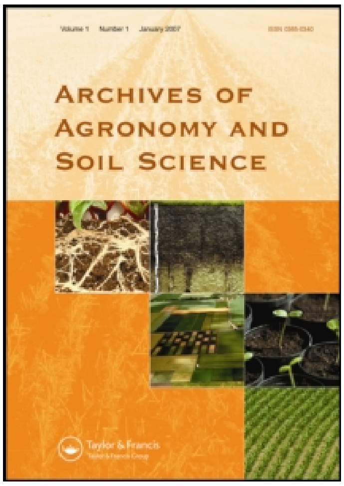

Archives of Agronomy and Soil Science
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453776

Effect of cropping system on production and chemical and biological properties of soil

S. N. Sharma[a]; R. Prasad[a]; M. K. Dwivedi[a]; Sandeep Kumar[a]; M. R. Davari[a]; Moola Ram[a]
[a] Department of Agronomy, Indian Agricultural Research Institute, New Delhi, India

To cite this Article Sharma, S. N. , Prasad, R. , Dwivedi, M. K. , Kumar, Sandeep , Davari, M. R. and Ram, Moola(2009) 'Effect of cropping system on production and chemical and biological properties of soil', Archives of Agronomy and Soil Science, 55: 4, 429 — 438

To link to this Article: DOI: 10.1080/03650340802585197

URL: http://dx.doi.org/10.1080/03650340802585197

Archives of Agronomy and Soil Science
Vol. 55, No. 4, August 2009, 429–438

Effect of cropping system on production and chemical and biological properties of soil

S.N. Sharma*, R. Prasad, M.K. Dwivedi, Sandeep Kumar, M.R. Davari and Moola Ram

Department of Agronomy, Indian Agricultural Research Institute, New Delhi, India

(*Received 16 June 2008; final version received 27 October 2008*)

A field study was carried out at the Indian Agricultural Research Institute, New Delhi, India, for three crop years (2000–2001 to 2003–2004) to find out the effect of cropping systems on the production and chemical and biological properties of soil. Rice-potato-mungbean cropping system gave 59–89% higher productivity, 30–46% higher protein yield, 18–38% higher energy output and resulted in 7–16% higher available P, 60% higher fungi population, 15% higher actinomycetes population, 14% higher microbial biomass and 3% higher CO_2 evolution in soil than rice-wheat cropping system. Rice-rapeseed-mungbean cropping system also gave 12–15% higher productivity, 19–26% higher protein yield and resulted in 11–18% higher available P, 65% higher fungi population, 22% higher actinomycetes population, 12% higher microbial biomass and 2% higher CO_2 evolution in soil than rice-wheat cropping system. However, the rice-potato-mungbean cropping system was significantly superior to the rice-rapeseed-mungbean cropping system in productivity, protein yield and energy output and thus recommended as in alternative to rice-wheat cropping system.

Keywords: available K; available P; CO_2 evolution; economic yield; energy output; microbial biological; microbial population; productivity; protein yield, rice-wheat; rice-potato-mungbean; rice-rapeseed-mungbean

Introduction

The rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping systems (RWCS) occupy about 28.8 million hectares (m ha) in Asia's five countries, namely, India, Pakistan, Nepal, Bangladesh and China (Prasad 2005). These five countries actually represent 43% of the world's population and 20% of the world's arable land (Singh and Paroda 1994). Taking these five countries together, RWCS cover 28% of the total rice area and 35% of the total wheat area. In India, RWCS occupy 12 m ha and contribute about 31% of the total food grain production (Kumar et al. 1998). Similarly, in China RWCS occupy about 13 m ha (Jiaguo 2000) and contribute about 25% of the total cereal production in the country (Lianzheng and Yixian 1994). Thus, RWCS are of considerable significance in meeting Asia's food requirements. However, the practice of following a cereal-cereal cropping system on the same piece of land over years has led to soil fertility deterioration and questions are being raised on its sustainability (Duxbury et al. 2000; Ladha et al. 2000; Prasad 2005). Efforts are therefore underway to find alternative cropping systems specially those involving legumes which have soil recuperative properties (Sharma and Sharma

*Corresponding author. Email: snsharma_agro@yahoo.com

ISSN 0365-0340 print/ISSN 1476-3567 online

DOI: 10.1080/03650340802585197
http://www.informaworld.com

2004; Singh and Dwivedi 2006). The present investigation was undertaken to study the effect of crop diversification on production and chemical and biological properties soil.

