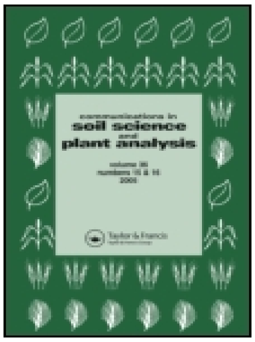

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Long-Term Wheat Residue Management and Supplementary Nutrient Input Effects on Phosphorus Fractions and Adsorption Behavior in a Vertisol

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The management of crop residues coupled with external nutrient inputs is important for improving and conserving soil fertility and productivity. We assessed the long-term effects of three wheat residue management options (RMO) (residue burning, incorporation, and surface retention) in combination with three supplementary nutrient inputs (SNI) [control, fertilizer, and farmyard manure (FYM)] on phosphorus (P) fractions and adsorption behavior of a Vertisol under soybean–wheat system. Wheat residue incorporation and retention improved the labile inorganic P [sodium bicarbonate ($NaHCO_3$-P_i)] by 3.2 and 5.0 mg kg^{-1} and the labile organic P ($NaHCO_3$-P_o) by 2.4 and 4.2 mg kg^{-1}, respectively, as compared to residue burning. The soils under residue incorporation and retention had 38 and 26% more moderately labile organic P [sodium hydroxide (NaOH-P_o)], respectively, than the soil under residue burning. The SNI either as fertilizer or FYM further enhanced $NaHCO_3$-P_i, $NaHCO_3$-P_o, and NaOH-P_o. In contrast, less labile P fractions [hydrochloric acid (HCl)-P and residual-P] remained unaffected by RMO and SNI treatments. Residue retention or incorporation decreased P adsorption over the residue burning for all the three nutrient inputs. The P-adsorption data fitted well to the Langmuir equation (R^2 ranged from 0.970 to 0.994). The P-adsorption maximum (b), bonding energy constant (k), differential P-buffering capacity (DPBC), and standard P requirement (SPR) were lower with residue incorporation or surface retention than with residue burning. The SPR followed the order residue burning > incorporation > retention for RMOs and control > fertilizer > FYM for SNI treatments. The $NaHCO_3$-P_i, $NaHCO_3$-P_0, and NaOH-P_o had negative correlation with P-adsorption parameters and showed positive correlation with soybean P uptake. Wheat residue incorporation or retention plus FYM could be an effective strategy for enhancing the P fertility of Vertisols under a soybean–wheat system.

Keywords Crop residue, FYM, fertilizer, P adsorption, P fractions, soybean–wheat system

Introduction

Crop residues are a vital resource for conserving soil quality and productivity, as they not only serve as a source of soil organic matter but also provide essential plant nutrients.

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In many developing countries including India, crop residues were traditionally removed from the fields and used for varied purposes such as animal feed and roofing material. However, with the advent of mechanized harvesting of crops, the crop residue is now left in the field itself and cannot be easily collected and used for traditional purposes. In central India, where wheat is mechanically harvested using combine harvesters, the management practice in vogue is to burn such residues in situ. The field burning of crop residues is undoubtedly a wasteful practice as it results in loss of some plant nutrients and organic matter. According to Sharma and Mishra (2001), burning of wheat residue results in the loss of nitrogen (N), sulfur (S), phosphorus (P), and potassium (K) to the extents of 100, 75, 22.2, and 21.8%, respectively. The ash resulting from burning of biomass is nearly free from N but is as valuable source of other plant nutrients, particularly P, K, and several micronutrients, and thus can improve soil fertility (Sander and Andren 1997; Patterson et al. 2004; Lopez et al. 2009). The biomass ashes, produced under control conditions, have been shown to enhance crop yields (when applied with N fertilizers) and have liming effects on the amelioration of acidic soils (Schiemenz and Eichler-Löbermann 2010). Furthermore, biomass ashes can also stimulate soil microbial activity (Demeyer, Nkana, and Verloo 2001). Despite these benefits of biomass ashes, the field burning of crop residues as a management practice is discouraged because of its negative effects on environment and soil quality (Sahai et al. 2011; Verhulst et al. 2011). In contrast, long-term incorporation or retention of crop residues coupled with appropriate fertilization have been shown to enhance soil quality and productivity (Singh, Singh, and Timsina et al. 2005; Malhi et al. 2011) and are increasingly advocated as effective alternatives to in situ residue burning. Literature is replete with studies assessing the effects of crop residue management practices on crop yields and soil quality with a special focus on soil N dynamics and N recovery (Prasad, Gangaih, and Aipe 1999; Montoya-González et al. 2009). In the recent studies, soil P fractions and phytoavailability were shown to increase with the addition of crop residues or biomass ash derived from burning of crop residues (Schiemenz and Eichler-Löbermann 2010; Noack et al. 2012). However, little is known about the comparative effects of different crop residue management options (burning versus incorporation or retention) and supplementary nutrient input sources on cycling of P in soils. Understanding of soil P transformation and availability in response to long-term crop residue management practices will facilitate the development of strategies for efficient utilization of P in cropping systems.

