure 4). Wheat yield, in contrast, was always lower after green manuring than after fertilizer application (typically by 0.5 t ha^{-1} to 1.0 t ha^{-1}) and in six of the eight years the effect was significant. Also there were no differences in wheat yield between the (rice) green manuring and the control treatments (treatments 9 and 1 in Table 2) in any year. Green manuring is equivalent, therefore, to an application of 70 : 17 : 17 kg N : P : K ha^{-1} for rice but has no value for wheat.

Recommended fertilizer application. Comparison of yields of both rice and wheat with and without fertilizer showed that fertilizer application lead to increased yields of both

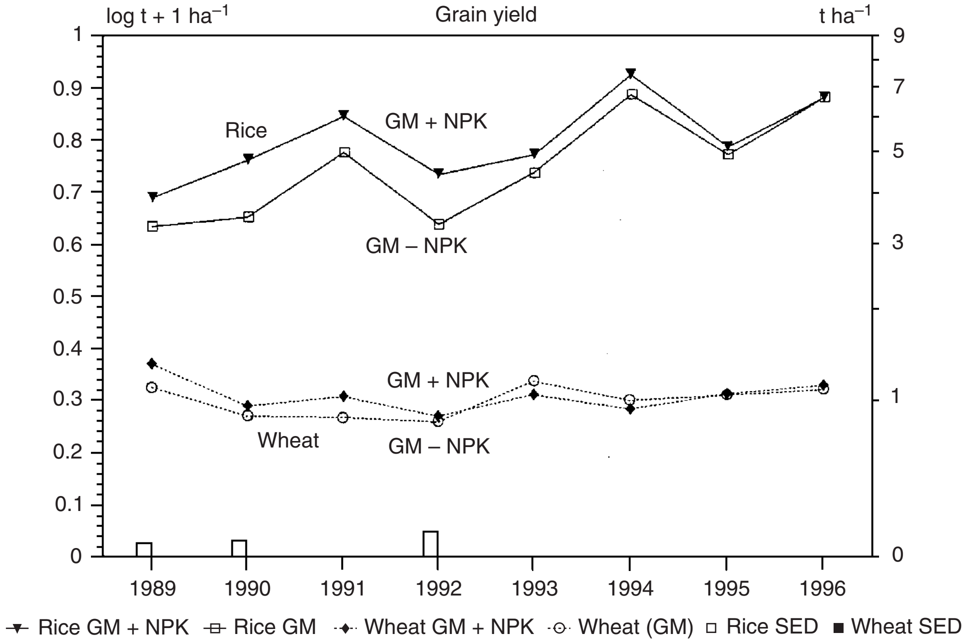

Figure 3. Effect of applying 35:17:17 kg N:P:K ha^{-1} to rice crop with pre-rice *Sesbania aculeata* green-manuring (GM) on grain yields in a rice-wheat rotation (1988–1996). Standard errors of differences for comparing two means (*s.e.d.*) are given for either crop only when the contrast effect is significant at $p < 0.10$.

rice (five out of eight years) and wheat (seven out of nine years) in most years. The mean yield increase was 1.51 t ha^{-1} (43%) for rice, and 0.69 t ha^{-1} (70%) for wheat over the period of the experiment (Figure 5).

Effects in the 1997 (residual) rice crop yield

The residual effects of treatments on grain yield were greater than on straw yield. Green manuring [contrast 6] had a larger and more significant ($p = 0.01$ v. $p = 0.07$) residual effect on grain yield than fertilizer application [contrast 9]. The residual effect of green manuring was to increase paddy yield by 34% (from 2.92 t ha^{-1} to 3.92 t ha^{-1}) while the residual effect of the fertilizer application was to increase paddy yield by 23% (from 2.92 t ha^{-1} to 3.60 t ha^{-1}).