Materials and methods

Site and soil

Field experiments were conducted during the three crop years (June–July) from 2001–2002 to 2003–2004 at the Indian Agricultural Research Institute, New Delhi, India (28°38′ N latitude, 77°11′ E longtitude and 228.6 m above mean sea level). The soil of the experimental field was a sandy clay loam, Ustochrept of pH 8.2 (1:2.5 soil to water ratio) (Table 1). It contained 5.8 g kg^{-1} soil organic C, 585 mg kg^{-1} soil Kjeldahl N, 7.1 mg kg^{-1} soil 0.5 M $NaHCO_3$ extractable P and 223 mg kg^{-1} soil 1 N NH_4OAC extractable K.

Experimental design and treatments

The experiments were laid out in a randomized block design with six replications. The treatments consisted of three cropping systems, namely, rice-wheat, rice-potato (*solanum tuberosum*)-mungbean (*Vigna radiata*) and rice-rapeseed (*Brassica compestris var. Toria*)-mungbean. The treatments were allocated to different plots randomly using Fisher and Yates (1983) random number table. The gross plot size was 50 × 7 m and net plot size was 48 × 6 m.

Cropping systems

There are three growing seasons in India in a year, namely, rainy (July to November), winter-spring (November to April) and summer (April to June). In the rice-wheat cropping system (RWCS) rice was grown during the rainy season followed by wheat during winter-spring season and the field was kept fallow during summer. In rice-rapeseed-mungbean cropping system (RRMCS), rice was grown in rainy season, rapeseed during winter-spring and mungbean during summer season. Similarly in rice-potato-mungbean cropping system (RPMCS), rice was grown during the rainy season followed by potato in winter-spring and mungbean during summer.

Table 1. Mechanical and chemical characteristics of soil of the experimental field at the start of experiment.

Particulars	Value
Mechanical composition	
Sand	52.5%
Silt	21.0%
Clay	26.5%
Textural class	Sandy clay loam
pH (1:2.5 soil:water ratio)	8.1
Electrical conductivity	0.82 dS m^{-1}25°C
Cation exchange capacity	14.65 C.mol kg^{-1} soil
Organic C	6.2 g kg^{-1} soil
Total Kjeldahl N	650 mg kg^{-1} soil
Available P	6.1 mg kg^{-1} soil
Available K	223 mg kg^{-1} soil

Field techniques

During summer, the plots under RWCS were kept fallow and received no fertilizer. The plots under RPMCS and RPMCC were irrigated and tilled at optimum moisture level. Mungbean variety PS 16 was seeded at a uniform row spacing of 30 cm in the last week of March each year. The crop received a basal dose of 20 kg N ha^{-1} as urea and 26 kg P ha^{-1} as diammonium phosphate (DAP) at sowing. The crop was harvested in the last week of June.

During the rainy season, the field was flooded with water and puddled with a tractor drawn off-set disc harrow. A basal dose of 26 kg P ha^{-1} of DAP, 33 kg K ha^{-1} as muriate of potash (MOP) and 4.5 kg ha^{-1} as zinc sulphate heptahydrate was applied at final puddling. Nitrogen at 120 kg N ha^{-1} as urea was applied in two splits, half the dose at 10 days after transplanting (DAT) and the rest at 30 DAT. The rice (variety, Pusa Basmati 1) was transplanted in mid-July with 2–3 seedlings of 21–25 days of age $hill^{-1}$ at a spacing of 20 $\times$ 10 cm. Rice was harvested in the first week of November.

