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Diversification of rice with pigeonpea in a rice–wheat cropping system on a Typic Ustochrept: effect on soil fertility, yield and nutrient use efficiency

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Abstract

Continuous adoption of rice–wheat cropping system (RWCS) has led to depletion of inherent soil fertility resulting in a serious threat to its sustainability in the Indo-Gangetic plain region (IGPR) of India. The inclusion of legumes in RWCS assumes a great significance to restore soil fertility. But farmers in the IGPR rarely grow legumes in the system. We, therefore, carried out farmers' participatory diagnostic survey in the Upper Gangetic plain zone (UGP) to understand farmers' fertilizer management practices for wheat (*Trititicum aestivum* L. *Emend Fiori & Paol*) following rice (*Oryza sativa L.*) or pigeonpea (*Cajanus cajan*(L.)*Millsp*). The survey indicated that most of the farmers in UGP grew pigeonpea in place of rice under RWCS as only a break crop at a 2–3 year interval. The farmers applied, on average, 11 kg N ha^{-1} and 24 kg P ha^{-1} to wheat sown after rice, and 12 kg N ha^{-1} and 19 kg P ha^{-1} to wheat sown after pigeonpea. Wheat yields, however, were lower (3.3 t ha^{-1}) when sown after pigeonpea than after rice (3.7 t ha^{-1}). The survey was followed by a field experiment at Modipuram (29° 4′ N), Meerut, India that continued during the three consecutive years (1998–1999 to 2000–2001) to examine the effect of inclusion of pigeonpea in place of rice on soil fertility, N and P use efficiency and yields of wheat. In 1998–1999, wheat yields after pigeonpea were lower than after rice, but improved significantly ($p < 0.05$) by 11.4–15.1% in pigeonpea plots compared with those in rice plots during 1999–2000 and 2000–2001, respectively. The use efficiency of applied N and P fertilizers in wheat, measured as agronomic efficiency and apparent recovery, was increased with combined use of fertilizer N and P at recommended rate, and also with inclusion of pigeonpea in place of rice. The post-wheat harvest NO_3–N in soil profile beyond 45 cm depth was significantly greater under rice–wheat system than under pigeonpea–wheat system, suggesting that inclusion of pigeonpea may help in minimizing NO_3–N leaching to deeper profile layers beyond root zone. Similarly, in the treatments receiving both 120 kg N and 26 kg P ha^{-1}, NO_3–N beyond 45 cm soil depth was lower compared to those receiving N or P alone. Inclusion of pigeonpea in place of rice enhanced carbon accumulation in the soil profile. The available P content was, however, invariably low under pigeonpea plots as compared to that under rice. With continuous rice–wheat cropping, the bulk density (BD) of soil was

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increased, especially in the 30–45 cm soil profile. Inclusion of pigeonpea in the system not only helped maintaining soil BD at initial level in the surface (0–15 cm) soil layers, but also in decreasing ($p < 0.05$) BD in sub-surface layers (15–30 cm and 30–45 cm). Compared to rice, a statistically significant ($p < 0.05$) positive effect of pigeonpea on root volume (58%) and root weight (99.5%) of succeeding wheat was also recorded. The net economic returns under pigeonpea–wheat system were greater compared with rice–wheat system.

Keywords: Nutrient use efficiency; Rice–wheat; Pigeonpea–wheat; Bulk density; Mineral-N; Wheat yields; Typic ustochrept

1. Introduction

It appears that productivity potential of the rice–wheat cropping system (RWCS) has been stretched to a maximum limit in northwest India, as the kind of yield gains that were witnessed in 1960s and 1970s are not being realized at present. In fact since 1990, in the high productivity areas like Trans-Gangetic plain (TGP) and Upper Gangetic plain (UGP) zones of the Indo-Gangetic plain region (IGPR), yields have started showing sign of stress with production fatigue and a declining annual growth rate of productivity (Chauddhary and Harrington, 1993). Therefore, farmers are being compelled to apply increasing rates of the fertilizers, particularly N fertilizer, to maintain the yield levels attained previously with less fertilizer use (Pagiola, 1995; Dwivedi et al., 2001).

During the rice–wheat cropping cycle, soil undergoes drastic changes, i.e., anaerobic to aerobic environment, leading to several chemical and electro-chemical transformations. Besides the contrasting needs of each crop, continuous rice–wheat cropping for longer periods with low system diversity, and often with poor crop management practices, resulted in loss of soil fertility due to emergence of multiple nutrient deficiency (Fujisaka et al., 1994; Singh and Singh, 1995; Dwivedi et al., 2001) and deterioration of soil physical properties (Tripathi, 1992), and decline in factor productivity and crop yields in high productivity areas (Yadav, 1998). Diagnostic surveys on nutrient management practices prevailing in RWCS dominated areas of western Uttar Pradesh (UGP) revealed that nearly one-third of the farmers practicing RWCS apply as high as 180 kg fertilizer N ha^{-1} to each rice and wheat crop as against local recommendation of 120 kg N ha^{-1} (Dwivedi et al., 2001). In these areas, indiscriminate use of fertilizer N needs to be curbed, for a further increase in fertilizer application rate may not be only uneconomic but also environmentally unsafe (Yadav et al., 2000). Unbalanced use of fertilizer N may enhance nitrate leaching beyond root zone, posing a potential threat of the pollution of ground water used for drinking purposes in rural areas (Singh et al., 1995). The fertilizer N use efficiency in these coarse-textured permeable soils is very low (21–31% in rice and 32–52% in wheat) due to excessive N losses (Katyal et al., 1985; Singh et al., 1991; Aulakh and Singh, 1997). Hence there is a need to increase fertilizer N use efficiency, and not the application rates, to sustain the productivity levels of RWCS, as also to minimize the environmental hazards.

Balanced fertilizer use, complementary use of organic nutrient inputs with fertilizers and inclusion of legumes are the possible agro-techniques to sustain yield, increase fertilizer use efficiency and to restore soil fertility under intensive cropping (Yadav et al., 1998a; Timsina and Connor, 2001; Dwivedi et al., 2003). Introduction of a legume crop in RWCS may have advantages well beyond the N addition through BNF including nutrient recycling from deeper soil layers, minimizing soil compaction, increase in soil organic matter, breaking of weed and pest cycles and minimizing harmful allelopathic effects (Sanford and Hairston, 1984; Wani et al., 1995). In RWCS, legumes can be grown as a green manure, as a catch crop during post-wheat summer season, or as a substitute crop to rice or wheat (Singh et al., 2002). Constraints like cost of raising a green manure legume during post-wheat summer season, and delay in rice planting or wheat sowing due to long duration of summer/monsoon grain legumes, however, restrict the integration of legumes in cereal–cereal systems on a large-scale (Ali, 1999). Nonetheless, development of short-duration and uniformly maturing varieties of summer legumes (black gram and green gram), and short to extra-short duration varieties of pigeonpea in recent years may enhance the feasibility of inclusion of grain legumes in RWCS, although such options have not been systematically evaluated. The present study aims at: (i) understanding farmer's fertilizers management practices for wheat following rice versus pigeonpea, and (ii) comparing the changes in soil fertility parameters, yield and nutrient use efficiency in wheat grown in sequence with rice or pigeonpea, with or without adequate N and P fertilizer inputs.

2. Materials and methods

2.1. Farmers' participatory diagnostic survey

Meerut (29° 4′ N, 77° 46′ E, 237 m asl) and Bulandshahar (28° 43′ N, 78° 28′ E., 235 m asl) districts of western Uttar Pradesh, which represent irrigated, mechanized, input-intensive RWCS areas of the UGP, were selected as the study sites. Irrigation is available for 89% of the cultivated area in district Meerut and 86% of the cultivated area in district Bulandshahar. During 2000–2001, the annual consumption of fertilizer nutrients ($N + P_2O_5 + K_2O$) was 59,829 t in district Meerut and 74,215 t in district Bulandshahar (FAI, 2001). The farmers selected for the diagnostic surveys were chosen from these two districts, following stratified sampling techniques (Sukhatme et al., 1984).

A participatory field survey was undertaken during the 1997–1998 wheat growing season to collect information on agronomic management, especially fertilizer application practices, in wheat in Meerut and Bulandshahar districts of UGP. Fifty farmers each in the two districts practicing RWCS or pigeonpea–wheat system were chosen for the survey, using standard stratified sampling technique. The participatory rural appraisal (PRA) methodologies (Fujisaka et al., 1994) were used to seek the information on various aspects influencing, directly or indirectly, the nutrient management practices in wheat after rice or pigeonpea. A formal questionnaire was prepared to collect information on date of wheat sowing, type of fertilizer used and its quantity, number of irrigations given to wheat and wheat grain yield.

Farmers themselves managed the crops, with their own choice of fertilizer applications. All the crop management practices were recorded through fortnightly interviews with farmers during the wheat-growing season. The main objective was to characterize agronomic causes of differences in wheat yield and fertilizer use efficiency in these cropping systems under farmers' management conditions. We, therefore, did not give any recommendations to the farmers prior to the start of the survey. Wheat grain yields were recorded from 4 m^2 area harvested from four randomly selected spots in each farmer's field, and the grain moisture content was adjusted at 14%.

2.2. On-station experiment

2.2.1. The experimental site

Following the survey, a field experiment was initiated during the 1998–1999 which was continued for three consecutive years, i.e., up to 2000–2001 on a Typic Ustochrept soil of the Research Farm of the Project Directorate for Cropping Systems Research, Modipuram, Meerut to study changes in soil fertility, yield and nutrient use efficiency of wheat grown in sequence with rice or pigeonpea. The climate of the experimental site is semi-arid sub-tropical, with dry hot summers and cold winters. The average annual rainfall is 810 mm, and nearly 80% of the total rainfall is received through northwest monsoons during July–September. The average monthly minimum temperatures fluctuate from 6.7 to 7.5 °C in January (the coolest month) and from 23.4 to 25.2 °C in May (the hottest month). The respective maximum temperatures range from 17.9 to 21.7 °C in January and 38.1 to 40.9 °C in May. The soil of the experimental site was a sandy loam (18% clay, 19.5% silt and 62.5% sand) of Gangetic alluvial origin, very deep (>2 m), well drained, flat (about 1% slope), and represented an extensive soil series, i.e., Sobhapur series of northwest India.

