



Springer

Dear Author:

Please find attached the final pdf file of your contribution, which can be viewed using the Acrobat Reader, version 3.0 or higher. We would kindly like to draw your attention to the fact that copyright law is also valid for electronic products. This means especially that:

- You may not alter the pdf file, as changes to the published contribution are prohibited by copyright law.
- You may print the file and distribute it amongst your colleagues in the scientific community for scientific and/or personal use.
- You may make an article published by Springer-Verlag available on your personal home page provided the source of the published article is cited and Springer-Verlag is mentioned as copyright holder. You are requested to create a link to the published article in LINK, Springer's internet service. The link must be accompanied by the following text: The original publication is available on LINK **<http://link.springer.de>**. Please use the appropriate URL and/or DOI for the article in LINK. Articles disseminated via LINK are indexed, abstracted and referenced by many abstracting and information services, bibliographic networks, subscription agencies, library networks and consortia.
- You are not allowed to make the pdf file accessible to the general public, e.g. your institute/your company is not allowed to place this file on its homepage.
- Please address any queries to the production editor of the journal in question, giving your name, the journal title, volume and first page number.

Yours sincerely,

Springer-Verlag Berlin Heidelberg

S.K. Gami · J.K. Ladha · H. Pathak · M.P. Shah
E. Pasuquin · S.P. Pandey · P.R. Hobbs · D. Joshy
R. Mishra

Long-term changes in yield and soil fertility in a twenty-year rice-wheat experiment in Nepal

Received: 19 June 2000 / Published online: 19 May 2001
© Springer-Verlag 2001

Abstract A long-term rice-wheat experiment was conducted at Parwanipur, Nepal, to study the effects of organic and mineral sources of nutrients on yield and nutrient status of the soil. Twelve treatments comprising different combinations of inorganic N, P, and K; farmyard manure (FYM); and wheat chopped straw (WCS) were included. On average during a 20-year period, the control plot with an indigenous nutrient supply supported 2.06 Mg rice ha⁻¹ and 0.69 Mg wheat ha⁻¹. The application of 100 kg N ha⁻¹ increased yields, but the addition of P, K, Zn, and S gave no response, indicating that the soil supply of these nutrients did not limit yield. The grain yield of rice and wheat was maintained over the years. Soil analyses of the past 6 years (1994–1999) showed that treatments receiving organic sources of nutrients increased total soil C and N from 18% to 62% and 15% to 48%, respectively, compared with the NPK treatment. There was a buildup of total P and Olsen P in plots receiving FYM. However, total and available soil K were similar in all the treatments. The apparent N and P balances for the rice-wheat system were positive in the NPK, FYM, and WCS treatments, whereas the K balance was negative in all the treatments except with the application of FYM to both rice and wheat. Rice and wheat in most years yielded <3.15 Mg ha⁻¹ and <2.16 Mg ha⁻¹, respectively. These yields are only 40–50% of the poten-

tial attainable yields of this region. Possible reasons for low yields are discussed.

Keywords Long-term experiment · Rice-wheat system · Organic manure · Soil fertility · Nutrient balance

Introduction

Rice and wheat are the most important staple food crops of the world and they are mostly grown in sequence in South Asia. The rice-wheat system is currently practised on about 13.5 million ha of prime agricultural land in Bangladesh, India, Nepal, and Pakistan, with another 12 million ha in China (Ladha et al. 2000). The production of both crops has increased markedly with the introduction of modern technologies based on early maturing, N-responsive, semi-dwarf cultivars. The removal of nutrients with harvested grain and straw has also increased markedly. There are indications that the yields of rice and wheat, and partial factor productivity (PFP) which is the measure of grain output for a single input, such as N, have declined (Hobbs and Morris 1996; Duxbury et al. 2000; Yadav et al. 2000). The depletion of soil nutrients, particularly K, is reported to be a possible cause of such a decline (Bhandari et al. 2001; Regmi et al., unpublished data). Deficiency of Zn and S is also reported to be associated with yield decline in some cases (Duxbury et al. 2000). The decline in PFP results in increasing costs because farmers have to apply additional inputs of fertilizer to obtain the same yields. Non-judicious use of nutrients also has a negative environmental effect in terms of their losses in gaseous forms and through leaching. Since arable land is limiting, productivity has to be improved to meet the region's future food demand. Maintenance of soil fertility will be essential, therefore, to improve and sustain yields.