Sesbania aculeata yield

The fresh weight yield of *Sesbania* at incorporation varied significantly between years (from a minimum of 2.3 t ha^{-1} in 1990 to a maximum of 41.1 t ha^{-1} in 1996) with a mean yield of 19.9 t ha^{-1}. Using dry matter and N contents of *Sesbania* from the follow-up experiment given above (DRDS, 2001a), this represents a mean value of 96 kg N ha^{-1}, 10 kg P ha^{-1} and 80 kg K ha^{-1} added per green-manuring crop. These values agree well with those reported elsewhere for *Sesbania aculeata* (e.g. Singh, 1984). There was no relationship between the date of planting *Sesbania* and its subsequent

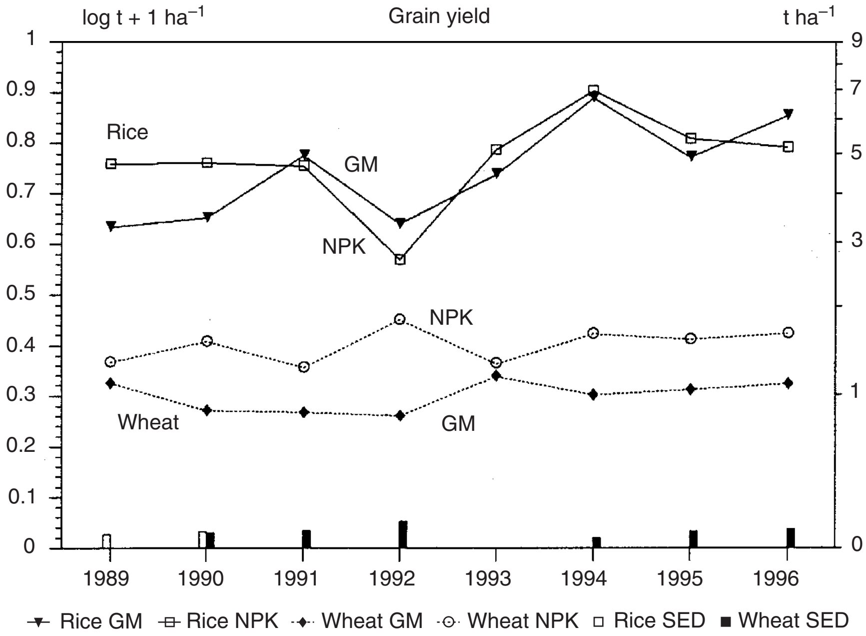

Figure 4. Effect of replacing the recommended fertilizer application (70:17:17 kg N:P:K ha^{-1}) to rice with pre-rice *Sesbania aculeata* green manuring (GM) on grain yields in a rice-wheat rotation (1988–1996). Standard errors of differences for comparing two means (*s.e.d.*) are given for either crop only when the contrast effect is significant at $p < 0.10$.

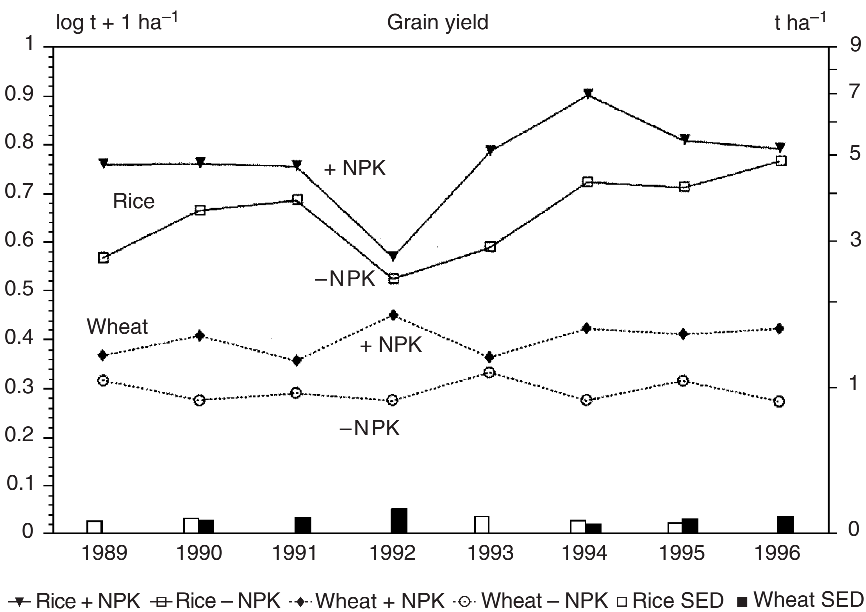

Figure 5. Effect of the recommended fertilizer application (70/60:17:17 kg N:P:K ha^{-1}) to rice/wheat crops on grain yields in a rice-wheat rotation (1988–1996). Standard errors of differences for comparing two means (*s.e.d.*) are given for either crop only when the contrast effect is significant at $p < 0.10$.