Phosphorus deficiency is one of the major nutritional constraints to crop production in Indian Vertisols (Bansal and Sekhon 1994). Consequently, large inputs of P are required for optimum crop production. Because of economic compulsions and ecological considerations, use of renewable organic resource such as animal manures and crop residues has been suggested to supplement chemical fertilizers. Inclusion of crop residues can recycle the P absorbed by the previous crop. The effects of organic inputs on P dynamics in soils have been investigated intensively (Iyamuremye and Dick 1996; Damodar Reddy, Subba Rao, and Takkar 1999b), but these studies mainly focused on importance of inorganic P for plant nutrition. However, organically bound P can constitute a significant portion of total P, ranging from 20 to 80% in arable soils and contribute substantially to plant-available P (Ebengreuth, Yang, and Schubert 2010). It is important therefore to consider both organic and inorganic P fractions for soil P fertility evaluation. Although a laboratory incubation study has shown that addition of wheat residue can considerably increase soil labile organic and inorganic, moderately labile organic P fractions and can decrease P adsorption in a Vertisol (Damodar Reddy, Subba Rao, and Singh 2001), little information is available on the subject for different wheat residue management practices under field conditions. The objective of the present investigation was to quantify the changes in P fractions and adsorption behavior of a Vertisol in response to long-term wheat residue management options and supplementary nutrient input sources under soybean–wheat annual rotation.

Material and Methods

Experimental Details

A 5-year field experiment was started in 2000–2001 at the research farm of the Indian Institute of Soil Science, Bhopal, to evaluate mechanical harvest-borne wheat residue management practices with and without supplementary nutrient input sources under a soybean–wheat system on a Vertisol. The experimental site is situated at 23° 18′ N, 77° E, with an altitude of 435 m above mean sea level. The climate of the area is subhumid tropical with a mean annual air temperature of 25 °C and annual rainfall of 1208 mm. The soil of the experimental site is classified at the family level as fine, montmorillonitic, hyperthermic, Typic Haplustert with pH 8.1, cation exchange capacity (CEC) 42 C mol (P^+) kg^{-1}, and organic carbon (C) 4.6 g kg^{-1}. The composite soil sample was collected before the initiation of the experiment and its fertility status assessed. The available N, P, and K statuses of initial soil were determined by the alkaline permanganate method (Subbaiah and Asija 1956), 0.5 M sodium bicarbonate (Olsen et al. 1954), and neutral 1 N ammonium acetate (Hanway and Heidel 1952) methods, respectively, and were 112, 6.8, and 209 mg kg^{-1} soil, respectively.

The field experiment was laid out using a randomized complete block design with a split-plot treatment arrangement and three replicates during soybean cropping (i.e., soybean following wheat). The main-plot treatments consisted of three wheat residue management options (RMO) such as residue burning (residue burnt and conventional tillage followed), residue incorporation (residue incorporated into the soil by conventional tillage), and residue retention (residue retained on soil surface and no tillage done as in conservation tillage). The subplot treatments involved three supplementary nutrient inputs (SNI), which included control (no N and P inputs), fertilizer (28 kg N and 30 kg P ha^{-1} as chemical fertilizers), and farmyard manure (FYM) at 4 t ha^{-1} equivalent to 28 kg N ha^{-1}. The N and P were supplied at the rates as before through fertilizers urea and single superphosphate, respectively, under fertilizer treatment. For the FYM treatment, the rate of FYM was decided on an N equivalence basis to supply 28 kg N ha^{-1}. The rate of FYM was 4 t ha^{-1} in the first year of experimentation and was kept the same in the following years because the nutrient contents in FYM did not differ much from year to year. The FYM used in field experiment contained, on an average, 0.71% N and 0.13% P. The P was applied at the rate of 30 kg ha^{-1} through single superphosphate (SSP) after adjusting for the P supplied though FYM. Soybean (var. JS-335) was grown in rainy season (July–October) every year. Wheat (var. WH-147) was grown with uniform N and P rates of 68 N and 30 kg P ha^{-1} in the following winter season (November–March) under irrigated conditions (one presowing and two postsowing irrigations). Crop yields were recorded every year. Soybean plant samples (grain and stover) were collected, oven dried at 60 °C for 48 h, and finely ground to pass through a 0.5-mm sieve prior to analysis for P. The plant samples were digested in triacid medium [nitric acid (HNO_3) + sulfuric acid (H_2SO_4) + perchloric acid ($HClO_4$)] in the ratio of 10:1:4 by v/v), and the P concentration in the digests was measured by the vanado-molybdate method. Uptake of P by soybean crop was calculated as the product of P concentration and biomass in aboveground parts of the crop. The composite soil samples

(0–0.15 m deep) from all the treatment plots collected at end of five cycles of soybean–wheat annual rotation were air dried, ground to pass through a 2-mm sieve, and used in P fractionation and adsorption studies.