Long-term experiments (LTEs) are valuable for evaluating the effects of continuous cropping on the capacity of a system to sustain nutrient supply and productivity. In Nepal, four long-term experiments on rice-wheat be-

J.K. Ladha (✉) · H. Pathak · E. Pasuquin
Crop, Soil and Water Sciences Division,
International Rice Research Institute (IRRI),
DAPO 7777, Metro Manila, Philippines
e-mail: J.K.LADHA@CGIAR.ORG
Fax: +63-2-8911292/8450606

S.K. Gami · M.P. Shah · S.P. Pandey · R. Mishra
Regional Agricultural Research Station,
Nepal Agricultural Research Council,
Parwanipur, Bara, Nepal

P.R. Hobbs
CIMMYT, P.O. Box 5186, Kathmandu, Nepal

D. Joshy
Central Soil Science Division,
Nepal Agricultural Research Council, Khumaltar, Nepal

gan in the late 1980s. Earlier we analysed a rice-rice-wheat long-term experiment at Bhairahwa, Nepal, and hypothesised that a delay in sowing and K deficiency were the possible causes of a yield decline in wheat, whereas poor water management and K deficiency were responsible for rice-yield decline (Regmi et al., unpublished data).

In the present study, we used another rice-wheat LTE conducted over a 20-year period at the Regional Agricultural Research Station, Parwanipur, Nepal, to: (1) examine the effects of organic and mineral fertilization on yield and yield trends of rice and wheat, (2) monitor changes in nutrient contents of soil under continuous cropping, and (3) estimate apparent input-output balances of N, P, and K.

Materials and methods

A long-term permanent plot experiment began in June 1980 at the Regional Agricultural Research Station, Parwanipur, Nepal. The site is located in the central piedmont of Nepal at 120 m above mean sea level at 27°21'N and 84°53'E. The soil is an Inceptisol formed on Himalayan residuum with the following characteristics in the top 15-cm profile: clay 8.0%, silt 17.0%, sand 75.0% (loamy sand), pH (1:2 soil:water) 7.0, total N 0.86 g kg⁻¹, total C 6.5 g kg⁻¹, NH₄OAc-extractable K 0.054 g kg⁻¹, Olsen P 0.015 g kg⁻¹, saturation extract exchangeable cations 1.4 dS m⁻¹, and bulk density 1.6 Mg m⁻³. The area has a subtropical climate highly influenced by the southwestern monsoon. The average annual rainfall is around 1,550 mm. More than 85% of the rainfall occurs from mid-June to the end of September. November and December are the driest months and light precipitation can be expected in January and February. The mean monthly temperature ranges from a minimum of 8.5°C in January to a maximum of 34.5°C in May. The source of irrigation is groundwater pumped from 200-m-deep tube wells.

The experiment included two crops per year, rice (July–November) and wheat (December–April), with 12 treatments (T1–T12) arranged in a randomized complete block design with three replicates (Table 1). Plots were 6 m long and 4 m wide. Fertilizers were applied based on the recommendations set at the time of initiation of the experiment by the Nepal Agricultural Research Council. All the P as (NH₄)₂HPO₄, K as muriate of potash, and Zn and S as ZnSO₄ were applied as basal fertilizer. N was applied in two splits, 50% at transplanting of rice and sowing of wheat as (NH₄)₂HPO₄ plus urea and the remaining 50% topdressed as urea at 25–30 days after transplanting (DAT) of rice and at 21–25 days after sowing (DAS) of wheat. Farmyard manure (FYM) containing 20.0 g N kg⁻¹, 4.5 g P kg⁻¹, and 10.0 g K kg⁻¹ (dry-weight basis) was applied 4–7 days before transplanting/sowing. Wheat chopped straw (WCS), containing 5.0 g N kg⁻¹, 1.0 g P kg⁻¹, and 3.0 g K kg⁻¹ (dry-weight basis), in 2-cm pieces was incorporated into the soil 4–7 days before transplanting of rice. Two rice seedlings (25–30 days' old) were transplanted at 20×20 cm spacing. Wheat (120 kg seed ha⁻¹) was sown in rows 25 cm apart. In all the years, high-yielding, semi-dwarf varieties of rice and wheat were used. Transplanting of rice and sowing of wheat were done on 15–30 July and 5–15 December, respectively, every year. Irrigation was given in rice to maintain a submerged condition (3- to 5-cm water layer). However, soil moisture frequently dropped below field capacity because of high temperature, high evapotranspiration, and an inadequate supply of irrigation water due to electricity and/or machine failure. Plots were drained about 15 days before the rice harvest. In wheat, three irrigations were given at crown root initiation (21 DAS), maximum tillering (55 DAS), and flowering (100 DAS). Hand weeding was done to manage the weeds and plant protection measures were applied as needed to