2.2.2. Treatments and crop culture

The treatments comprised two levels of fertilizer N (0 and 120 kg N ha^{-1}) and two levels of fertilizer P (0 and 26 kg P ha^{-1}) that were applied to wheat crop, grown in sequence with rice or pigeonpea. Eight treatment combinations (2 N rates × 2 P rates × 2 crop rotations, i.e., rice–wheat and pigeonpea–wheat) were randomized within a block, and four such blocks were maintained. The plot size was 5 m × 6 m. The pigeonpea cv. 'UPAS 120' was sown as per treatment in rows that were 75 cm apart using 25 kg seed ha^{-1}

during the first week of June in all the 3 years. Twenty-five-day old healthy seedlings of rice cv. 'Saket 4' were transplanted at 20 cm × 15 cm spacing during first week of July. The rice crop was fertilized with 120 kg N, 26 kg P and 33 kg K ha^{-1}, whereas pigeonpea crop received a starter dose of 18 kg N and 20 kg P ha^{-1} only. Both rice and pigeonpea crops were harvested from ground level using sickle, on 12 October and 24 November in the first year, 9 October and 20 November in the second year, and 8 October and 21 November in the third year, respectively. Just after the harvest of rice and pigeonpea crops, the plots were irrigated and prepared for sowing of succeeding wheat, using two cultivator and two harrow followed by a planking operation. Wheat cv. UP 2338 was sown on 8 November 1998, 13 November 1999 and 10 November 2000 in rice plots and on 3 December 1998, 1 December 1999 and 29 November 2000 in pigeonpea plot in the undisturbed layout. The wheat crop was sown in rows established 20 cm apart using 100 kg seed ha^{-1}. The wheat crop received N through urea (46.4% N) and P through single superphosphate (6.99% P). K was applied at a uniform rate of 33 kg ha^{-1} through muriate of potash (49.6% K). One-third dose of N, and entire P and K were applied to soil just before wheat sowing, and the remaining N top-dressed in two equal splits, 25 and 60 days after sowing (DAS).

All the crops were grown under assured irrigated conditions. Two irrigations, one pre-sowing and the other at 20 DAS, were applied to pigeonpea. In rice, 11 irrigations during 1998–1999 and 13 irrigations each during 1999–2000 and 2000–2001 were applied through flood irrigation. At each irrigation, 7 cm standing water was maintained, and the interval between two irrigations depended on the disappearance of standing water. Wheat crop received five irrigations at the critical stages for water stress, viz., crown root initiation (21 DAS), maximum tillering (45 DAS), jointing (65 DAS), ear emergence (85 DAS) and milking (105 DAS). At maturity, wheat was harvested manually from ground level using sickles, and the harvested aboveground biomass was removed from the plots.

2.2.3. Root studies in wheat

During the 2000–2001 season, wheat roots were collected at the flowering stage, i.e., shortly after ear emergence, assuming that the development of root system might have been complete by that stage. Samples were taken by a core sampler (8 cm diameter) up to a 105 cm soil depth at four locations in each plot. The sampling depths were 0–15, 15–30, 30–45, 45–60, 60–75, 75–90 and 90–105 cm. The samples were soaked in water for at least 12 h following Bohm (1979). The soil–root suspension was stirred and then passed through a 0.5 mm sieve. Root and organic debris retained on the sieve were stored at 5 °C in plastic bags containing 17% (v/v) acetic acid solution. The roots were separated from organic debris. The root volume was measured using kerosene oil, following liquid displacement method (Misra and Ahmed, 1988). The root samples were then dried in sun and finally in oven at 70 °C for 48 h and weighed.

2.2.4. Soil and plant analysis

Soil samples were collected from 0–105 cm profile-depth at 15 cm interval, from four places in the experimental field using a core sampler of 8 cm diameter before commencement of the experiment in 1998–1999. The sub-samples so obtained were mixed and bulked, and representative soil samples for each depth were drawn for chemical analysis. The post-wheat harvest soil samples (0–105 cm profile-depth at 15 cm interval) were also drawn following the same procedure after completion of each crop cycle in both rice–wheat as well as pigeonpea–wheat system. In all, four sub-samples for a given profile-depth interval of 15 cm were collected from each plot of all four replications. The sub-samples for each depth in a plot were mixed thoroughly to obtain a representative sample for chemical analysis. The initial and post-harvest soil samples were pulverized using wooden pestle-mortar and sieved through a 100-mesh sieve. The processed samples from each plot were analyzed separately for organic carbon (Walkley and Black's method), mineral N (Bremner and Keeney, 1965) and available (0.5 M $NaHCO_3$, pH 8.5 extractable) P content (Olsen and Sommers, 1982). The bulk density (BD) of soil in different profile-depths in the initial and the terminal (post-wheat 2000–2001) soil samples was measured using aluminum cores. Soil organic carbon (OC) in different profile layers was computed in Mg ha^{-1}, taking in to account the BD of individual profile layer. The OC content of all seven

Table 1
Physico-chemical characteristics of soil measured at the commencement of field experiment during 1998–1999

Soil profile -depth (cm)	Bulk density ($Mg\ m^{-3}$)	pH	EC ($dS\ m^{-1}$)	Organic carbon ($Mg\ ha^{-1}$)	NO_3–N ($mg\ kg^{-1}$)	NH_4–N ($mg\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)
0–15	1.48	8.01	0.11	10.2	6.4	11.3	7.3
15–30	1.53	7.89	0.12	8.7	6.5	12.4	6.4
30–45	1.56	7.91	0.10	7.7	6.2	12.6	6.1
45–60	1.57	7.85	0.11	6.1	5.6	10.7	5.2
60–75	1.61	7.78	0.10	4.8	5.0	10.1	4.6
75–90	1.64	7.79	0.13	3.9	4.6	9.0	4.2
90–105	1.65	7.72	0.12	3.2	4.3	8.0	4.0

profile-depths of a treatment was summed-up to find total carbon accumulation in soil profile (0–105 cm) for that treatment. The initial samples were also analyzed for pH and electrical conductivity (1:2 soil–water suspension) and mechanical composition (international pipette method), following standard analytical procedures (Page et al., 1982). Important physico-chemical characteristics of the soil before commencement of the experiment are presented in Table 1.

At the final harvest, representative whole plants (aboveground portion) of pigeonpea, rice and wheat were collected from four spots in each plot, and grain and straw were separated. The grain and straw samples were washed thoroughly with tap water and deionised water, chopped, homogenised and dried at 70 °C in a hot-air oven. The dried samples were ground in a stainless steel Wiley mill, and wet-digested in concentrated H_2SO_4 for determination of total N and in di-acid mixture (HNO_3 and $HClO_4$ mixed in 4:1 ratio) for determination of total P. The N content was determined by Kjeldahl method using Kjeltec auto-analyzer, and P by vanadomolybadate yellow color method (Piper, 1966) using an UV–vis spectrophotometer.

After harvest of pigeonpea the dry leaf litter fall was collected from marked 1 m^2 area and weighed. The root nodules of pigeonpea at maximum flowering and root stubbles after harvest of rice and pigeonpea were dug-out up to 75 cm soil depth in 50 cm^2 area of each plot, washed thoroughly and weighed after oven drying (70 °C) and expressed on a hectare basis. Their dry matter was also analyzed for total N and P content in order to measure N and P recycling to soil through these residues.

2.2.5. Statistical analysis

For treatment comparisons in the field experiments, '*F*-test' was used, following the procedures of factorial randomized block design (Cochran and Cox, 1957). The CD (critical difference), defined as the least significant difference beyond which all treatment differences are statistically significant, was computed to determine statistically significant treatment differences in Tables 3–7, and Figs. 1–6 as:

$$\mathrm{CD} = (\sqrt{2}\,V_{\mathrm{E}} r^{-1}) \times t_{5\%} \qquad (1)$$

Where V_E is the error variance, r the number of replications of the factor for which CD is calculated, $t_{5\%}$ the table value of 't' at 5% level of significance at error degrees of freedom. The data on post-wheat harvest soil analysis, and on wheat root weight and volume as illustrated in Figs. 1–6 have been subjected to log-transformation prior to computation of CD.

In order to quantify the effect of fertilizer N and P input and cropping system on the nutrient (N or P) use efficiencies in wheat, computations were made using following equations.

$$\mathrm{AE}_{\mathrm{N\,or\,P}} = \Delta Y\, F_{\mathrm{n}}^{-1} \qquad (2)$$

$$\mathrm{AR}_{\mathrm{N\,or\,P}} = \Delta U\, F_{\mathrm{n}}^{-1} \times 100 \qquad (3)$$

Where $\mathrm{AE}_{\mathrm{N\ or\ P}}$ is the agronomic efficiency of applied N or P fertilizer, ΔY the incremental yield due to fertilizer N or P input with reference to 0-N or 0-P plots, F_n the amount of fertilizer N or P applied, $\mathrm{AR}_{\mathrm{N\ or\ P}}$ the apparent recovery of fertilizer nutrients, and ΔU the incremental uptake of N or P due to fertilizer application with reference to 0-N or 0-P plots. The ΔY, ΔU and F_n are expressed as kg ha^{-1}.