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yield, or between the yield of *Sesbania* and the rice crop yield response to green manuring across the years.

Soil analyses

There was no effect of any of the nine contrasts on the soil variables measured in the pre-1989 wheat crop (Table 3). These results confirm a uniform experimental soil and represent the soil nutrient status at the start of the experiment. Levels of organic carbon and available K are rated as moderate, and available P (Bray), Zn and Fe are rated as low for crop production (RGoB/DASA, 1995). Soil total nitrogen levels were not determined for these samples.

Within the pre-1996 wheat crop soil sample results, there were significant effects of the contrasts only on organic C, total N, available K and base saturation in the pre-1996 wheat crop soil samples. These effects, which represent the relative effect of treatments on soil properties over the course of the experiment, are summarized as follows.

- Applications of 7 t FYM ha^{-1} to both the rice and the wheat crops when N, P and K were not limited (contrasts 1 and 2) increased organic C, from 1.4% to 1.6% in both contrasts (*s.e.d.* = 0.11 and $p = 0.11$).
- Use of green manuring, when compared with no manuring (contrast 6) and with fertilizer use (contrast 8), increased soil total N levels from 0.07% to 0.10% and 0.08% to 0.10% respectively ($p = 0.01$ and $p = 0.10$; *s.e.d.* 0.01).
- Green manuring was the only treatment to affect available K levels but its effect was variable. Green manuring compared with no manuring (contrast 6) increased available K from 29 mg kg^{-1} to 55 mg kg^{-1} ($p = 0.01$; *s.e.d.* 7.00) and, when replacing fertilizer (contrast 8), from 30 mg kg^{-1} to 55 mg kg^{-1} ($p = 0.03$). However, when fertilizer was used as a supplement to green manuring (contrast 7) the supplementary fertilizer application reduced available K from 56 mg kg^{-1} to 21 mg kg^{-1} ($p = 0.03$).
- Green manuring compared with no manuring (contrast 6) reduced base saturation from 96 to 77% ($p = 0.06$; *s.e.d.* 6.60).

A feature of the results was that there was no significant effect of contrast 5, which examined the effect of applying 34 kg P ha^{-1} to the rotation (i.e. 17 kg P ha^{-1} to rice and 17 kg P ha^{-1} to wheat), on available P levels.

The comparison between pre-1989 wheat and pre-1996 wheat crop soil sample results represent the absolute effects of treatments on soil properties over the course of the experiment. Between 1989 and 1996, organic C levels increased (from 1.22 to 1.46%), available P decreased (from 14.3 to 8.9 mg kg^{-1}) and available K decreased (from 124 to 38 mg kg^{-1}), although only the effect on available K was significant ($p = 0.01$). However, results for available K need to be treated with caution as the extraction method differed between sampling dates (ammonium acetate in 1989 and calcium chloride in 1996). There was no evidence of an interaction between the sampling times and treatment contrasts.

DISCUSSION

Alternative manuring practices

The focus of the experiment on the use of FYM, phosphorus nutrition and green manuring as an alternative manuring practice is understandable. A recent study in the Punakha-Wangdue valley (DRDS, 2001b) has confirmed that traditional manuring systems for rice in the Punakha-Wangdue valley, based on the use of FYM, are already under pressure. Phosphorus is generally regarded as being the next most important limiting nutrient to crop yield in Bhutan after nitrogen, and rarely is it applied to rice crops in fertilizers. Pre-rice green manuring is frequently cited as a potential alternative manuring practice.