Table 1 Treatments used in the long-term rice-wheat experiment in Parwanipur, Nepal. FYM Farmyard manure, WCS wheat chopped straw

Treatment	Rice				Wheat			
	N	P	K	Organic	N	P	K	Organic
	(kg ha ⁻¹)				(kg ha ⁻¹)			
1	0	0	0	0	0	0	0	0
2	100	0	0	0	100	0	0	0
3	100	13.1	0	0	100	13.1	0	0
4	100	0	25	0	100	0	25	0
5	100	13.1	25	0	100	13.1	25	0
6	100	0	0	0	100	13.1	25	0
7	50	0	0	0	50	0	0	0
8	50	8.7	0	0	50	8.7	0	0
9	0	0	0	FYM ^a	0	0	0	FYM ^a
10 ^b	100	13.1	25	0	100	13.1	25	0
11	50	0	0	FYM ^a	100	13.1	25	0
12	50	0	0	WCS ^c	100	13.1	25	0

^a FYM added at 4 Mg ha⁻¹ (dry-weight basis). It contained 20.0 g N kg⁻¹, 4.5 g P kg⁻¹, and 10.0 g K kg⁻¹

^b 25 kg ha⁻¹ ZnSO₄ added to rice

^c WCS added at 5 Mg ha⁻¹ (dry-weight basis). It contained 5.0 g N kg⁻¹, 1.0 g P kg⁻¹, and 3.0 g K kg⁻¹

control pests. Crops were harvested manually 5 cm above the ground using sickles, and straw was removed from the field. The grains were separated from the straw manually. Crops were harvested from a 10-m² area in the centre of the plot at maturity and grain yield was adjusted to 140 g water kg⁻¹ and 120 g water kg⁻¹ for rice and wheat, respectively.

Soil sampling and analysis

Soil samples of five selected treatments (1, 5, 9, 11, and 12) were collected after each crop of wheat starting in year 14 (1994) to study the effect of organic and inorganic fertilizers on soil nutrient content. Soil samples from the 0- to 20-cm layer were collected from three sites in each plot with a core sampler at about 5–10 days after the harvest of wheat. The entire volume of soil was weighed and mixed thoroughly and a subsample was taken to determine dry weight. The fresh soil was air-dried for 7 days, sieved through a 2-mm screen, mixed, and stored in sealed plastic jars for analysis. Representative sub-samples were drawn to determine total C and total N (CHN analyser), total P (Page et al. 1982), Olsen P (Olsen et al. 1954), total K and NH₄OAc-exchangeable K (Page et al. 1982), and pH (1:2 soil:water suspension). Some 200–300 g dry soil was kept in air-tight plastic bottles for future reference. All the soils archived over the years were analysed at the same time for this study in May 2000. The bulk density of soil was measured in situ in 1998–1999 using metal rings (Arshad et al. 1996).

Apparent nutrient (N, P, and K) budgets were developed for selected treatments (1, 5, 9, 11, and 12) following the method described by Regmi et al. (unpublished data) using different inputs and outputs measured by us during the present experiment and by Mishra (1980), Brown et al. (1999), and Smaling and Fresco (1993). Among inputs, N, P, and K contents in mineral fertilizer and organic manure were measured in the present study. The N, P, and K contributions of 11.0, 0.2, and 20 kg ha⁻¹ year⁻¹ with irrigation water (150 cm year⁻¹) plus rainfall were based on the data reported by Mishra (1980) for Pantnagar, India (29°N and 79°5'E and an altitude of 244 m above mean sea level), which has geographic and climatic features similar to those of the area under study. Similar values for N input from irrigation water were also reported by Brown et al. (1999) for Nepal. N input from biological

N₂ fixation was considered to be at the rate of 10 kg ha⁻¹ during rice and 5 kg ha⁻¹ during wheat cultivation (Brown et al. 1999). The quantities of N, P, and K added to the soil with rice seedlings (dry weight 75.6 kg ha⁻¹) and wheat seeds (120 kg ha⁻¹) were obtained by considering N, P, and K contents as 41.0, 4.0, and 30.0 g kg⁻¹ in rice seedlings (dry weight) and 20.0, 3.6, and 4.0 g kg⁻¹ in wheat seeds, respectively.