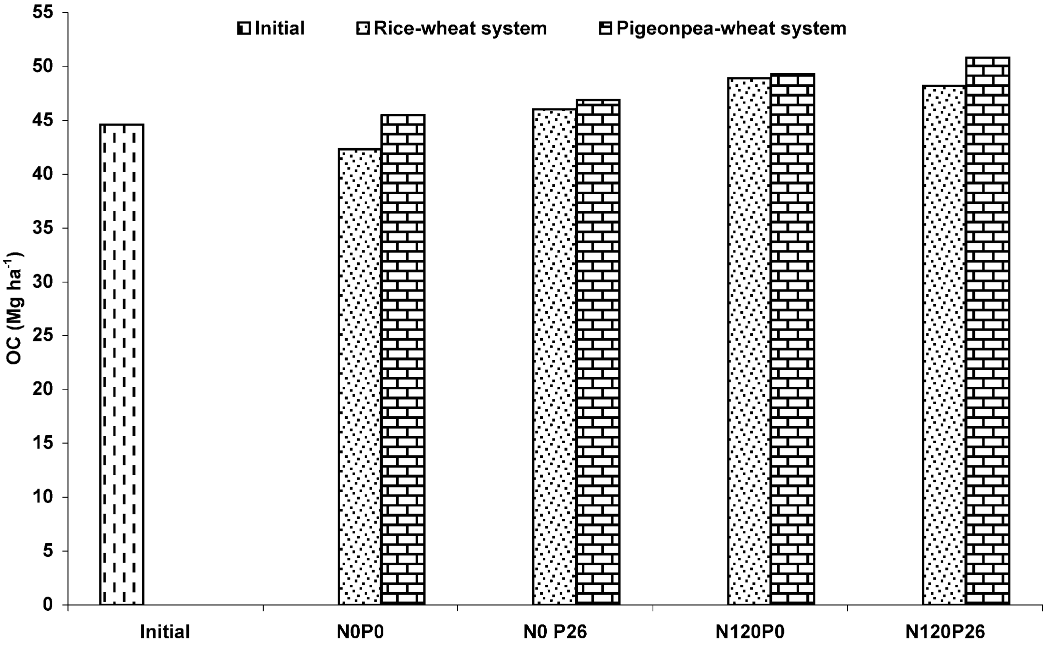

Fig. 1. Effect of fertilizer NP and cropping systems on carbon accumulation in a 0–105 cm soil profile after 3 years of cropping at Modipuram, India. CD ($p < 0.05$) for cropping system (C) is not significant (NS), for fertilizer (F) 3.8 and for C × F NS.

2.2.6. Economic analysis

For economic evaluation of pigeonpea–wheat versus rice–wheat system and fertilizer NP treatments, averaged data of three crop cycles was used. The total cost of cultivation (TCC) of rice, wheat and pigeonpea was calculated on the basis of different operations performed and materials used for raising the crops, including the cost of fertilizer N and P. For rice, the operations and materials used were seed, nursery raising and its maintenance, transplanting, weeding and herbicide application, irrigation, harvesting and threshing. For pigeonpea and wheat, the operations and materials used were seed, seedbed preparation, sowing, irrigation, herbicide application, harvesting and threshing. The cost of labour for top-dressing of fertilizer N in rice and wheat was also included. The costs (in indian rupees, 1 Rs. = US $0.022) incurred were: Rs. 25 kg^{-1} of rice seed, Rs. 20.50 kg^{-1} of wheat seed and Rs. 40 kg^{-1} of pigeonpea seed, and Rs. 10.50 kg^{-1} of N, Rs. 50 kg^{-1} of P and Rs. 8.70 kg^{-1} of K. Among field operations, the cost of irrigation was taken as Rs. 50 h^{-1}, labour Rs. 90 $\mathrm{unit}^{-1}\,\mathrm{day}^{-1}$, plowing/harrowing, Rs. 280 ha^{-1} $\mathrm{operation}^{-1}$, and puddling Rs. 1040 ha^{-1}.

Gross returns (GR) were calculated by multiplying grain yield with grain price, i.e., Rs. 5.40 kg^{-1} for rice, Rs. 6.20 kg^{-1} for wheat and Rs. 13.60 kg^{-1} for pigeonpea. Net returns (NR) were calculated as:

$$\mathrm{NR} = \mathrm{GR} - \mathrm{TCC} \qquad (4)$$

The NR of rice or pigeonpea were added to the NR of wheat in respective treatments to comppute the cropping system's net returns (SNR) as:

$$\mathrm{SNR} = \mathrm{NR}_{\mathrm{R\,or\,PP}} + \mathrm{NR}_{W} \qquad (5)$$

where $\mathrm{NR}_{\mathrm{R\ or\ PP}}$ is the net returns from rice or pigeonpea and NR_{W} the net returns from wheat.

3. Results

3.1. Farmers' fertilizer use pattern

The diagnostic survey revealed that in UGP, farmers usually grew pigeonpea as a break crop at a 2–3 year interval to disrupt the cycle of noxious weeds such as *Echinocloa* in rice and *Phalaris minor* L. in wheat. Sowing time of wheat usually varied between

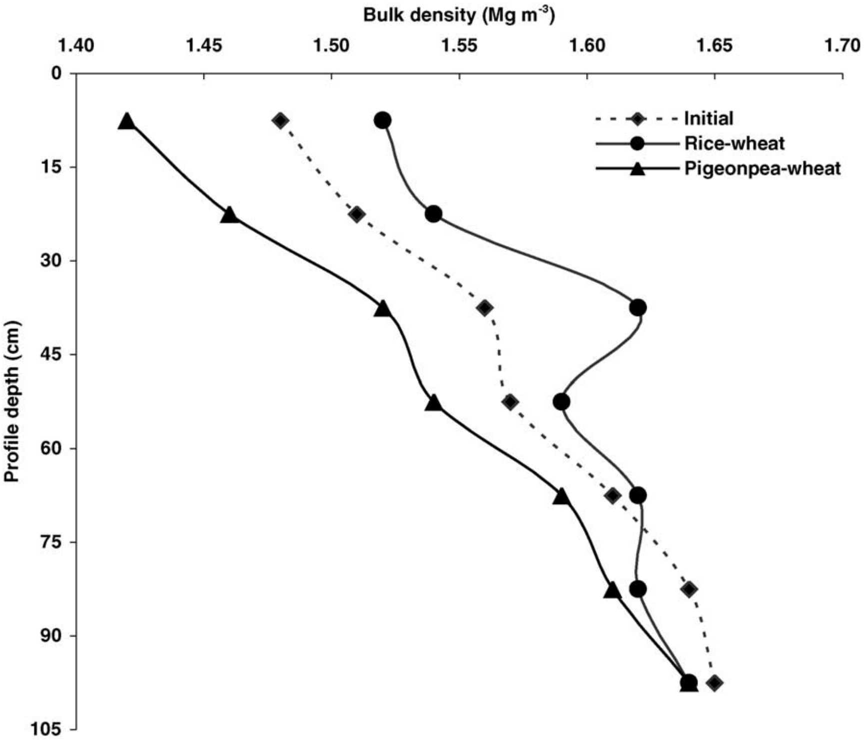

Fig. 2. Changes in bulk density of soil at different profile-depths after three crop cycles as influenced by substitution of rice with pigeonpea in RWCS. CD ($p < 0.05$) for cropping system (C) or initial vs. C is 0.04, for profile-depth (D) 0.06 and for C × D 0.09.

5 November and 5 December, when sown after rice, and 28 November–8 January, when sown after pigeonpea (Table 2). N applied to wheat in this region varied from 64 to 156 kg ha^{-1} after rice and 45 to 188 kg ha^{-1} after pigeonpea. The average N application rate, however, was 111 kg ha^{-1} after rice and 126 kg ha^{-1} after pigeonpea. The P application rate varied from 14 to 29 kg ha^{-1} after rice, and 16 to 23 kg ha^{-1} after pigeonpea. Only 32% farmers applied K to wheat and the amount varied from 23 to 62 kg ha^{-1}. The major sources of these nutrients were urea (46.6% N), di-ammonium phosphate (18% N and 20.1% P) and muriate of potash (49.6% K). The most commonly used fertilizer in wheat was urea followed by di-ammonium phosphate under both the systems. At sowing, farmers applied 1/3rd N, and full dose of P and K. The remaining dose of N was applied after first irrigation, i.e., at about 18 days after sowing (DAS) in both the systems. The second top dressing of urea N (remaining 1/3rd dose) was done after second irrigation at 47 DAS in rice–wheat system and at 38 DAS in pigeonpea–wheat system. The wheat yields on farmer's field varied from 3.0 to 4.2 t ha^{-1} with an average of 3.7 t ha^{-1} in rice–wheat system, and 2.8–3.8 t ha^{-1} with an average of 3.3 t ha^{-1} in pigeonpea–wheat system (Table 2).

3.2. *On station studies*

3.2.1. *Studies in rice and pigeonpea*

The average grain yield of pigeonpea was 1.8 t ha^{-1} in the initial year, 1.7 t ha^{-1} in the second and 1.6 t ha^{-1} in the terminal year (Table 3). The corresponding rice yields were 4.6, 4.2 and 4.1 t ha^{-1}, respectively. Compared with rice, pigeonpea removed 58–72% greater N and 31–50% greater P during different years.