During the winter season, the field was irrigated after the rice harvest and at optimum soil moisture level, the land was prepared by disking and planking. Potato (variety Kufri Badshah) and rapeseed (variety Pusa bold) were sown during the second week of November, while the wheat (variety HD 2627) was sown in the third week of November. The potato crop received 60 kg N ha^{-1} as urea, 26 kg P ha^{-1} as DAP and 67 kg K ha^{-1} as MOP at sowing and 60 kg N ha as urea at 40 days after sowing (DAS). The wheat received 60 kg N ha^{-1} as urea, 26 kg P ha^{-1} as DAP and 33 kg K ha^{-1} as MOP at sowing and 60 kg N ha^{-1} as urea at 40 DAS. The rapeseed received 40 kg N ha^{-1} as urea, 26 kg P ha^{-1} as DAP, 33 kg K ha^{-1} as MOP at sowing and 40 kg N ha^{-1} as urea at 40 DAS. Potato and rapeseed were harvested in the second week of March and wheat in the second week of April. All the crops were irrigated. In all the three years, wheat received four irrigations (21, 45, 70 and 95 DAS), potato received six irrigations (20, 40, 60, 80, 100 and 120 DAS) and rapeseed three irrigations (30, 45 and 65 DAS). Mungbean received two irrigations (25 and 45 DAS).

Soil sampling and chemical analysis

Soil samples (0–20 cm depth) were collected from the experimental field before the start of the experiment and analysed for soil particle composition (Piper 1950), organic C, total Kjeldahl-N, 0.5 M $NaHCO_3$ extractable P, 1 N NH_4OAC extractable K and pH using the procedures described by Prasad et al. (2006) and data are given in Table 1. Again after completing each cycle of different cropping systems, soil samples (0–20 cm depth) for each plot were collected and analysed for organic C, total Kjeldahl-N, 0.5 M $NaHCO_3$ extractable P and 1 N NH_4OAC extractable K. At the end of three cycles of different cropping systems the soil (0–20 cm) was also analysed for the population of bacteria, fungi and actinomycetes and microbial biomass as per procedure described by Subba Rao (1977).

Data collection and statistical analysis of data

Net plot of each treatment of each replication was harvested and threshed separately. The grain/seed was cleaned and weighed. The grain/seed yield was adjusted at 14% moisture for rice and at 8% moisture for other crops. The straw yield was obtained by subtracting the grain seed yield from total biomass of the net plot. The data obtained for each character were analysed by applying the techniques of 'Analysis of Variance' (Gomez and Gomez 1984). The significance of the treatment was tested by F-test and Least Significant Difference (LSD) at 5% error probability was calculated to compare the means of different treatment.

Rice equivalents, protein yield and energy output

The productivity of different cropping systems cannot be compared on the basis of grain/tuber yields per se because the winter crops differ in the value of their economic produce. Therefore rice equivalents of different crops were calculated using the following expression:

$$\text{rice equivalents } (\text{Mgha}^{-1}) = \text{Ya} \times \text{Pa}/\text{Pr}$$

where, Ya is the economic yield of crop a (other than rice) in Mg ha^{-1}, Pa is the unit price of the economic produce of crop a and Pr is the unit price of rice grain in Indian Rupees Mg^{-1}. Since the data on rice equivalents are subject to variation in commodity prices, which differ in different countries, protein yield ha^{-1} and energy output ha^{-1} were also computed for comparing the cropping systems from the human and animal nutrition viewpoint. Protein content in rice grains was obtained by multiplying N concentration of grain with a factor 5.95 (Juliano 1985), whereas the protein content in grain/seed/tubers of other crops was calculated by multiplying N concentration with a factor 6.25. The protein yield of different crops was calculated by multiplying their protein concentration with grain/seed/tuber yield. The energy output was calculated by multiplying energy content of grain/seed/tuber of different crops as obtained by Singh et al. (1996) with their yield.