Plant uptake of N, P, and K was estimated using the QUEFTS (quantitative evaluation of fertility of tropical soils) model calibrated for rice (Witt et al. 1999) and wheat (Pathak et al., unpublished data). Total loss (gaseous plus leaching) of fertilizer N was taken to be 700 g kg⁻¹ for rice and 600 g kg⁻¹ for wheat (Tandon 1994). These high estimates of fertilizer-N losses are possible due to the relatively low yields of rice and wheat in this experiment. Losses of soil N and manure N were estimated based on data reported by Smaling and Fresco (1993) and Kundu and Ladha (1995). Green manure N was assumed to behave similarly to fertilizer N (Singh et al. 1992). We assumed that there would be no loss of P through leaching or otherwise from the soil system. The leaching loss of K was taken to be 150 g kg⁻¹ of K input (Smaling and Fresco 1993; Bhandari et al. 2001).

Data analysis

Regression analysis was done to determine grain yield trends over the years. ANOVA was done to test the differences between treatments. The maximum yields of rice and wheat discussed in the paper were the average of three maximum yields from 20 years of the experiment.

Results and discussion

Grain yield

On average during a 20-year period, the unfertilized plot with an indigenous nutrient supply supported 2.06 Mg rice ha⁻¹ and 0.69 Mg wheat ha⁻¹. Rice responded to N application (100 kg N ha⁻¹) (T2), increasing yield to an average of 2.89 Mg ha⁻¹ (Table 2). The application of P (T3), K (T4) or both P and K (T5) with N did not improve the yield further. Likewise, the amendment of ZnSO₄ (T10) had no effect on grain yield of rice. This indicated that P, K, S, and Zn were not limiting yields. Maximum yields obtained with different treatments during 20 years also showed similar trends, but they were higher by 1 Mg ha⁻¹ in the control (T1) and by 1.71 Mg ha⁻¹ in the NPK treatment (T5) than those of average yields (Table 2).

Like rice, wheat responded to the addition of N. Both average and maximum wheat yields were highest in treatments with full applications of NPK either with (T10) or without Zn (T5, T6, T11, and T12). Using 50% N reduced the wheat yield compared with 100% N, suggesting that N really limited wheat yield (Table 2). The maximum wheat yields of the control (T1) and NPK treatment (T5) were 0.67 Mg ha⁻¹ and 1.0 Mg ha⁻¹ higher, respectively, than average yields. Omission of either P (T4), K (T3), or both (T2) led to yields similar to those of NPK (T5), indicating that wheat did not respond to P and K. The lack of a significant response, particularly in wheat, may be partly due to very low yields. No residual effect of FYM (T11) and WCS (T12) applied to rice was

Table 2 Yields of the 20-year long-term rice-wheat experiment in Parwanipur, Nepal. Means followed by the *same letter* in a column did not differ significantly ($P \leq 0.05$) according to Duncan's multiple range test (DMRT)

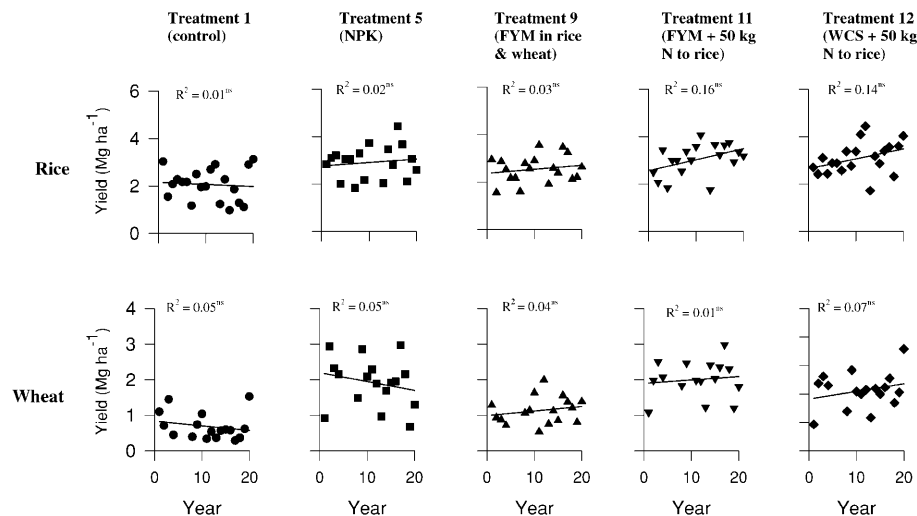
Treatment	Rice		Wheat	
	Mean (Mg ha ⁻¹)	Maximum ^a (Mg ha ⁻¹)	Mean (Mg ha ⁻¹)	Maximum (Mg ha ⁻¹)
1	2.06c	3.02c	0.69d	1.36d
2	2.89ab	4.21ab	1.51b	2.55a
3	2.94ab	4.28ab	1.60b	2.51a
4	3.05ab	4.35ab	1.73b	2.85a
5	3.13a	4.84a	1.92ab	2.92a
6	3.00ab	4.54a	2.01ab	2.85a
7	2.47bc	3.70bc	1.32c	2.09bc
8	2.81ab	4.22ab	1.48bc	2.33b
9	2.65ab	3.91ab	1.14c	1.73cd
10	3.15a	4.56a	2.16a	2.85a
11	3.13ab	4.21ab	2.07a	2.86a
12	3.08ab	4.18ab	2.13a	3.01a