Farmyard manure. The results presented here show that while the FYM application rate of current farmers' practice does not provide adequate P, it does help to maintain soil organic matter levels. Definitive studies on the economics of FYM use in the area are not available. However, because a shortage of household labour to produce and apply FYM is the major factor limiting its use, and as labour availability will continue to decline, the opportunity cost of FYM use is predicted to continue to increase (DRDS, 2001b). This will lead, in turn, to increased dependence on alternative manuring practices. From an economics point of view, the most attractive option is the use of fertilizers, especially urea. Though more costly, the more sustainable option is the use of green manures.

This experiment, in common with other long-term nutrient management experiments in rice-wheat systems in South Asia (e.g. Abrol *et al*., 2000; Dawe *et al*., 2000), includes a treatment involving FYM application according to farmers' practice. These experiments, however, do not examine the effect of varying FYM application rates, and particularly of increasing FYM application. Although the lack of attention to FYM is understandable given the socio-economic trends that do not favour its use, it is unfortunate. Emerging evidence indicates that soil organic matter quality is an important factor determining production sustainability (Ladha *et al*., 2000). Thus there is a need to examine FYM effects in any future long-term experiments. This need is reflected in the design of the follow-up experiment to that reported here which includes treatments to examine the effect of doubling farmers' practice FYM application rates (DRDS, 2001a).

Phosphatic fertilizers. The use of fertilizers is the first choice alternative manuring practice to the use of FYM and although most farmers use fertilizers on rice, it is only in the form of urea and as a top dressing. While this is a rational economic choice, the sustainability of this practice is low and farmers already recognize the negative impact of urea application on soil properties, notably in increased soil hardness. The effects of fertilizer application in general, and phosphorus application in particular, on yields in this experiment are consistent with earlier work in the area (FAO, 1990) and confirm the importance of supplementing the supply of phosphorus from FYM to improve crop nutrition in the area.

The declining response in rice yield to P with time (Figure 1) suggests that although P applied through FYM may not be sufficient initially, there is a cumulative effect of P application by both fertilizer and FYM, which reduces the need for P application in subsequent years. This reinforces the need to review fertilizer P recommendations in rice-wheat systems at intervals (in this case, after five years) to account for changes in response to P application (Ladha *et al*., 2000).

The average annual yield increase due to the application of 17 kg P ha^{-1} over the first four years of recommended NPK fertilizer application in rice was 0.74 t grain ha^{-1}. A marginal rate of return of 480% for the use of single super-phosphate to supply this P appears economically attractive but in farming practice few farmers apply fertilizers containing P. Lack of fertilizer P use is due mainly to the much larger yield response to an easily applied top-dressing of urea than to P, but also the low awareness amongst farmers of the benefits of fertilizers with a balanced nutrient composition.

Green manuring. The yield benefits obtained here for pre-rice green manuring with *Sesbania* and its ability to substitute for recommended fertilizer applications in rice are consistent with results from South and East Asia (Singh, 1984; Mann and Garrity, 1994). Regmi (1998) has also reported the lack of a green-manuring effect on wheat. Despite consistent and large yield returns to pre-rice green manuring in research studies and considerable support intervention by government and other agencies, rates of adoption have been low. Ali and Narciso (1994) identify the major constraint to adoption of green manuring in the region as economic, despite clear short term (on yield of rice and following crops) and long-term (on soil conditions) benefits. Although regional and Asian experience (Ladha and Garrity, 1994) suggests that adoption rates will be low, the potential for adoption of green manuring in Bhutan is comparatively high as a result of high fertilizer costs due principally to high transport costs.