Results

Productivity

The study was started with the rice crop, and its grain yield was almost similar in all the three cropping systems in the first year, whereas in the second and third years, grain yield of rice was significantly influenced by the crops grown during winter and summer seasons (Table 2). The cropping systems having summer mungbean, a legume (RRMCS and RPMCS) produced significantly more rice grain than RWCS. During the winter seasons wheat yield ranged from 4.5–5.7 Mg ha^{-1} in RWCS, rapeseed from 1.5–1.9 Mg ha^{-1} in RRMCS and potato from 24.9–26.5 t ha^{-1} in RPMCS. During the summer seasons, mungbean yields were similar in RRMCS and RPMCS and ranged from 0.6–0.9 Mg ha^{-1} in the different years of the study.

As regards total productivity of different cropping systems, RPMCS gave the highest value of rice equivalents, significantly more than RRMCS, which in turn, gave significantly more rice equivalents than RWCS in all the three years of study. Higher value of rice equivalents in RPMCS was due to 4.3–4.9 times higher yield of potato than wheat yield and additional contribution by mungbean; of course, the price of wheat was 2.5 times higher than price of potato. The higher value of rice equivalents in RRMCS, on the other hand, was due to 2.4 times higher price of rapeseed than that of wheat and additional contribution by mungbean; of course the wheat yields were 2.4–3.3 times higher than rapeseed yields. Also, the rice yields were higher in RPMCS and RRMCS than in RWCS.

Protein yield

There was no significant difference between protein yield of rice in the three cropping systems during the first year, whereas in second and third years, protein yield of rice in RRMCS and RPMCS was similar but significantly higher than the protein yield of rice in RWCS (Table 3). During the winter season, potato gave the highest protein yield which was significantly more than that of wheat and rapeseed; the latter two did not differ in their protein yield in all the three years of study. During summer, protein yield of mungbean was similar in RRMCS and RPMCS in all the years of the study. As regards total protein yield of a cropping system, RPMCS gave significantly higher protein yield than RRMCS, which in turn, was significantly superior to RWCS in all the three years.

Table 2. Effect of cropping systems on economic yield (Mg ha^{-1}) of different crops.

Cropping systems	Rice	Winter crop	Mungbean	Rice equivalents* of cropping system
			2001–2002	
RWCS	6.2	4.4	–	9.6
RRMCS	6.2	1.8	0.6	10.8
RPMCS	6.2	28.6	0.7	15.6
LSD ($p = 0.05$)	NS	NC	NS	0.8
			2002–2003	
RWCS	4.7	4.9	–	8.4
RRMCS	5.2	1.5	0.9	9.7
RPMCS	5.6	27.6	0.9	15.9
LSD ($p = 0.05$)	0.68	NC	NS	0.9
			2003–2004	
RWCS	5.1	5.7	–	9.5
RRMCS	5.7	2.0	0.7	10.6
RPMCS	5.8	24.8	0.8	15.1
LSD ($p = 0.05$)	0.61	NC	NS	1.0

NS: Non-significant; NC: non-comparable; *Rice equivalents were calculated based on current prices of Rice: Rs. 8000 Mg^{-1}, Wheat: Rs; 6200 Mg^{-1}, Potato: Rs. 2500 Mg^{-1}, Rapseed: Rs. 15000 Mg^{-1} and Mungbean: Rs. 15000 Mg^{-1}.

Table 3. Effect of cropping systems on protein yield (Mg ha^{-1}) of different crops.