^a Average of 3 years' maximum yields

found in wheat as similar yields were recorded to those of inorganic NPK (T5) or inorganic N (T6). On the contrary, the application of FYM to both rice and wheat (T9) led to lower wheat yields than in T5 and T11, which could have been due to a low N supply (80 kg crop⁻¹) and slow mineralization of N from FYM (Becker et al. 1994; Clement et al. 1995). This suggests that the integrated use of N is better than supplying it only through FYM.

Grain yields of rice and wheat (Fig. 1) fluctuated over the years. Changes in crop management caused yield fluctuations as different persons handled the experiment during different years. The trend analysis showed that grain yields of both rice and wheat were maintained over the years in treatments with NPK (T5), FYM (T9), FYM plus 50 kg N ha⁻¹ to rice (T11), and WCS plus 50 kg N ha⁻¹ (T12), as well as in unfertilized plots (T1). However, the yields of both rice (maximum 3.15 Mg ha⁻¹) and wheat (maximum 2.16 Mg ha⁻¹) were low and were only 40–50% of the maximum attainable yield in this region (unpublished data). A delay in the sowing of wheat was a likely reason for lower yields, as wheat was planted on 5–15 December. A yield loss of 40 kg ha⁻¹ day⁻¹ has been reported if wheat is planted after 15 November (Hobbs et al. 1996; Regmi et al., unpublished data). We suspect that poor crop and water management in this long-term experiment has also contributed to the lower yield. Because of a water shortage, the experimental plots often did not receive irrigation. Another reason for the low yield of rice was the single topdressing of N at 25–30 DAT. Normally, at least two N topdressings are recommended to achieve high yields (Cassman et al. 1996). It is known that a single N application during crop growth is not adequate, particularly in loamy sand soils in which N losses are high.

Fig. 1 Trends in yields of rice and wheat in the long-term experiment at Parwanipur, Nepal. *FYM* Farmyard manure, *WCS* wheat chopped straw, *ns* not significant at $P < 0.05$



Soil Properties

Total C and Total N

Total C and N contents were analysed in selected treatments in soil samples archived from 1994 to 1999. Regression analysis showed no change as the slopes were not significant in all the treatments, suggesting that C and N established an equilibrium (Fig. 2). These results are consistent with our analysis of other rice-wheat long-term experiments in the Indo-Gangetic Plains (Bhandari et al. 2001; Regmi et al., unpublished data). However, both C and N differed significantly among treatments (Table 3). Compared with the control (T1) and full NPK (T5), C and N differed significantly in treatments where either FYM or WCS was applied (T9, T11, and T12). The treatment with FYM applied to both rice and wheat crops (T9) accumulated the most C and N, which were 62% and 67% higher than in the NPK (T5) treatment, respectively. Both the unfertilized control (T1) and NPK (T5) treatments had similar total soil C and N. No increase in soil N content in the NPK treatment suggests that N applied as an inorganic source is readily lost and it is difficult to build up soil N with the application of inorganic N alone. Though the input of N was less ($160 \text{ kg ha}^{-1} \text{ year}^{-1}$) in the FYM treatment (T9) than in the NPK treatment (T5) ($200 \text{ kg ha}^{-1} \text{ year}^{-1}$), lower losses of N in the FYM treatment due to the slow release of N from FYM (T9) may be responsible for such an increase in total soil N (Bhandari et al. 1992; Yadav et al. 2000). Organic fertilizers such as compost or FYM are known to stimulate biological N_2 fixation in the soil, which may also have been responsible for the increase in total soil N (Ladha et al. 1989).