Total N recycled through pigeonpea residue (root, stubble, nodule and leaf litter) averaged across NP treatments in preceding crop of wheat ranged between 38 and 42 kg ha^{-1}, and total P recycled between 3.1 and 4.2 kg ha^{-1} during different years. The N and P recycled through rice root and stubble was compara-

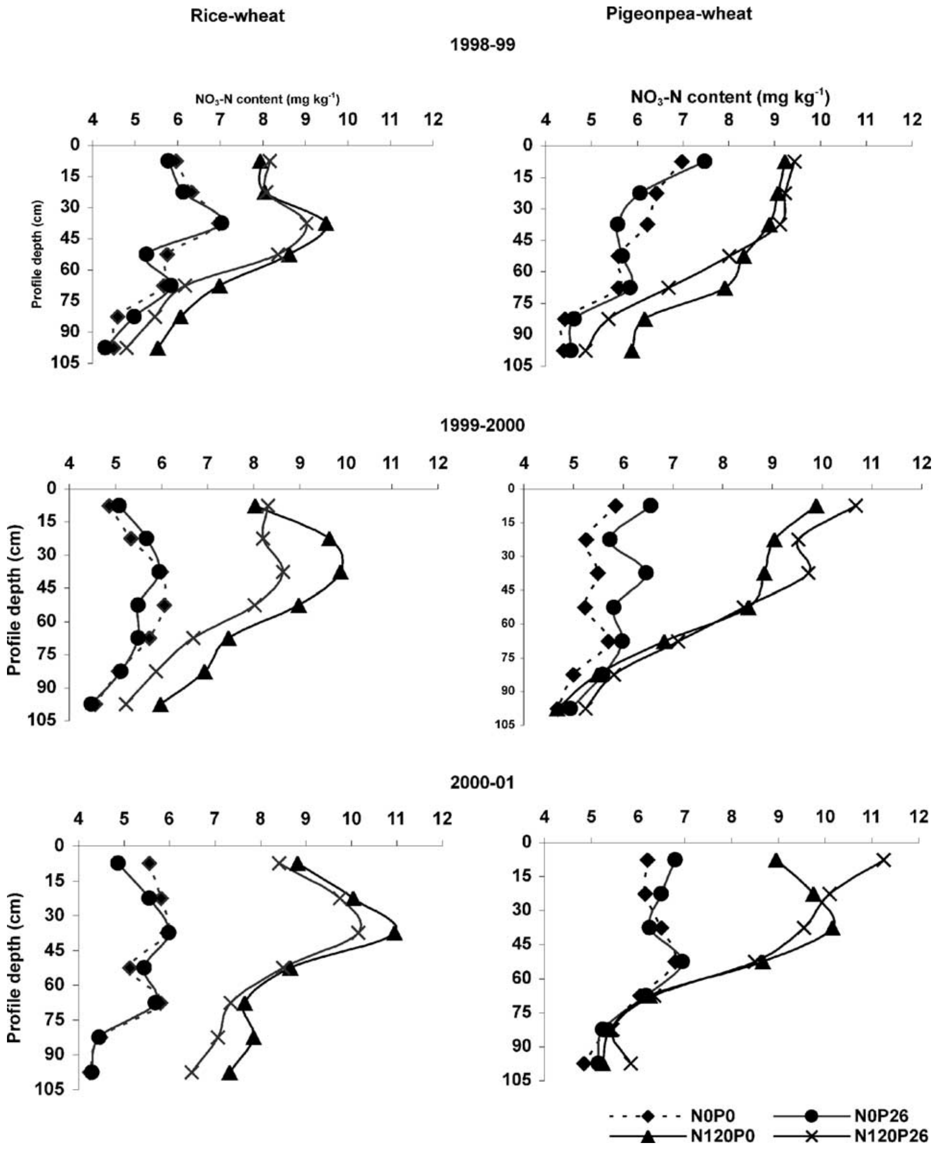

Fig. 3. Effect of NP fertilization to wheat, and replacement of rice with pigeonpea in RWCS on the distribution of nitrate–N in soil profile after wheat harvest in different years. CD ($p < 0.05$) for cropping system (C) is 0.10, for fertilizer (F) 0.13 and for C × F 0.19 during 1998–1999. The corresponding CD values during 1999–2000 are 0.11, 0.16 and 0.22, and during 2000–2001 are 0.13, 0.18 and 0.25, respectively.

tively smaller, which ranged between 3.6 and 4.5 kg ha^{-1} for N, and 0.9–1.2 kg ha^{-1} for P in different years of study (Table 3). In second and terminal years, variable NP application rates in preceding wheat marginally influenced the yield, nutrient uptake, production of residues and recycling of nutrients through rice or pigeonpea crops (data not shown in Table).

3.2.2. Grain yield, nutrient uptake and nutrient use efficiencies of wheat

Wheat grain yields after pigeonpea, averaged over fertilizer N and P rates, were greater ($p < 0.05$) than those after rice by 11.4 and 14.6% during the second and the terminal years, respectively, though the wheat yield in the two cropping systems did not differ significantly during the initial year (Table 4). The

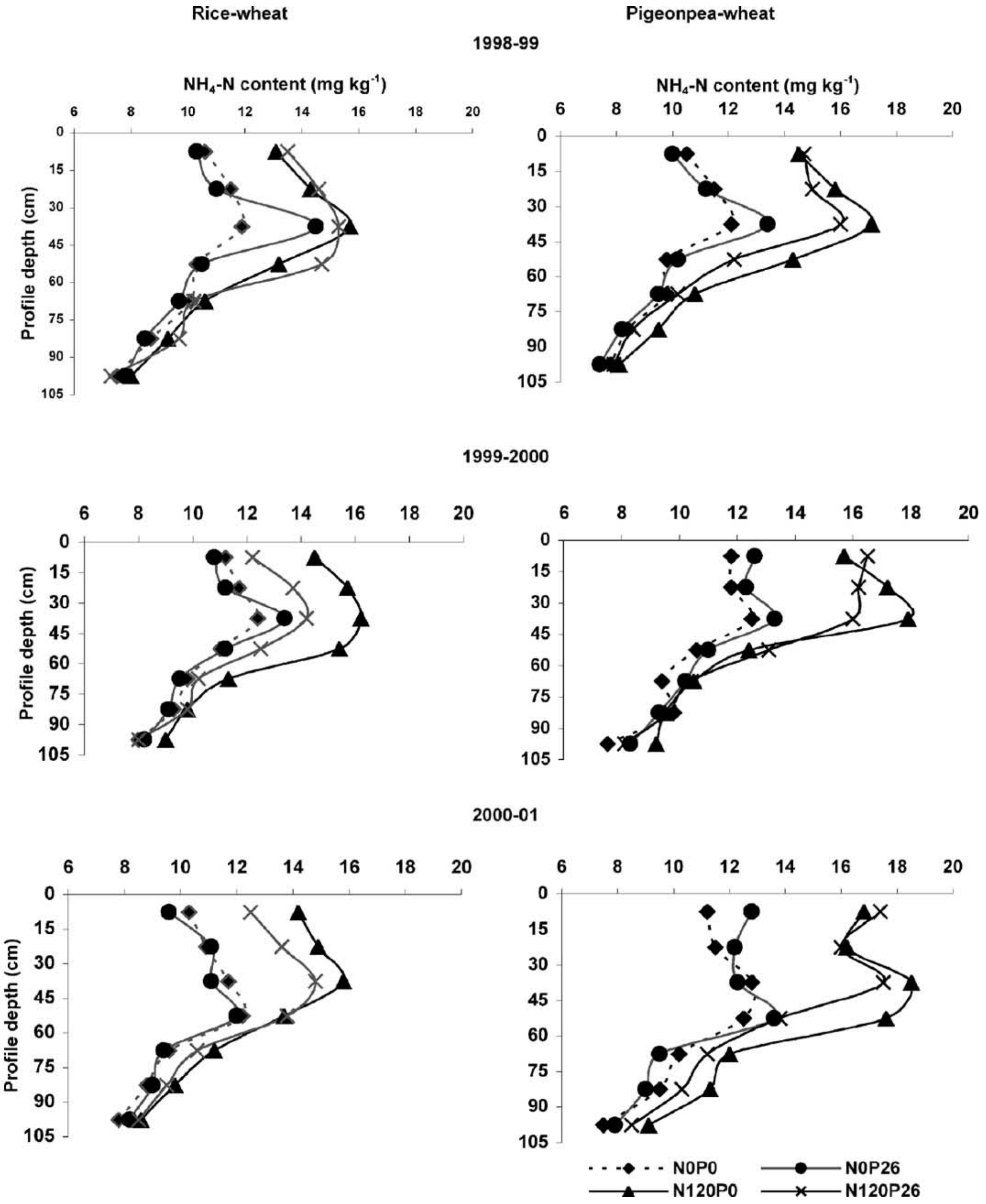

Fig. 4. Effect of NP fertilization to wheat, and replacement of rice with pigeonpea in RWCS on the distribution of ammonium–N in soil profile after wheat harvest in different years. CD ($p < 0.05$) for cropping system (C) is NS, for fertilizer (F) 0.29 and for C × F 0.41 during 1998–1999. The corresponding CD values during 1999–2000 are 0.32, 0.45 and 0.64, and during 2000–2001 are NS, 0.22 and 0.31, respectively.

treatment with application of 120 kg N ha^{-1} out-yielded ($p < 0.05$) no N treatment by 1.49–2.48 t ha^{-1} in different years. Wheat yield response to fertilizer P increased with continuous cropping, and was always greater when rice was substituted with pigeonpea during monsoon season. The magnitude of increase in wheat grain yield due to application of 26 kg P over no P under rice–wheat system was 11% in 1998–1999,