Cropping systems	Rice	Winter crop	Mungbean	Total
		2001–2002		
RWCS	0.36	0.45	–	0.81
RRMCS	0.37	0.46	0.14	0.97
RPMCS	0.37	0.56	0.15	1.08
LSD ($p = 0.05$)	NS	0.04	NS	0.10
		2002–2003		
RWCS	0.33	0.45	–	0.78
RRMCS	0.37	0.41	0.20	0.98
RPMCS	0.39	0.55	0.20	1.14
LSD ($p = 0.05$)	0.03	0.04	NS	0.12
		2003–2004		
RWCS	0.34	0.50	–	0.84
RRMCS	0.37	0.47	0.16	1.00
RPMCS	0.38	0.54	0.17	1.09
LSD ($p = 0.05$)	0.03	0.05	NS	0.11

NS: Non-significant.

Energy outputs

During the rainy season, there was no significant difference between energy outputs of rice grown in the three cropping systems in the first year, whereas in the second year, rice in RPMCS resulted in significantly higher energy outputs than rice in RRMCS, which in turn gave significantly higher energy outputs than rice in RWCS (Table 4). During the third year, energy outputs of rice in RRMCS and RPMCS did not differ significantly, which was significantly more than that of RWCS. During the winter season, potato gave significantly higher energy outputs than wheat, which in turn, resulted in significantly higher energy outputs than rapeseed in all the three years of study. During summer, mungbean grown under RRMCS and RPMCS resulted in almost similar energy outputs. Regarding total energy outputs of a cropping system, RPMCS resulted in highest energy outputs (44.5–47.0 K cal $ha^{-1} \times 10^6$) followed by RWCS (33.6–37.8 K cal $ha^{-1} \times 10^6$) and RRMCS (30.6–34.8 K cal $ha^{-1} \times 10^6$), the latter two cropping systems did not differ significantly.

Chemical properties of soil

Cropping systems had no significant effect on organic C, Kjeldahl-N and 1 N NH_4OAC extractable K in all the three years of study, whereas 0.5 M $NaHCO_3$ extractable P content in soil differed significantly under different cropping systems. RRMCS and RPMCS resulted in significantly higher 0.5 M $NaHCO_3$ extractable P in soil than RWCS in all the three years of study (Table 5).

Biological properties of soil

There was no significant effect of cropping system on the number of bacteria in soil, whereas number of fungi and actinomycetes were significantly more under RRMCS and RPMCS than under RWCS (Table 6). Similarly microbial biomass and CO_2 evolution in soil were also significantly more under RRMCS and RPMCS than under RWCS, RRMCS and RPMCS being on a par in both the parameters (Table 7).

Table 4. Effect of cropping systems on energy output (K cal $\times 10^{-6}$ ha^{-1}) of different crops.

Cropping systems	Rice	Winter crop	Mungbean	Total
		2001–2002		
RWCS	21.7	15.5	–	37.2
RRMCS	21.8	10.9	2.1	34.8
RPMCS	21.8	22.8	2.4	47.0
LSD ($p = 0.05$)	NS	2.0	NS	4.8
		2002–2003		
RWCS	16.5	17.1	–	33.6
RRMCS	18.3	9.1	3.2	30.6
RPMCS	19.6	23.7	3.2	46.5
LSD ($p = 0.05$)	1.5	1.9	NS	3.1
		2003–2004		
RWCS	18.0	19.8	–	37.8
RRMCS	20.0	11.9	2.4	34.3
RPMCS	20.3	21.3	2.9	44.5
LSD ($p = 0.05$)	1.9	1.5	NS	4.1

Table 5. Effect of cropping systems on chemical properties of soil after completion of one cycle of different rice-based cropping systems.

Cropping systems	Organic C ($g\ kg^{-1}$ soil)	Kjeldahl N ($mg\ kg^{-1}$ soil)	0.5 M $NaHCO_3$ extractable P ($mg\ kg^{-1}$ soil)	1N NH_4OAC extractable K ($mg\ kg^{-1}$ soil)
		2001–2002		
RWCS	6.12	620	5.94	214
RRMCS	6.25	647	7.01	225
RPMCS	6.20	647	6.38	225
LSD ($p = 0.05$)	NS	NS	0.30	NS
		2002–2003		
RWCS	6.20	656	6.38	211
RRMCS	6.32	678	7.28	215
RPMCS	6.29	683	7.41	213
LSD ($p = 0.05$)	NS	NS	0.38	NS
		2003–2004		
RWCS	6.18	692	6.78	178
RRMCS	6.56	705	7.50	186
RPMCS	6.38	710	7.59	181
LSD ($p = 0.05$)	NS	NS	0.34	NS

Table 6. Effect of cropping systems on microbial population in soil after completion of three cycles of rice-based cropping systems.