Soil Phosphorus Fractionation (Sequential Extraction)

Soil samples were subjected to sequential P fractionation using a modified version of the Hedley, Stewart, and Chauhan (1982) procedure as outlined by Zhang and Mackenzie (1997). Soil samples (0.5 g) were placed in 50-ml centrifuge tubes and sequentially extracted with 30 ml each of 0.5 M sodium bicarbonate ($NaHCO_3$) (pH 8.5), 0.1 M sodium hydroxide (NaOH), and 1.0 M hydrochloric acid (HCl). After shaking with each extractant for 16 h, the suspensions were centrifuged for 10 min at 8000 rpm and filtered. Then the soil residue was digested with H_2SO_4–hydrogen peroxide (H_2O_2) to extract chemically more stable P (residual P). The aliquots of $NaHCO_3$, NaOH, and HCI extracts were neutralized using P nitrophenol indicator, and their inorganic P ($NaHCO_3$-P and HCI-P) concentration was determined colorimetrically (Murphy and Riley 1962). Additionally, the aliquots of $NaHCO_3$ and NaOH extracts were digested with acidified ammonium persulfate [$(NH_4)S_2O_8$] and analyzed for total P (Pt). The organic P (P_o) in $NaHCO_3$ and NaOH extracts was obtained as the difference between Pt and Pi of respective extracts.

Phosphorus Adsorption

Phosphorus adsorption behavior of soils under different residue management options was studied following the method of Fox and Kamprath (1970). Three g of soil were equilibrated with 30 ml of 0.01 M calcium chloride ($CaCl_2$) solution containing graded concentrations of P (2, 4, 8, 16, 24, 32, and 40 mg P L^{-1}, corresponding to P addition rate of 20, 40, 80, 160, 240, 320, and 400 mg P kg^{-1} soil, respectively) in 50-mL plastic centrifuge tubes for 6 days at 25 ± 1 °C. Two drops of toluene were added to suspensions to inhibit microbial activity. During the equilibration period, the soil suspensions were shaken for 30 min twice daily. After 6 days of equilibration, the suspensions were centrifuged and filtered. The concentrations of P in the filtrate were determined. The amount of P adsorbed was calculated as the difference between P initially added and P remaining in solution by Eq. (1):

$$q = (\mathrm{Ci} - \mathrm{Ce})\,\frac{V}{W} \tag{1}$$

where q is the amount of P adsorbed per unit mass of soil (mg kg^{-1}), Ci is the initial solution P concentration (mg L^{-1}), Ce is the equilibrium solution P concentration (mg L^{-1}), V is the volume of solution added (mL), and W is the weight of soil (g).

The P adsorption isotherms were plotted using the linearized Langmuir model:

$$\frac{\mathrm{Ce}}{q} = \frac{1}{kb}\,\frac{\mathrm{Ce}}{b} \tag{2}$$

where Ce is equilibrium solution P concentration (mg P L^{-1}), q is amount of P adsorbed (mg P kg^{-1}), b is P adsorption maximum (mg P kg^{-1}), and k is the constant related to bonding energy of P adsorption (L mg^{-1} P).

The adsorption maximum (b) and bonding energy (k) were computed respectively from slope ($1/b$) and intercept ($1/kb$) of the Langmuir P adsorption isotherms. The maximum P buffer capacity (MPBC) was calculated by multiplying adsorption coefficients, b and k, as advocated by Kuo, Jellum, and Pan (1988). Further standard P requirement of soil (SPR) was determined as amount of P sorbed at a solution P concentration of 0.2 mg P L^{-1} (Fox and Kamprath 1970).

Phosphorus Uptake by Soybean Crop

Soybean plant samples (grain and stover) were collected, oven dried at 60 °C for 48 h, and finely ground to pass through 0.5-mm sieve prior to analysis for P. The plant samples were digested in tri-acid medium ($HNO_3 + H_2SO_4 + HClO_4$ in the ratio of 10:1:4 by v/v), and the P concentration in the digests was measured by vanado-molybdate method. Uptake of P by soybean crop was calculated as the product of P concentration and biomass in aboveground parts of the crop.