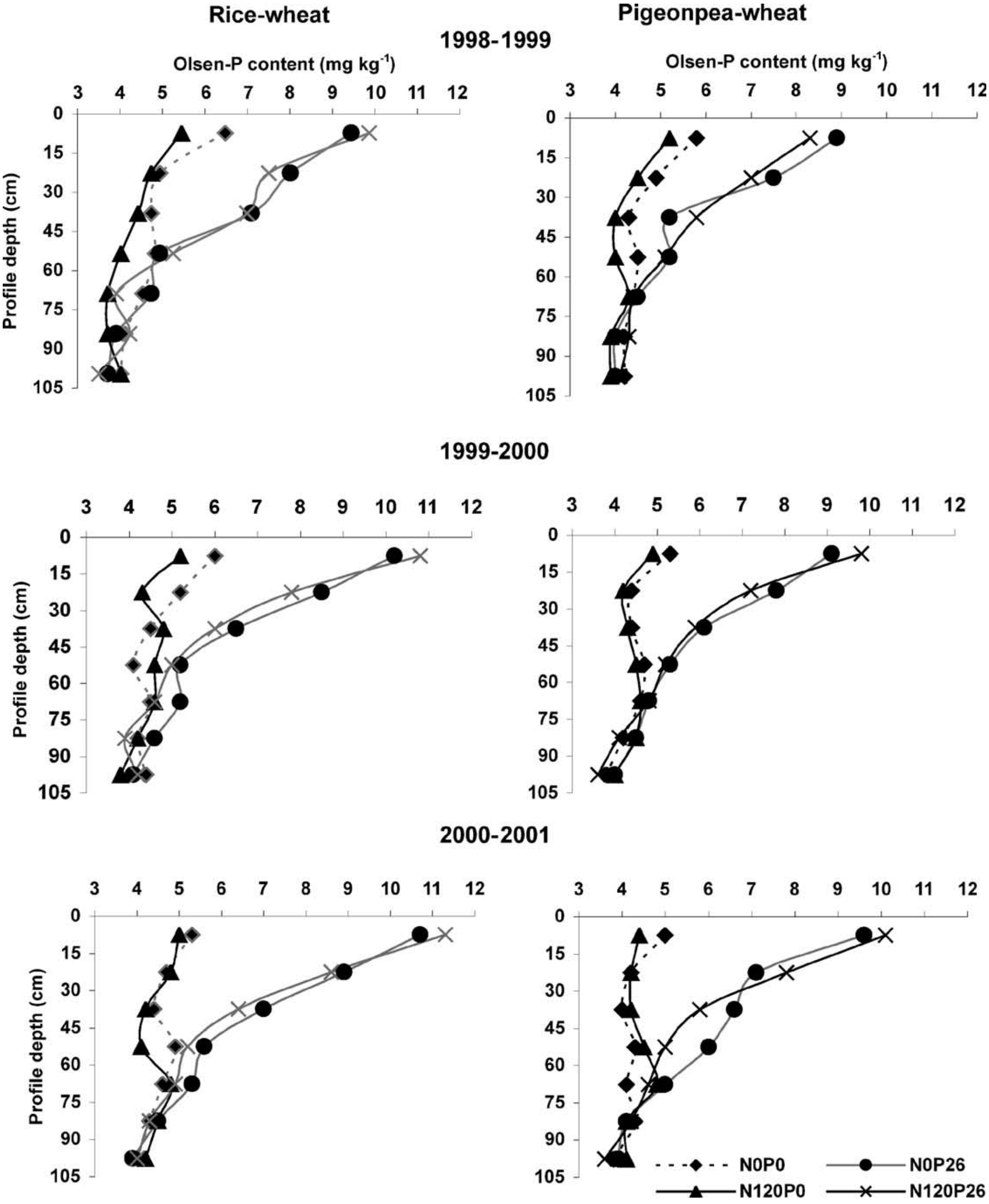

Fig. 5. Available P in soil profile after wheat harvest in different years as influenced by fertiliser N and P application to wheat and inclusion of pigeonpea in RWCS. CD ($p < 0.05$) for cropping system (C) is NS, for fertilizer (F) 0.20 and for C × F NS during 1998–1999. Corresponding CD values during 1999–2000 are 0.17, 0.24 and NS, and during 2000–2001 are 0.15, 0.21 and 0.30, respectively.

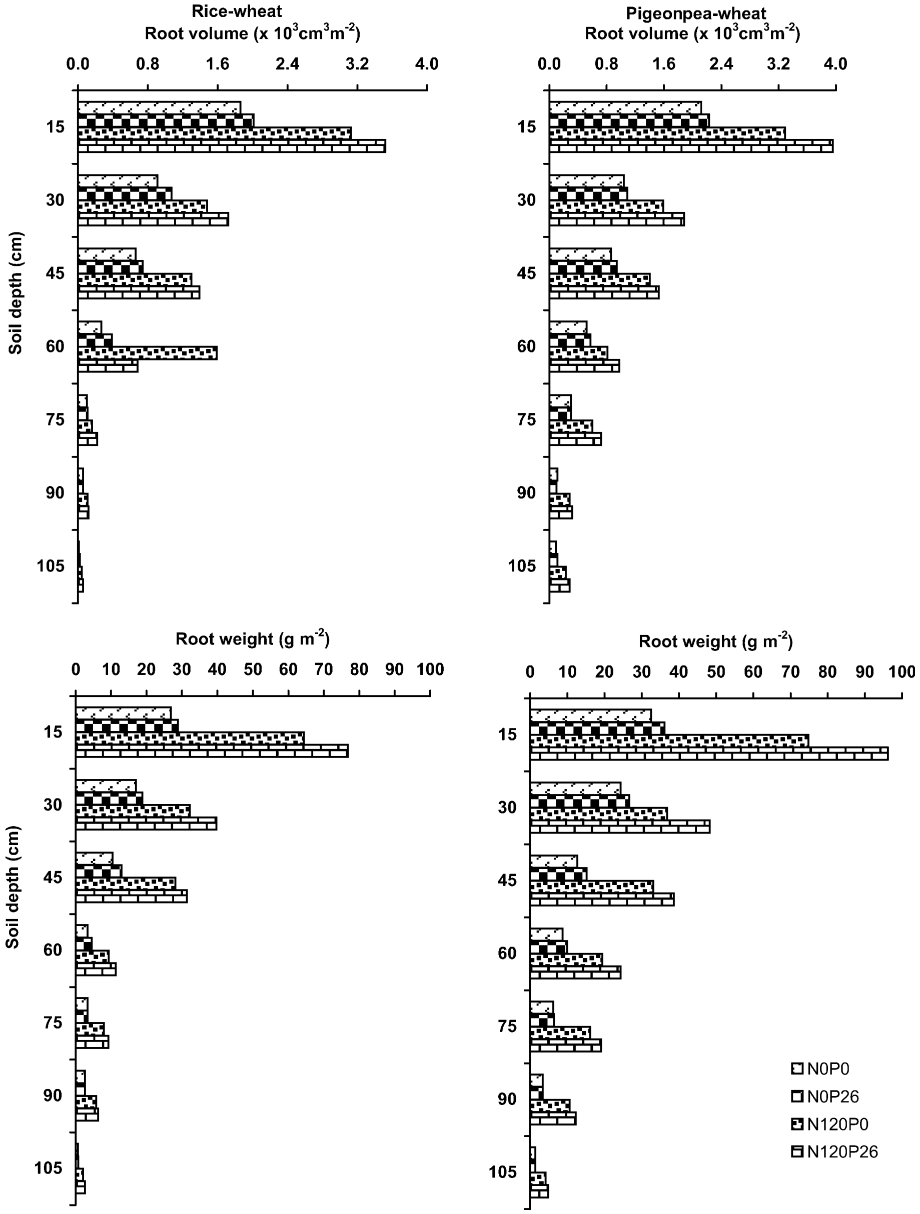

Fig. 6. Root volume and root weight of wheat as influenced by preceding rice and pigeonpea during 2000–2001. For root volume, CD ($p < 0.05$) for cropping system (C) is 0.03, for fertilizer (F) 0.04 and for F × C 0.06. Corresponding CD for root weight is 0.51, 0.73 and 1.03, respectively.

14% in 1999–2000 and 17% in 2000–2001. The corresponding yield increases under pigeonpea–wheat system were 16% in 1998–1999, 25% in 1999–2000 and 36% in 2000–2001. The N × P interaction was statistically significant ($p < 0.05$) in all the three wheat seasons. Similarly a significant ($p < 0.05$) interaction between N rates and cropping systems was observed during 1998–1999 and 2000–2001, and between P rates and cropping systems during 2000–2001.

The mean N uptake by wheat under no N plots, across fertilizer P and cropping system treatments, was 30.6 kg ha^{-1} in 1998–1999, 23.3 kg ha^{-1} in 1999–2000 and 25.0 kg ha^{-1} in 2000–2001, which

Table 2
Fertilizer management and irrigation practices in wheat following rice versus pigeonpea on farmers' field in Meerut and Bulandshahar districts of western Uttar Pradesh representing Upper Gangetic plain zone

Particulars	Wheat after rice					Wheat after pigeonpea[a]				
	Number of cases	Min.	Max.	Mean	S.E. ±	Number of cases	Min.	Max.	Mean	S.E. ±
Sowing date	50	5 November	5 December	17 November	7.5	50	28 November	8 January	23 December	9.8
Nutrient applied (kg ha^{-1})										
N	50	64	156	111	3.0	50	45	188	126	4.7
P	48	14	29	24	1.9	50	16	23	19	12.2
K	16	23	60	33	1.2	16	23	62	35	2.6
Irrigation (days after sowing)										
First	50	15	20	18	0.3	50	15	20	17	0.3
Second	50	40	55	47	0.7	50	30	45	38	0.7
Third	50	70	90	82	0.8	50	60	85	74	1.0
Fourth	32	100	112	105	0.9	50	80	100	92	0.9
Fifth	20	118	128	120	0.6	40	100	118	110	0.7
Grain yield (t ha^{-1})	50	3.0	4.2	3.7	0.1	50	2.8	3.8	3.3	0.1

S.E. = Standard error of mean.