Cropping system	Bacteria (cells $\times$ 10^6 g^{-1} soil)	Fungi (cells $\times$ 10^4 g^{-1} soil)	Actinomycetes (cells $\times$ 10^4 g^{-1} soil)
RWCS	5.4	2.0	12.9
RRMCS	5.8	3.3	15.8
RPMCS	6.1	3.2	14.9
LSD ($p = 0.05$)	NS	0.9	1.7

Table 7. Effect of cropping systems on microbial biomass and CO_2 evolution in soil after completion of three cycles of different rice-based cropping systems.

Cropping system	Microbial biomass ($\mu g\ g^{-1}$ soil)	CO_2 evolution ($\mu g\ g^{-1}$ soil 24^{-1} hours)
RWCS	184.0	521.0
RRMCS	205.3	533.5
RPMCS	209.4	536.4
LSD ($p = 0.05$)	20.1	10.2

Discussion

Currently there is a growing concern on the sustainability of RWCS (Duxbury et al. 2000; Ladha et al. 2000; Prasad 2005) and therefore there is an urgent need for finding alternative cropping systems. Duxbury et al. (2000) reported that eight out of 11 experiments on RWCS showed a decline in rice yield over time, whereas only three centres showed a decline in wheat yield. Similarly, Ladha et al. (2000) from a study of seven long-term experiments on RWCS observed that none had a decline in wheat yield, while at two centres, there was a decline in rice yield. Using CERES and SUCROS model, Timsina et al. (1995) also confirmed yield decline in RWCS. One of the major causative factors for such a decline in crop yield in RWCS is reported to be the decreasing availability of K (Regmi et al. 2002) and micronutrients Zn, Mn, Cu and Fe (Yadav 1998). Due to increasing salinity/sodicity problem in the RWCS belt of north-western India (Abrol et al. 1998) it is difficult to find a crop that can substitute rice, which tolerates the soil salinity/sodicity. Therefore, attempts were made to substitute wheat by rapeseed, an oilseed, or potato. Both these crops fetch more money than wheat in the Indian market. Also the country is facing an acute shortage of edible oil and during 2003–2004, 5.29 million tonnes of edible vegetable oil, worth approximately US $ 2.5 million, was imported in India (Fertilizer Association of India [FAI] 2006). Also, based on our earlier experience (Sharma et al. 1995a, 2000; Sharma and Prasad 1999) a summer mungbean crop was added to the two cropping systems. As expected, both RPMCS and RRMCS were found to be more profitable, as judged by rice equivalents, than RWCS. It was also found that growing of summer mungbean increased rice yields in the second and third year of study. Since the two cropping systems RRMCS and RPMCS did not differ significantly in respect of their effect on rice yield it is concluded that the benefits were mainly due to summer mungbean. The advantage of growing a legume in a cropping system is also reported by Voss and Shrader (1979), Rickerd et al. (1988), Kurtz et al. (1984), Ebelhar et al. (1984) and John et al. (1989). In addition to the N contribution by legumes increased P, K and micronutrient concentration and uptake by the succeeding crop has also been reported (Copeland and Crookston 1992).

The 0.5 M $NaHCO_3$ extractable P content in soil was also significantly affected by the different cropping systems. RRMCS and RPMCS recorded significantly more 0.5 M $NaHCO_3$ extractable P in soil than RWCS in the second and third year of study due to higher amount of P applied in RRMCS and RPMCS than in RWCS. RRMCS and RPMCS received 78 kg P ha^{-1} each year of study against 52 kg P ha^{-1} applied per year to RWCS.