Total and available P and K

Plots receiving FYM in both rice and wheat (T9) had 59% and 70% higher total and Olsen P, respectively,

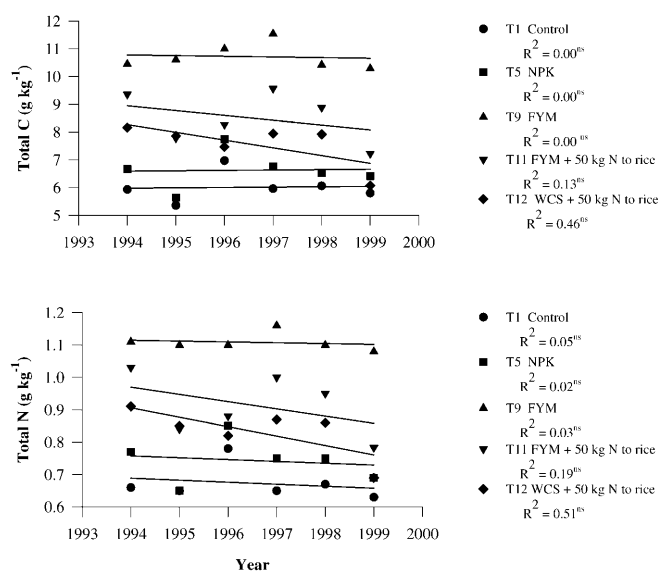


Fig. 2 Changes in total C and total N in soil from 1994 to 1999 due to rice-wheat cropping. The changes in total C and N with time (coefficients of the x variable) were not significant in all the cases. For abbreviations, see Fig. 1

whereas the application of FYM in rice only (T11) gave 50% and 70% higher total and Olsen P, respectively, than those of the NPK (T5) treatment (Table 3). Treatment 12 with WCS also had a lower total and Olsen P than the FYM treatments (T9 and T11). The difference in total soil P between the NPK and FYM treatments is related to differences in added P. The addition of P with FYM was higher ($36 \text{ kg ha}^{-1} \text{ year}^{-1}$) than that added in the fertilizer NPK treatment ($26.2 \text{ kg ha}^{-1} \text{ year}^{-1}$). The application of FYM increased Olsen P because of its P content, and possibly by reducing precipitation as Ca phosphate (Gupta et al. 1988). Only 1.92–3.15% of total P was present in the soil as Olsen P.

Total and available soil K remained unchanged in the different treatments (Table 3). Total K was in the range

Table 3 Total C, N, P, and K, Olsen P, available K, bulk density, and pH of soils during 1998–1999. Means followed by the *same letter* in a column did not differ significantly ($P \leq 0.05$) by DMRT. For abbreviations, see Table 1

Treatment	Total C (g kg ⁻¹)	Total N (g kg ⁻¹)	Total P (g kg ⁻¹)	Olsen P (g kg ⁻¹)	Total K (g kg ⁻¹)	NH ₄ OA _c - extractable K (g kg ⁻¹)	Bulk density (Mg m ⁻³)	pH
Control (T1)	6.06 ^{da}	0.68 ^c	0.26 ^{bc}	0.005 ^c	11.90 ^a	0.022 ^a	1.65 ^a	7.1 ^a
NPK (T5)	6.67 ^d	0.75 ^c	0.34 ^b	0.010 ^b	11.57 ^a	0.022 ^a	1.49 ^a	6.7 ^a
FYM (T9)	10.80 ^a	1.11 ^a	0.54 ^a	0.017 ^a	11.37 ^a	0.022 ^a	1.40 ^a	7.3 ^a
FYM plus 50 kg N to rice (T11)	8.77 ^b	0.94 ^b	0.51 ^a	0.017 ^a	11.40 ^a	0.021 ^a	1.41 ^a	6.8 ^a
WCS plus 50 kg N to rice (T12)	7.87 ^c	0.86 ^b	0.30 ^b	0.008 ^b	11.45 ^a	0.023 ^a	1.40 ^a	6.5 ^a