[a] Farmers grow pigeonpea as a break crop at 2–3-year interval in RWCS.

was increased to 74.1 in 1998–1999, 75.4 in 1999–2000 and 75.8 kg ha^{-1} in 2000–2001, due to N application at 120 kg ha^{-1} (Table 5). Compared with no P treatments, total N uptake by the crop was greater in the treatments receiving 26 kg P ha^{-1} ($p < 0.05$) during 1999–2000 and 2000–01, and the magnitude of response was greater ($p < 0.05$) in treatments that received P in combination with 120 kg N during 2000–2001. Inclusion of pigeonpea in place of rice during monsoon season resulted in a smaller N uptake during first year, especially at 120 kg N application rate, but an opposite response was observed during the second and final seasons, and N uptake improved significantly ($p < 0.05$). Total N uptake by wheat following

Table 3
Yield, N and P uptake, and nutrient recycling in rice and pigeonpea grown during monsoon seasons of 1998–1999, 1999–2000 and 2000–2001

Parameters	1998–1999				1999–2000				2000–2001			
	Min.	Max.	Mean	S.E. ±	Min.	Max.	Mean	S.E. ±	Min.	Max.	Mean	S.E. ±
Pigeonpea												
Grain yield (t ha^{-1})	1.7	1.8	1.8	0.02	1.6	1.9	1.7	0.09	1.4	1.8	1.6	0.10
[a]Total N uptake (kg ha^{-1})	131	140	136	1.5	120	143	131	4.1	109	134	121	6.4
[a]Total P uptake (kg ha^{-1})	16	20	18	0.3	15	20	17	0.3	14	19	17	0.3
[b]N recycled through residues (kg ha^{-1})	36	45	42	2.4	32	46	39	3.1	30.8	46	38	2.5
[b]P recycled through residues (kg ha^{-1})	2.9	4.7	4.2	0.12	2.8	4.4	3.5	0.09	2.7	4.2	3.1	0.17
Rice												
Grain yield (t ha^{-1})	4.1	4.8	4.6	0.08	3.7	4.5	4.2	0.21	3.6	4.5	4.1	0.18
Total N uptake (kg ha^{-1})	83	88	86	1.5	72	81	76	3.2	68	80	75	3.2
Total P uptake (kg ha^{-1})	11	13	12	0.2	10	15	13	0.5	11	15	12	0.3
[c]N recycled through residues (kg ha^{-1})	3.9	4.8	4.5	0.1	3.7	4.3	3.9	0.2	3.5	4.0	3.6	0.2
[c]P recycled through residues (kg ha^{-1})	1.1	1.3	1.2	0.04	0.8	1.2	1.0	0.04	0.7	1.2	0.9	0.03

S.E. = Standard error of mean; $n = 16$.

[a] Total N and P uptake values exclude the amount of N and P recycled through leaf litter.

[b] Nutrient recycled through pigeonpea residue, i.e., root and stubble + nodules + leaf litter.

[c] Nutrient recycled through rice residue, i.e., root and stubble.

Table 4
Effect of fertilizer N and P applied to wheat on the grain yield of wheat (t ha^{-1}) as influenced by substitution of rice with pigeonpea in RWCS

Fertilizer NP rate (kg ha^{-1})	1998–1999			1999–2000			2000–2001		
	Rice–wheat	Pigeonpea–wheat	Mean	Rice–wheat	Pigeonpea–wheat	Mean	Rice–wheat	Pigeonpea–wheat	Mean
N_0P_0	1.5	1.7	1.6	1.1	1.3	1.2	1.3	1.4	1.3
N_0P_{26}	1.7	1.9	1.8	1.2	1.6	1.4	1.4	1.6	1.5
Mean	1.6	1.8	1.7	1.2	1.4	1.3	1.3	1.5	1.4
N_{120} P_0	3.6	3.0	3.3	3.3	3.4	3.4	3.2	3.3	3.2
$N_{120}P_{26}$	4.0	3.6	3.8	3.8	4.3	4.0	3.8	4.7	4.3
Mean	3.8	3.3	3.6	3.6	3.8	3.7	3.5	4.0	3.7
Mean of P rates									
P_0	2.6	2.4	2.5	2.2	2.3	2.3	2.2	2.3	2.3
P_{26}	2.8	2.8	2.8	2.5	2.9	2.7	2.6	3.2	2.9
Overall mean	2.7	2.6	–	2.4	2.6	–	2.4	2.8	–

	Cropping system (C)	Fertilizer N (N)	C × N	Fertilizer P (P)	C × P	N × P	C × N × P
CD ($p < 0.05$)							
1998–1999	NS	0.16	0.22	0.16	NS	0.22	NS
1999–2000	0.17	0.15	NS	0.15	NS	0.21	NS
2000–2001	0.16	0.15	0.21	0.15	0.21	0.21	0.30

NS = Not significant at $p < 0.05$.

pigeonpea was greater than that following rice by 12.9% in the 1999–2000 and by 20.6% in 2000–2001.

The mean P uptake by wheat in different seasons varied from 3.4 to 4.7 kg ha^{-1} under N_0P_0 (control) and from 15.9 to 17.4 kg ha^{-1} under N_{120} P_{26} treatments under rice–wheat system (Table 6). The corresponding P uptake values under pigeonpea–wheat system were 3.6–5.5 kg ha^{-1} and 15.6–19.0 kg ha^{-1}, respectively. When averaged across fertilizer N and cropping system treatments, total P uptake with 26 kg fertilizer P compared with no P was greater by 65.3% in the first season, 73.4% in the second season and 80.3% in the

Table 5
Total N uptake in wheat as influenced by fertilizer N and P application to wheat and substitution of rice with pigeonpea in RWCS

Fertilizer NP rate (kg ha^{-1})	1998–1999			1999–2000			2000–2001		
	Rice–wheat	Pigeonpea–wheat	Mean	Rice–wheat	Pigeonpea–wheat	Mean	Rice–wheat	Pigeonpea–wheat	Mean
N_0P_0	26.1	32.8	29.5	19.7	23.4	21.6	21.2	26.0	23.6
N_0P_{26}	28.3	35.1	31.7	20.5	29.3	24.9	22.7	29.9	26.3
Mean	27.2	33.9	–	20.1	26.4	–	22.0	27.9	–
$N_{120}P_0$	74.2	62.8	68.5	68.3	69.9	69.1	62.9	67.9	65.4
$N_{120}P_{26}$	81.6	77.7	79.7	76.3	86.3	81.3	75.8	96.5	86.2
Mean	77.9	70.2	–	72.5	78.1	–	69.4	82.2	–
Mean of P rates									
P_0	50.2	47.8	49.0	44.0	46.7	45.4	42.1	46.9	44.5
P_{26}	55.0	56.4	55.7	48.4	57.8	53.1	49.3	63.2	56.3
Overall mean	52.6	52.1	–	46.3	52.3	–	45.7	55.1	–

Years	Cropping system (C)	Fertilizer N (N)	C × N	Fertilizer P (P)	C × P	N × P	C × N × P
CD ($p < 0.05$)							
1998–1999	NS	3.4	4.8	3.4	NS	4.8	NS
1999–2000	3.9	3.9	NS	3.9	NS	5.4	NS
2000–2001	3.2	3.2	4.6	3.2	4.6	4.6	6.5

NS = Not significant at $p < 0.05$.

Table 6
Total P uptake in wheat as influenced by fertilizer N and P application to wheat and substitution of rice with pigeonpea in RWCS

Fertilizer NP rate (kg ha^{-1})	1998–1999			1999–2000			2000–2001		
	Rice–wheat	Pigeonpea–wheat	Mean	Rice–wheat	Pigeonpea–wheat	Mean	Rice–wheat	Pigeonpea–wheat	Mean
N_0P_0	4.7	5.5	5.1	3.4	3.6	3.5	3.7	4.0	3.9
N_0P_{26}	7.0	7.6	7.3	5.3	5.8	5.6	5.8	6.8	6.3
Mean	5.9	6.5	–	4.4	4.7	–	4.7	5.4	–
$N_{120}P_0$	10.2	8.1	9.2	9.7	9.0	9.4	8.8	9.7	9.3
$N_{120}P_{26}$	17.4	15.6	16.5	16.9	17.2	17.1	15.9	19.0	17.5
Mean	13.8	11.8	–	12.9	13.1	–	12.4	14.4	–
Mean of P rates									
P_0	7.5	6.8	7.2	6.5	6.3	6.4	6.2	6.9	6.6
P_{26}	12.2	11.6	11.9	10.7	11.5	11.1	10.9	12.9	11.9
Overall mean	9.9	9.2	–	8.6	8.9	–	8.6	9.9	–

Years	Cropping system (C)	Fertilizer N (N)	C × N	Fertilizer P (P)	C × P	N × P	C × N × P
CD ($p < 0.05$)							
1998–1999	0.53	0.53	0.76	0.53	NS	0.76	NS
1999–2000	NS	0.51	NS	0.51	NS	0.72	NS
2000–2001	0.70	0.70	0.99	0.70	NS	0.99	1.41

NS = Not significant at $p < 0.05$.

final season. Fertilizer N application not only increased P uptake compared with N-skipped plots, but also magnified the response to P fertilization. Substitution of rice by pigeonpea in rice–wheat system enhanced P uptake in wheat by 9.3 and 15.1% during the second and the final year of the study. The changes in P uptake due to N or P fertilizers, and due to N × P interaction were significant ($p < 0.05$) during all the years.

The N use efficiency indices, viz., AE_N (kg grain kg^{-1} N) and AR_N (%) were greater ($p < 0.05$) in wheat following pigeonpea than wheat following rice in 2000–2001, but reverse was true in 1998–1999 (Table 7). During 1999–2000, the AE_N and AR_N in the two cropping systems did not differ significantly. Averaged across P rates, the mean value of AE_N under rice–wheat system was 19 in 1998–1999, 20 in 1999–2000 and 18 in 2000–2001, and that of AR_N 42 in 1998–1999, 44 in 1999–2000, and 41 in 2000–2001. The corresponding values of these N use efficiency indices under pigeonpea–wheat system ranged between 13 and 21 for AE_N, and 31 and 45 for AR_N during different wheat seasons. Use of 26 kg P ha^{-1} along with 120 kg N ha^{-1} increased the AE_N and AR_N values; the advantages were of course greater when pigeonpea preceded wheat.

The P use efficiency, computed as AE_p and AR_p was greater ($p < 0.05$) when wheat followed pigeonpea instead of rice, particularly in treatments that received both N and P fertilizers (Table 7). With adequate NP fertilization, AE_p in both the systems and AR_p in pigeonpea–wheat system increased with the passage of time, being highest in the terminal wheat crop.