As regards biological properties of soil, the population of fungi and actinomycetes was significantly more in RRMCS and RPMCS than in RWCS. Nair (1973) in a study with five different rice-based multiple cropping systems including rice-wheat, rice-potato-wheat, rice-rapeseed-mungbean, observed that the temperature had a dominating effect on bacterial population. In the present study, the possible reason for higher microbial population in RRMCS and RPMCS than in RWCS was due to the fact that growing mungbean kept soil temperatures lower by providing soil cover and also the crop received two irrigations. On the other hand, in the fallow plots the hot summer sun (maximum temperature up to 45°C) and lack of moisture in soil reduced microbial population. Temperature and moisture are the two main regulatory factors for microbial growth (Sharma et al. 1995b). Higher microbial population resulted in higher microbial biomass and microbial activity derived from CO_2 evolution in soil under RRMCS and RPMCS than under RWCS.

Conclusion

The present study shows that the rice-potato-mungbean cropping system holds considerable promise as an alternative to the rice-wheat cropping system. The proposed cropping system can also help in reducing the shortage of pulses in India.

References

Abrol IP, Yadav JSP, Masond FI. 1998. Salt-affected soils and their management. FAO soils Bull. 39. Rome: Food Agriculture Organization.

Copeland PJ, Crookstan RK. 1992. Crop sequence effects on nutrient composition of corn and soybean grown under high fertility. Agron J. 84:503–509.

Duxbury JM, Abrol IP, Gupta RK, Bronson K. 2000. Analysis of long-term soil fertility experiments with rice-wheat rotation in South Asia. In: Abrol IP, Bronson K, Duxbury JM, Gupta RK, editors. Long-term soil fertility experiments in rice-wheat cropping system. Rice-Wheat Consortium Res. Ser. No. 6. New Delhi: Rice-Wheat Consortium for the Indo-Gangetic Plains. p. vii–xxii.

Ebelhar SA, Frye WW, Blevins RL. 1984. Nitrogen from legume cover crops for no-tillage. Agron J. 76:51–55.

Fertilizer Association of India (FAI). 2006. Fertilizer statistics. 2005–2006. New Delhi, India: FAI.

Fisher RA, Yates F. 1983. Statistical tables for biological, agricultural and medical research. 6th ed. London: Oliver and Boyd.

Gomez KA, Gomez AA. 1984. Statistical procedure for agricultural research. 2nd ed. New York: Wiley.

Jiaguo Z. 2000. Rice-wheat cropping system in China. In: Hobbs PR, Gupta RK, editors. Soil and crop management practices for enhanced productivity of the rice-wheat cropping system in Sichuan Province of China. Rice-Wheat Consortium Paper Ser. 9. New Delhi: Rice-Wheat Consortium for the Indo-Gangetic Plains. p. 1–50.

John PS, Prasad R, Singh S, George M, Sharma SN. 1989. Effect of lentil residues on the yield and response of succeeding nitrogen. J Agron Crop Sci. 163:177–180.

Juliano BO. 1985. Polysaccharides, protein and lipids of rice. Rice chemistry and technology. Los Banos: The Philippines: International Rice Research Institute (IRRI). p. 98.

Kumar P, Joshi PK, Johanson C, Asokan M. 1998. Sustainability of rice-wheat based cropping systems in India. Econ Pol Wkly. 33:A152–158.

Kurtz LT, Boone LV, Peck TR, Hoeft RG. 1984. Crop rotation for efficient nitrogen use. In: Hanek RD, editor. Nitrogen in crop production. Madison (WI): American Society of Agronomy. p. 295–300.

Ladha JK, Fisher 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. Los Banos, Philippines: IRRI. p. 1–31.