Table 4 Apparent average N, P, and K balances in rice-wheat long-term experiment, Parwanipur, Nepal. For abbreviations, see Table 1

Crop	Treatments				
	Control (T1)	NPK (T5)	FYM (T9)	FYM plus 50 kg N to rice (T11)	WCS plus 50 kg N to rice (T12)
	N (kg ha ⁻¹ year ⁻¹)				
Rice	-12	4	45	53	17
Wheat	-12	3	42	-16	-2
Rice+Wheat	-24	7	87	37	15
	P (kg ha ⁻¹ year ⁻¹)				
Rice	-4	6	12	11	-2
Wheat	-2	7	15	7	7
Rice+Wheat	-6	13	27	18	5
	K (kg ha ⁻¹ year ⁻¹)				
Rice	-11	-5	20	14	-11
Wheat	-16	-28	12	-32	-33
Rice+Wheat	-27	-33	32	-18	-44

of 11.37–11.90 g kg⁻¹ soil, whereas available K ranged from 0.021 to 0.023 g kg⁻¹ soil. A small fraction (0.18–0.20%) of total soil K was in exchangeable form, i.e. available soil K.

Bulk density and pH

After 20 years of rice-wheat cropping, the bulk density of soils ranged from 1.40 Mg m⁻³ with the application of FYM in rice and wheat (T9) to 1.65 Mg m⁻³ in the unfertilized plot (T1); however, these values were on a par statistically. When the experiment began, the soil had a bulk density of 1.6 Mg m⁻³, indicating no significant change after rice-wheat cropping. Soil pH also did not differ among treatments after 20 years of cropping and ranged from 6.5 with WCS (T12) to 7.3 with FYM application in rice and wheat (T9) (Table 3), whereas the benchmark soil had pH 7.0.

Apparent N, P, and K balance

The apparent N balance was positive in the NPK (T5), FYM (T9 and T11), and WCS treatments (T12), but, in the unfertilized plot (T1), there was a net outflux of 24 kg N ha⁻¹ year⁻¹ (Table 4). The highest gain of 87 kg N ha⁻¹ year⁻¹ was estimated with the FYM treatment

(T9), whereas the NPK treatment had a net gain of 7 kg N ha⁻¹ year⁻¹. A net loss of 6 kg P ha⁻¹ year⁻¹ was estimated for the control treatment, whereas the NPK (T5) and FYM (T9) treatments had an apparent net P gain of 13 and 27 kg ha⁻¹ year⁻¹, respectively. The treatment with WCS had a net gain of 5 kg P ha⁻¹ year⁻¹. Apparent P balance estimates were in conformity with soil total P. The apparent K balance was negative in all plots except the FYM treatment (T9). The NPK (T5) and WCS (T12) treatments had net losses of 33 and 44 kg K ha⁻¹ year⁻¹, respectively, whereas with FYM application to rice and wheat (T9) there was a gain of 32 kg K ha⁻¹ year⁻¹. The control plot also had a negative balance of 27 kg K ha⁻¹ year⁻¹. The balance of N, P, and K between the FYM and WCS treatments was different because different quantities of N, P, and K were added through these two sources.

In conclusion, the grain yields of rice and wheat were maintained in a 20-year experiment at Parwanipur, though the yields fluctuated greatly over the years. In addition, both rice and wheat yields with full NPK or FYM treatments in most years were <3.15 Mg ha⁻¹ and <2.16 Mg ha⁻¹, respectively, which were only 40–50% of the potential attainable yields in the region. The following possible reasons for the large fluctuation and low yields of rice and wheat were identified: (1) changes in crop management as different persons handled the experiment during different years, (2) frequent water shortage

caused by poor irrigation facilities coupled with high water percolation, (3) a delay in the sowing of wheat, and (4) poor N timing in rice.

Acknowledgements We wish to thank Max Alumaga of IRRI for the carbon and nitrogen analyses and the technical staff of Nepal Agricultural Research Council in Parwanipur for preparing soil samples. Thanks also to Morten Jensen and Leny Bueno for their helpful advice.