3.2.3. Economics of pigeonpea–wheat versus rice–wheat system

Raising a rice crop involved nearly double the cost of raising a pigeonpea crop (Rs. 7389 ha^{-1}), which resulted in a greater cost of cultivation of rice–wheat system (on average Rs. 32,283 ha^{-1}) compared with that of pigeonpea–wheat system (on average Rs. 23,829 ha^{-1}) (Table 8). The net returns (NR) of wheat following rice or pigeonppea were negative in N_0P_0 and N_0P_{26} treatments. Application of 26 kg P along with 120 kg N ha^{-1}, however, produced greater NR of wheat following pigeonpea (Rs. 8839 ha^{-1}) than those following rice (Rs. 6648 ha^{-1}). When annual net returns of the cropping systems (SNR), i.e., NR of monsoon crop + NR of wheat were compared, pigeonpea–wheat system gave 68% greater SNR than rice–wheat system (Table 8).

3.2.4. Changes in physico-chemical characteristics of the soil

The carbon accumulation in soil profile (0–105 cm) measured as cumulative organic carbon (OC) content ranged between 42 and 48 Mg ha^{-1} in rice–wheat and

Table 7
N and P use efficiency of wheat as influenced by substitution of rice with pigeonpea in RWCS

Fertilizer NP rate (kg ha^{-1})	Agronomic efficiency (AE)			Apparent recovery (AR%)		
	1998–1999	1999–2000	2000–2001	1998–1999	1999–2000	2000–2001
Nitrogen						
Rice–wheat						
N_0P_0	–	–	–	–	–	–
N_0P_{26}	–	–	–	–	–	–
$N_{120}P_0$	18	18	16	40	41	35
$N_{120}P_{26}$	19	21	20	44	47	44
Mean	18.5	19.5	18.0	42.0	44.0	41.0
Pigeonpea–wheat						
N_0P_0	–	–	–	–	–	–
N_0P_{26}	–	–	–	–	–	–
$N_{120}P_0$	11	18	15	25	39	35
$N_{120}P_{26}$	14	22	26	36	48	56
Mean	12.5	20.0	20.5	30.5	43.5	45.5
Phosphorus						
Rice–wheat						
N_0P_0	–	–	–	–	–	–
N_0P_{26}	7.3	3.5	4.2	8.9	7.5	8.5
N_{120} P_0	–	–	–	–	–	–
$N_{120}P_{26}$	14	20	25	28	25	27
Mean	10.4	11.6	14.6	18.3	16.5	18.0
Pigeonpea–wheat						
N_0P_0	–	–	–	–	–	–
N_0P_{26}	6.5	11.9	7.3	8.1	8.2	10.7
$N_{120}P_0$	–	–	–	–	–	–
$N_{120}P_{26}$	24	34	57	29	32	36
Mean	15.0	22.7	32.1	18.6	20.0	23.2
CD ($p < 0.05$)						
Nitrogen						
Cropping system (C)	2.5	NS	1.8	3.9	NS	3.6
Fertilizer NP (F)	2.5	2.8	1.8	3.9	2.6	3.6
C × F	3.5	NS	2.6	5.5	NS	5.2
Phosphorus						
C	1.1	2.7	3.3	1.7	1.8	1.8
F	1.1	2.7	3.3	1.7	1.8	1.8
C × F	1.6	3.8	4.7	2.4	2.5	2.5

NS = Not significant at $p < 0.05$.

between 46 and 51 Mg ha^{-1} in pigeonpea–wheat system under different fertilizer treatments; the values were highest with $N_{120}P_{26}$ plots (Fig. 1). Combined use of N and P fertilizers in wheat in pigeonpea–wheat system increased cumulative soil OC content of the profile over the initial values by 13.9%, whereas the corresponding increase in soil OC content under rice–wheat system was 8.1% only. After 3 years of continuous cropping, carbon accumulation in NP fertilized plots under pigeonpea–wheat system was greater by 2.6 Mg ha^{-1} compared with that under rice–wheat system.

The bulk density (BD) of surface soil layer, i.e., 0–15 cm was 1.48 Mg m^{-3} at the onset of the experiment. It, however, increased with increasing soil profile depth, measuring 1.65 Mg m^{-3} in 90–105 cm soil layer (Fig. 2). At the end of experimentation in 2000–2001, N and P treatment to wheat did not influence soil BD. With continuous rice–wheat cropping for 3 years, the BD values at 30–45 cm soil depth were greater (1.62 Mg m^{-3}) compared with the initial BD (1.56 Mg m^{-3}) at this depth, indicating thereby a tendency of sub-surface soil compaction. In the plots having pigeonpea as monsoon crop, no such

Table 8
Cost of cultivation and annual net returns (in Indian rupees, 1 Rs. = US $0.022) under varying NP applications as influenced by substitution of rice with pigeonpea in RWCS

Treatment	Cost of cultivation (Rs ha^{-1})			Net returns (Rs ha^{-1})		
	Monsoon crop	Wheat	System's total	Monsoon crop	Wheat	System's total
Rice–wheat						
N_0P_0	15,842	15,686	31,528	6388	−7626	−1238
N_0P_{26}	15,842	16,986	32,828	7486	−8120	−634
Mean	15,842	16,336	32,178	6937	−7873	−936
$N_{120}P_0$	15,842	15,846	31,688	6676	4924	11,600
$N_{120}P_{26}$	15,842	17,243	33,085	8764	6648	15,412
Mean	15,842	16,545	32,387	7720	5786	13,506
Pigeonpea–wheat						
N_0P_0	7389	15,686	23,075	14,371	−6551	7820
N_0P_{26}	7389	16,986	24,375	15,686	−6467	9219
Mean	7389	16,336	23,725	15,029	−6509	8520
$N_{120}P_0$	7389	15,846	23,235	14,462	4118	18,580
$N_{120}P_{26}$	7389	17,243	24,631	17,000	8839	25,839
Mean	7389	16,545	23,933	15,731	6479	22,210

soil compaction was noticed. When averaged across fertilizer NP treatments, BD values at soil profile depths up to 45 cm were significantly ($p < 0.05$) smaller (1.42–1.49 Mg m^{-3}) under pigeonpea–wheat system, than those (1.56–1.62 Mg m^{-3}) under rice–wheat system.

The nitrate–N (NO_3–N) content of surface soil (0–15 cm) was greater ($p < 0.05$) in fertilizer N (120 kg ha^{-1}) treated plots compared with that in no N, as also greater ($p < 0.05$) in pigeonpea–wheat system compared with that in rice–wheat system, the differences being prominent in 1999–2000 and 2000–2001 (Fig. 3). When compared with initial content of surface soil layer, the NO_3–N content in 120 kg N ha^{-1} treated plots was greater by 2.44 mg kg^{-1} in the 2000–2001 under rice–wheat system and by 4.3 mg kg^{-1} under pigeonpea–wheat system. On the other hand, skipping of N to wheat in rice–wheat system led to NO_3–N depletion by 1.2 mg kg^{-1} over the initial status (6.4 mg kg^{-1}).

In rice–wheat system, the NO_3–N content in upper three soil layers, i.e., up to 45 cm profile depth, under N_0P_0 plot was measured less than the initial content, particularly after the terminal crop cycle. The NO_3–N content of soil beyond 45 cm profile-depth, however, was maintained at the initial level even under N_0P_0. In contrast, NO_3–N content in rice–wheat system having 120 kg N alone increased with increasing profile depth, with highest values at 30–45 cm soil layer. Combined application of 120 kg N and 26 kg P ha^{-1} resulted in lower contents of NO_3–N throughout soil profile, compared with 120 kg N alone. Substitution of monsoon rice with pigeonpea favoured a significantly greater NO_3–N retention in 0–45 cm profile depth, compared with rice–wheat system, as was evident from higher NO_3–N values in these upper soil layers. Such advantage of pigeonpea in profile distribution of NO_3–N content was, however, more spectacular in N-fertilized plots during second and terminal years of the study.

An application of N alone or in combination with P increased the ammonium–N (NH_4–N) content over the N_0P_0 or N_0P_{26} treatments in 0–15 cm soil layer; the increase was more spectacular under pigeonpea–wheat system (Fig. 4). When averaged across the P treatments, NH_4–N content of the surface soil layer (0–15 cm depth) in 120 kg N treated plots was greater than that in no N plots by 22–34% in rice–wheat system and by 32–43% in pigeonpea–wheat system.

Compared with the initial NH_4–N content, which was almost uniformly distributed throughout soil profile (0–105 cm), the values of NH_4–N in different soil layers up to 90 cm profile depth were greater under fertilizer N treated plots in both cropping systems during all years (Fig. 4). In no N plots, the NH_4–N content in upper three layers, i.e., up to 45 cm profile depth under rice–wheat system was measured less than the initial content, particularly after third crop cycle. The NH_4–N content of soil below these depths was, however, maintained at the initial level even under N_0P_0. Fertilizer NP as well as cropping system treatments markedly influenced the distribution of NH_4–N in soil profile. A constant increase in NH_4–N content was registered at all profile depths in treatments receiving 120 kg N alone (Fig. 4). Compared with rice–wheat system, pigeonpea–wheat system favoured greater ($p < 0.05$) NH_4-N content up to a profile depth of 0–60 cm, irrespective of fertilizer NP treatments.

Olsen-P content of the surface soil (0–15 cm) increased over the initial content, consequent to P fertilization at 26 kg ha^{-1} to wheat, and the magnitude of increase was greater in the terminal year of experimentation (Fig. 5). Conversely, available P content of surface soil (0–15 cm) under N_0P_0 plots, averaged across cropping systems, was depleted over the initial content (7.3 mg kg^{-1}) by 16% in the first, 22% in the second, and 29% in the third year. The extent of depletion over the initial P content was relatively greater (27–36% after wheat harvest in different years) in treatments that received 120 kg N ha^{-1} but no P.