Lianzheng W, Yixian G. 1994. Rice-wheat systems and their development in China. In: Paroda RS, Woodhead T, Singh RB, editors. Sustainability of rice-wheat production systems in Asia. Bangkok (ROAP): FAO.

Nair PKR. 1973. Quantitation changes in soil microorganisms under rice-based multiple cropping in northern India. Soil Biol Bioch. 5:387–388.

Piper CS. 1950. Soil and plant analysis. Australia: The University of Adelaide. p. 287.

Prasad R. 2005. Rice-wheat cropping system. Adv Agron. 86:285–339.

Prasad R, Shivay YS, Kumar Dinesh, Sharma SN. 2006. Learning of doing exercises in soil fertility. A practical manual for soil fertility. New Delhi: Division of Agronomy, Indian Agricultural Research Institute.

Regmi AP, Ladha JK, Pathak H, Pasuquin E, Bueno C, Dawe D, Hobbs PR, Joshy D, Maskey SL, Pandey SP. 2002. Analysis of yield and soil fertility trends in a 20-year rice-rice-wheat experiment in Nepal. Soil Sci Soc Am J. 66:857–867.

Rickerd DH, Gorden WB, Curl EA, Tonchton JT. 1988. Winter legume and tillage effects in cotton growth and soil ecology. Soil Tillage Res. 11:63–71.

Sharma SN, Prasad R, Singh S. 1995a. The role of mungbean residues and *Sesbania aculeata* green manure in the nitrogen economy of rice-wheat cropping system. Plant Soil. 172:123–129.

Sharma GD, Mishra RR, Ksattriya S. 1995b. Fungi and litter decomposition in the tropics. In: Reddy MV, editor. Soil organisms and little decomposition in the tropics. New Delhi: Oxford & IBH. p. 39–57.

Sharma SN, Sharma SK. 2004. Role of crop diversification and integrated nutrient management in resilience of soil fertility under rice-wheat cropping system. Arch Agron Soil Sci. 50:511–519.

Sharma SN, Prasad R. 1999. Effect of *Sesbania* green manuring and mungbean residue incorporation on productivity and nitrogen uptake of a rice-wheat cropping. Bioresource Tech. 67:171–175.

Sharma SN, Prasad R, Singh S, Singh P. 2000. On-farm trials of the effect of introducing a summer green manure of mungbean on the productivity of rice-wheat cropping system. J Agric Sci Camb. 134:169–172.

Singh RB, Paroda RS. 1994. Sustainability and productivity of rice-wheat system in the Asian-Pacific region: Research and technology development issues. In: Paroda RS, Woodhead T, Singh RB, editors. Sustainability of rice-wheat production system in Asia. Bangkok (ROAP): FAO. p. 1–35.

Singh VK, Dwivedi BS. 2006. Yield nitrogen use efficiency in wheat and soil fertility states as influenced by substitution of rice with pigeonpea in a rice-wheat cropping system. Austral J Exp Agric. 46:1185–1194.

Singh S, Pannu CJS, Singh S, Singh IP, Kaur S. 1996. Energy in Punjab agriculture. Ludhiana (India): Department of Farm Power and Machinery, Punjab Agriculture University. p. 3–6.

Subba R. 1977. Soil microorganisms and plant growth. New Delhi: Oxford and IBH.

Timsina I, Singh U, Singh Y, Lansigan FF. 1995. Addressing sustainability of rice-wheat system: Testing and application of CERES and SUCROS models. In: Fragile lives in fragile ecosystems. Manila (Philippines): IRRI. p. 633–656.

Voss RD, Shrader WD. 1979. Rotation effects and legume sources of nitrogen for corn. In: Bezdicek DA, Power JF, editors. Organic farming – current technology and its role in sustainable agriculture. ASA Spec. Pub. 46. Madison (WI): American Society of Agronomy. p. 61–68.

Yadav RL. 1998. Factor productivity tends in rice-wheat cropping system under long-term use of chemical fertilizers. Expl Agric. 34:1–8.