The potential of pre-rice green manuring in the Punakha-Wangdue valley is defined by economics, principally by its capacity to substitute for the recommended and currently economic fertilizer application. The primary constraint to adoption is the need to keep the marginal cost of green manuring below those of the recommended fertilizer application, currently Nu 2 070 ha^{-1} (46 Nu = US $1). The second constraint is the practical difficulty of providing early and extra irrigation to establish the green manure crop, especially where access to irrigation is managed communally (Chettri *et al*., 2000). Fertilizer prices to farmers in Bhutan are subsidized through transport and commission payments. This subsidy is scheduled to be phased out, however, in line with government policy. As the unsubsidized market price will mean a rise of between 30% and 60% of the current subsidized price, green-manuring use will compete more favourably with fertilizer use in the future. In essence, a more sustainable fertilizer supply system will encourage more sustainable soil fertility management systems. In anticipation of the reduction in subsidy, research and extension initiatives to increase the returns to green manuring and reduce costs of cultivation appear justified.

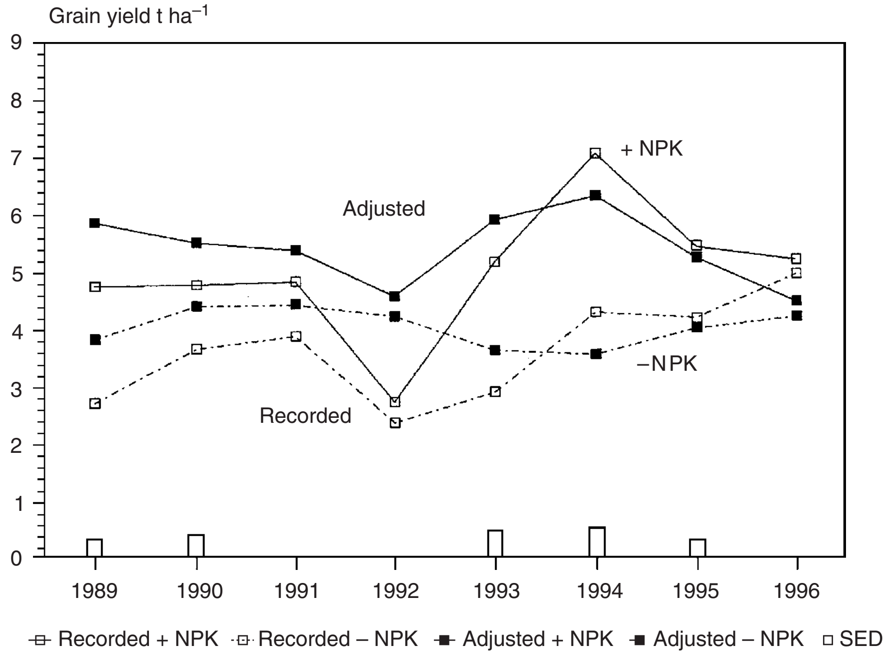

Figure 6. Effect of the recommended fertilizer application (70/60:17:17 kg N:P:K ha^{-1}) to rice/wheat crops in a rice-wheat rotation (1988–1996) on the recorded (open symbol) paddy yield (see Figure 5) and these yields adjusted (closed symbol) to a standard transplanting date of 1 July in each year. Standard errors of differences for comparing two means (*s.e.d.*) are given for either crop only when the contrast effect is significant at $p < 0.10$.

Yield trends

The results show two distinctive patterns over time. The first is the low yield of rice in 1992, which coincided with the greatest number of significant effects amongst the treatments, and the subsequent increasing mean rice yields, even for the green-manuring control treatment, from 1993 to 1996 (see Figure 2). There is no such yield trend in the corresponding wheat crops. The second pattern is the moderate though stable yield level in the no-manure control treatments for both rice and wheat.

Examination of the pattern of rice yield with year found that yield is significantly ($r^2 = 0.78$) linearly related to the transplanting date of the rice crop in each year. On average, one day's delay in transplanting after 27 June resulted in a loss in paddy yield of 185 kg ha^{-1}. This daily figure is equivalent to a 43% loss in yield due to a delay in transplanting from the third week of June to the second week of July.

To examine the effect on the results of transplanting date differences between years, the yield data for rice for all years were adjusted using the linear relationship above for the date of transplanting of 27 June. In Figure 6 the effect of the no-manure control (T1) and the recommended fertilizer application (T2) treatments on rice yield, as given in Figure 5, are presented as the recorded (untransformed data), and when adjusted for the date of transplanting. Once results are adjusted for transplanting date, yields show a high degree of stability over the period of the experiment. There is no statistical evidence of a consistent yield trend of rice or wheat with time.