Growing of pigeonpea during monsoon season in the place of rice led to greater depletion of Olsen-P content in no P plots, though the differences in Olsen-P content of the soil under pigeonpea–wheat and rice–wheat system were statistically significant in the second and the terminal year only (Fig. 5). With the use of 26 kg P ha^{-1}, the increase in available P content of soil over no P was also of smaller magnitude under pigeonpea–wheat system than under rice–wheat system. There was a decrease in available P content with an increase in soil depth, irrespective of the treatments imposed (Fig. 5). Fertilizer NP and cropping system treatments had marked influence on available P content of soil up to 45 cm depth; the effects under 15–30 cm and 30–45 cm profile were similar to that in surface (0–15 cm) soil layer. The P content below 45 cm soil depth hardly exhibited any treatment effect.

4. Discussion

In UGP, the optimum-sowing time of wheat is 15 November (Yadav et al., 1998b), whereas farmers could generally sow their wheat crop after rice harvest by 17 November and after pigeonpea harvest by 23 December (Table 2). Delay in wheat sowing beyond optimum time may cause 50 kg ha^{-1} day^{-1} loss in grain yield of wheat (Ortiz-Monasterio et al., 1994). In the high productivity areas of UGP and TGP, yield declines of even 0.5 t ha^{-1} t^{-1} increase in yield potential beyond 5.5 t ha^{-1} has been envisaged (Aggarwal et al., 2000). Therefore, to minimize yield reduction due to late sowing after pigeonpea, farmers might have adopted the practice of greater N application rate in wheat following pigeonpea. But a rapid increase in temperature towards the end of April in this zone causes forced maturity of late sown wheat, (Aggarwal and Kalra, 1994), making it difficult to compensate yield loss on one hand and resulting in under-utilization of applied inputs on the other.

In the researcher-managed experiment also, wheat grain yield during first year was 4.7% lower in pigeonpea–wheat system, though not significant compared to that in rice–wheat system (Table 4). The wheat yields following pigeonpea during subsequent years were, however, significantly ($p < 0.05$) greater than those following rice. The absence of legume effect (pigeonpea) in initial year may also be described in the light of delay in wheat sowing beyond optimum sowing date and nutrient (N and P) removal by monsoon crops, i.e., rice and pigeonpea. The extra short duration cultivars of pigeonpea, which mature up to three to four weeks earlier, could overcome the adverse effect of delayed planting of wheat (Dahiya et al., 2002). The benefits of legume crops to succeeding cereal crops are well documented, mainly by way of improving productivity, nutrient use efficiency, regenerating soil fertility through biological N fixation (BNF) and nutrient mining from relatively deeper soil profile (Buresh and De Datta, 1991; Timsina and Connor, 2001; Singh et al., 2002). In the present case, however, pigeonpea removed greater amounts of N and P under different treatments than the amounts recycled to soil through incorporation of root + stubble, nodules and leaf litter after pigeonpea harvest (Table 3). In case, the P use efficiency in pigeonpea is assumed to be 30–40% of the applied P fertilizer, a large portion of P uptake by pegionpea came from the soil. The share of soil N in the N uptake by a legume is also likely to be substantial, if 50–70% of the N accumulated in the dry matter is assumed to be derived from BNF (Awonaike et al., 1990). With long-duration legume crops and in case where a large portion of legume biomass is removed from the field, even depletion in soil fertility has been reported (Peoples and Herridge, 1990; Rego and Rao, 2000; Dwivedi et al., 2003). Nevertheless, the mineral N content, i.e., NO_3–N and NH_4–N, analyzed after wheat harvest (Figs. 3 and 4) in surface soil layer under pigeonpea–wheat system was greater ($p < 0.05$) than that under rice–wheat system during all years. The available P content of soil (0–15, 15–30 and 30–45 cm depth) in no P plots was, however, depleted from the initial levels, and even with P fertilization it was constantly lower than the rice–wheat plots (Fig. 5).

During the second and the terminal years, despite sizeable removal of N and P from the soil by pigeonpea, its inclusion in place of rice caused an increase in wheat yields (Table 4) as well as fertilizer use efficiency (Table 7). Greater wheat yields following pigeonpea may be explained in two ways. First, incorporation of pigeonpea roots and above ground residues, and their subsequent decomposition increased soil OC content over the initial OC throughout soil profile (Fig. 1), which could have favoured better establishment of the wheat crop (Killham, 1994). Second, a decreased sub-surface soil compaction as indicated by a reduction in bulk density particularly at 30–45 cm profile depth (Fig. 2) due to inclusion a tap-rooted legume (pigeonpea) favoured the growth and penetration of wheat roots (Cresswell and Kirkguard, 1995). Otherwise, impaired soil structure of puddled layer and compacted sub-soil in rice–wheat system, that often strengthens to from a hard pan of increased soil strength on drying after rice harvest, are the major impediment for establishment and growth of subsequent wheat crop (Gajri et al., 1992; Oussible et al., 1992; Aggarwal et al., 1995). The root volume and root weight of wheat measured under the two cropping systems in the present study revealed a drastic reduction beyond 45 cm profile depth when rice preceded wheat (Fig. 6). The root system, on the other hand, was well-distributed throughout soil-profile when wheat followed pigeonpea. Also, wheat grown after rice is reported to be more prone to lodging due to poor root development (Dahiya et al., 2001). It is due to these reasons that under continuous RWCS, the yields of wheat are often lesser than wheat yields in cropping systems involving a non-rice crop during monsoon season (Boparai et al., 1992; Singh et al., 2002).

In the present study, wheat yields were greater in treatments fertilized with 120 kg N and 26 kg P ha^{-1}, and skipping of either nutrients resulted in significant yield loss, irrespective of crop sequence (Table 4). Coarse textured soils having low organic matter can support high productivity only under assured and adequate supply of nutrients (Aulakh and Singh, 1997). There was a consistent effect of fertilizer N on the wheat yield, which remained largely unaffected due to substitution of monsoon rice with pigeonpea. Greater wheat yield responses to P over no P treatment in pigeonpea–wheat (16.3–36.1%) compared with those in rice–wheat system (10.5–17.3%) in different years (though significant in the terminal year only) are explicable in terms of relatively higher AE_P and AR_P values in wheat following pigeonpea (Table 7). An increase in use efficiency of N and P, particularly in AE_P and AR_P values, recorded in the terminal year compared with the initial year in wheat following pigeonpea may be attributed to the increase in wheat yield and nutrient uptake over the years under NP fertilized plots, and not to the decline in yield or uptake in 0-N or 0-P plots. Extensive wheat root growth under pigeonpea–wheat system, as measured in present investigation might have facilitated greater contact between the absorbing root surface and the available P in soil (Tisdale et al., 1993), resulting in an increased P use efficiency. The arguments supporting judicious fertilization of N and P in wheat are further substantiated in the present case, when results are explained in terms of the use efficiencies of N and P fertilizers. The AE_N, AR_N, AE_P and AR_P values computed as a measure of FUE of applied N and P in wheat revealed that both AE_N and AR_N were greater when 120 kg N was supplemented with 26 kg P ha^{-1}, and not applied alone. These results are consistent with the findings of long-term experiments in India, wherein recommended NPK fertilization increased annual crop productivity and FUE over N alone (Hegde and Dwivedi, 1992; Swarup and Wanjari, 2000).

After wheat harvest, the NO_3–N content below 30 cm soil profile-depth was smaller ($p < 0.05$) in NP treatments compared with those receiving N alone, and also smaller ($p < 0.05$) under pigeonpea–wheat compared with rice–wheat system during all three years (Fig. 3). As the NO_3–N content in soil profile was not measured after rice or pigeonpea harvest, it is difficult to explain the relatively low NO_3–N content in deeper profile layers under pigeonpea–wheat system in terms of N removal by pigeonpea. The NO_3–N distribution pattern in soil profile can, however, be explained in terms of better-root growth of wheat, i.e., 58% higher root volume and almost double root weight below effective root zone (below 45 cm depth) after pigeonpea compared with that after rice (Fig. 6). Ensuring a deep and exhaustive root system of wheat can considerably reduce the leaching of NO_3–N beyond the root zone (Singh and Singh, 2001). The root system of wheat extended to lower profile depths under pigeonpea–wheat treatments might have helped in efficient utilization of NO_3–N, resulting in low NO_3–N content at these depths, compared with rice–wheat treatments (Smith et al., 1996). If NO_3–N content of soil-profile beyond effective root zone is considered as an indicator of N leaching, the results of this study inferred that NO_3–N leaching, which is a serious environmental concern (Follett, 1992; Williams, 1992; Singh et al., 1995), could be minimized through diversification of rice with pigeonpea under RWCS. Improvement in N use efficiency is considered one of the most promising agro-techniques to curb NO_3–N leaching (Smith and Shepherd, 2000; Timsina and Connor, 2001). In the present study, an increase in N use efficiency in wheat was measured with the substitution of rice of RWCS with pigeonpea, and with the NP fertilization at recommended rate, indicating thereby the effectiveness of these agronomic options in minimizing NO_3–N leaching.

5. Conclusions

Our study infers that in the intensively cultivated UGP zone of the IGPR, where the prevailing RWCS have started exhibiting signs of stress, pigeonpea–wheat may prove a better alternative cropping system in terms of soil fertility restoration and economic gains. The frequently documented stagnation or even decline in the productivity of wheat following rice can be reversed by diversifying monsoon rice with pigeonpea. Since rice is a staple food grain, and the UGP is one of the major areas contributing towards total food grain production in India, permanent diversification of rice with pigeonpea may not be advisable from the food security viewpoint. Nevertheless, on soils exhibiting poor establishment and growth of post-rice wheat owing to sub-surface compaction under continuous RWCS, or on the coarse-textured soils that favour excessive nitrate-leaching under rice culture, the RWCS can be diversified for a certain time-interval, say for 3 years, by inclusion of pigeonpea in the rotation to sustain wheat productivity and restore soil health.

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