References

- Arshad MA, Lowery B, Grossman B (1996) Physical tests for monitoring soil quality. In: Doran JW, Jones AJ (eds) *Methods for assessing soil fertility*. Soil Science Society of America, special publication no. 49. Soil Science Society of America, Madison, Wis., pp 123–142
- Becker M, Ladha JK, Simpson IC, Ottow JCG (1994) Parameters affecting residue nitrogen mineralization in flooded soils. *Soil Sci Soc Am J* 58:1666–1671
- Bhandari AL, Sood A, Sharma KN, Rana DS (1992) Integrated nutrient management in a rice-wheat system. *J Indian Soc Soil Sci* 40:742–747
- Bhandari AL, Ladha JK, Pathak H, Dawe D, Gupta RK (2001) Trends of yield and soil nutrient status in a long-term rice-wheat experiment in Indo-Gangetic Plains of India. *Soil Sci Soc Am J* (in press)
- Brown S, Schreier H, Shah PB, Lavkulich LM (1999) Modelling soil nutrient budgets: an assessment of agricultural sustainability in Nepal. *Soil Use Manage* 15:101–108
- Cassman KG, Gines GC, Dizon MA, Samson MI, Alcantara JM (1996) Nitrogen use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. *Field Crops Res* 47:1–12
- Clement A, Ladha JK, Chalifour FP (1995) Crop residue effects on nitrogen mineralization, microbial biomass, and rice yield in submerged soils. *Soil Sci Soc Am J* 59:1595–1603
- Duxbury JM, Abrol IP, Gupta RK, Bronson KF (2000) Analysis of long-term soil fertility experiments with rice-wheat rotations in South Asia. In: Abrol IP, Bronson KF, Duxbury JM, Gupta RK (eds) *Long-term soil fertility experiments with rice-wheat rotations in South Asia*. Rice-Wheat Consortium paper series no. 6. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, pp 7–22
- Gupta AP, Antil RS, Narwal RP (1988) Effect of farmyard manure on organic carbon, available N, and P content of soil during different periods of wheat growth. *J Indian Soc Soil Sci* 262:269–273
- Hobbs PR, Morris ML (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 DF, pp 1–45
- Hobbs PR, Harrington LW, Adhikari C, Giri GS, Upadhyaya SR, Adhikari B (1996) Wheat and rice in the Nepal Tarai: farm resources and production practices in Rupandehi District. NARC, CIMMYT, Mexico DF, pp 1–44
- Kundu DK, Ladha JK (1995) Efficient management of soil and biologically fixed N₂ in intensively-cultivated rice fields. *Soil Biol Biochem* 27:431–439
- Ladha JK, Padre AT, Punzalan GC, Garcia M, Watanabe I (1989) Effect of inorganic N and organic fertilizers on nitrogen-fixing (acetylene-reducing) activity associated with wetland rice plants. In: Skinner et al. FA (eds) *N₂ fixation with non-legumes*. Kluwer, Dordrecht, pp 263–272
- Ladha JK, Fischer KS, Hossain M, Hobbs PR, Hardy B (2000) Improving the productivity and sustainability of rice-wheat systems of the Indo-Gangetic Plains: a synthesis of NARS-IRRI partnership research. Discussion paper no. 40. International Rice Research Institute, Makati City, Philippines, pp 1–31
- Mishra B (1980) A systems approach for fertilizer management practices in rice-wheat cropping systems. *Fert News* 258:14–18
- Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA circular no. 939. USDA, Washington DC
- Page AL, Miller RH, Keeney DR (editors) (1982) *Methods of soil analysis*. Part 2. Chemical and microbiological properties, 2nd edn. Agronomy no. 9. ASA-SSSA, Madison, Wis.
- Singh Y, Bijay Singh, Khind CS (1992) Nutrient transformation in soils amended with green manures. *Adv Soil Sci* 20:237–309
- Smaling EMA, Fresco LO (1993) A decision support model for monitoring nutrient balances under agricultural land use – NUTMON. *Geoderma* 60:235–256
- Tandon HLS (1994) Fertilizers, organic manures, recyclable wastes and biofertilizers. Fertilizer Development and Consultation Organization, New Delhi
- Witt C, Dobermann A, Abdurachman S, Gines HC, Guanghuo W, Nagarajan R, Satawathananont S, Tran Thuc Son, Pham Sy Tan, Le Van Tiem, Simbahan G, Olk DC (1999) Internal nutrient efficiencies in irrigated lowland rice of tropical and subtropical Asia. *Field Crops Res* 63:113–138
- Yadav RL, Dwivedi BS, Pandey PS (2000) Rice-wheat cropping system: assessment of sustainability under green manuring and chemical fertilizer inputs. *Field Crops Res* 65:15–30