The importance of establishing and accounting for variation in planting date in order to draw correct conclusions has important implications for the conduct of long-term experiments and for interpreting their results. A similar effect is reported from Nepal for the wheat crop in rice-wheat systems by Ladha *et al*. (2000). There are two aspects to consider. Firstly to remove year-to-year variation which, by inflating experimental variation, reduces the capacity of the experiment to detect treatment effects. Secondly, as here, to ensure that yield trends are correctly identified and attributed to a causal factor.

Increasing rice production is an important objective of the Royal Government of Bhutan's agricultural development policies and this policy is supported by a range of research and extension interventions for other technologies. Examples include variety improvement, pest and disease management and the use of fertilizers. Date of transplanting is an established factor determining the yield of rice. This is confirmed by this experiment, which also demonstrates the magnitude of the effect of early transplanting in obtaining high and stable rice yields in the area.

This experiment suggests the need for research to determine the potential yield loss in farming practice that is associated with the dates of planting currently practised, the constraints to earlier planting and the potential for achieving widespread earlier planting and consequent yield increases. Depending on the outcome of such research, agricultural research and development interventions may need to be adjusted to place a greater emphasis on irrigation management for early transplanting as a means of increasing rice yields.

Stable yields with time

The capacity of this soil to sustain moderate but stable yields of rice and wheat over the period of the experiment even in the no-manuring treatment is evidence of a pattern that is likely to be occurring in farming practice. Farmers in the area obtain moderate mean yields of paddy (4–6 t ha^{-1}) on soils which, like this one (Table 3), appear from soil analytical data to be of poor nutritional status and so offer potential to improve productivity through improvements in soil fertility management. These results suggest that farmers' FYM application of approximately 7 t FYM ha^{-1}, which is equivalent to the N, P and K removed by a rice grain crop of 4.5 t ha^{-1} (Datta, 1981), is sufficient to ensure stable and sustainable yield and maintain soil organic matter levels.

The practical implication of this result is that, in current farming practice in the Punakha-Wangdue valley, farmers are unlikely to be experiencing, or be concerned about, declining soil fertility and crop yields. Consequently, farmers are unlikely to perceive the need for and respond to research and extension programmes aimed at improving rice production through improvements in soil fertility management. Initiatives aimed at improving FYM production and management, use of green manures, and balanced fertilizer applications to supply P are unlikely to succeed under the present socio-economic circumstances.

CONCLUSIONS

- There was no consistent or significant effect of farmers' annual application of 7 t FYM ha^{-1} to both crops on the yield of either rice or wheat. However this application had the effect of increasing soil organic carbon levels from 1.4% to 1.6% over eight years.
- In the early years of the experiment, an annual application of 17 kg P ha^{-1} to each crop had a consistent and economically beneficial effect on increasing rice but not wheat yields. P applied through 7 t FYM ha^{-1} applied to each crop may not be sufficient initially but the cumulative effect of P application reduces the need for P application in subsequent years.
- Pre-rice green manuring with *Sesbania aculeata* increased rice yield in relation to no-manuring in all years and has the potential to replace the current recommended fertilizer application for rice, although the full effect of this may not be apparent in the first year of green manuring. Green-manuring had no effect on wheat yield.
- Year-to-year variation in rice yield was related to variation in transplanting date. A delay in transplanting from the third week of June to mid-July resulted in a 43% loss of yield or 185 kg ha^{-1} day^{-1}. Once rice yields were adjusted for transplanting date there was no evidence of a consistent trend in the yield of rice or wheat over the period of the experiment.
- The capacity of a soil with poor soil nutrient status to maintain moderate but stable rice and wheat yields with an application of 7 t FYM ha^{-1} per crop suggests that farmers are unlikely to be experiencing, or be concerned about, declining soil fertility and crop yields. Consequently farmers are unlikely to respond to research and extension programmes aimed at improving rice production through improvements in soil fertility management.

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