Statistical Analysis

Experimental data on different organic and inorganic P fractions were statistically analyzed by the standard analysis of variance (ANOVA) technique appropriate to split-plot design to test the significance of treatment effects. The treatment means were compared using least significant difference (LSD at $P = 0.05$). Simple correlations for relationships between different soil P fractions and P sorption characteristics of soil and P uptake by soybean crop were calculated.

Results and Discussion

Mean Grain Yield and Phosphorus Uptake

The grain yield of soybean varied from year to year, but the nature of yield response behavior among the different wheat RMOs and SNI treatments was more or less similar in different years (data not shown). The mean grain yield (over 5 years) ranged from 755 to 1568 kg ha^{-1} between different RMO and SNI treatment combinations and showed significant effects of RMO, SNI, and their interactions (Figure 1). Soil incorporation or surface retention of wheat residue generally resulted in better crop yields than residue burning. In the absence of external nutrient supplementation (control), the soybean yield was suppressed by soil incorporation of wheat residue as compared to burning or surface retention, possibly due to N immobilization. However, the yield-suppressing effect of residue incorporation alone was offset and yields increased significantly with the coapplication of nutrient input, either as fertilizer or FYM. These results are consistent with the findings of a study with cereals and oilseeds grown for 16 years, which has reported that incorporation of straw by plowing reduced crop yields compared to straw removed at no-N application but not at high N rates of 100 or 200 kg N ha^{-1} (Smith et al. 2004). The greatest yield was obtained with residue incorporation plus FYM. The relatively greater yield increases with FYM could also be due to additional beneficial effects of manure on soil properties and nutrient availability as the FYM contained not only N and P but also K and other secondary and micronutrients. Mean P uptake by soybean was affected by wheat RMO and SNI and varied from 7.3 to 16.6 kg ha^{-1} (Figure 1). The trend between treatments was

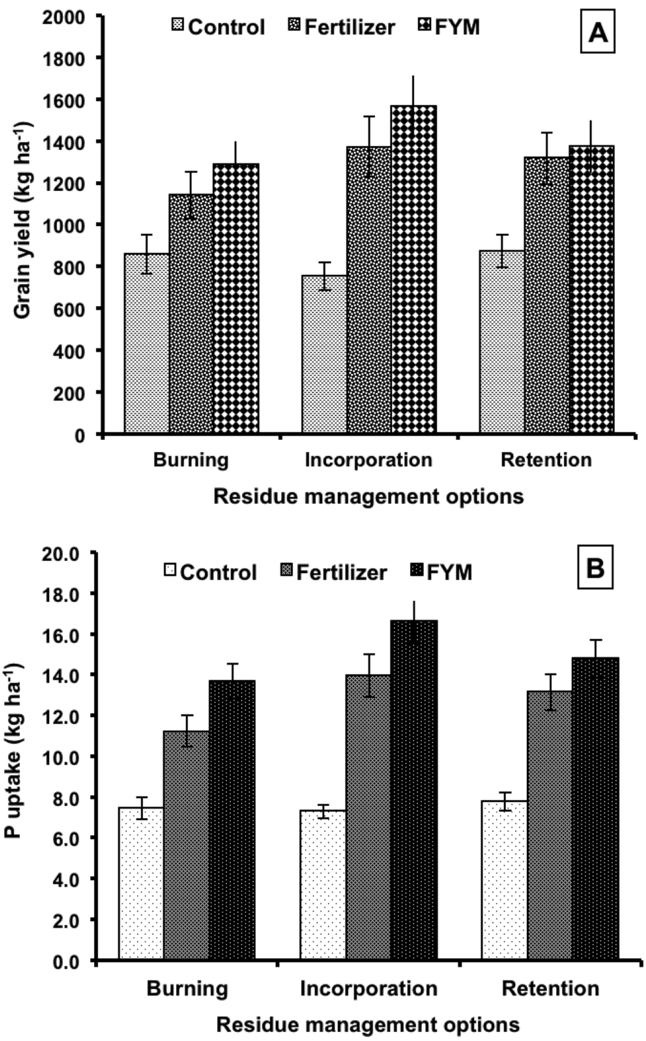

Figure 1. Mean grain yield (A) and phosphorus uptake (B) of soybean under different wheat residue management options as affected by supplementary nutrient inputs (control, fertilizer, and FYM). The vertical line bars represent ± standard error of mean.

similar to the crop yield trend. The mean P uptake followed the order residue incorporation > retention > burning for RMOs and FYM > fertilizer > control for SNI treatments. The greatest nutrient uptake was associated with residue incorporation or retention coupled with the application of FYM.

Phosphorus Fractions (Sequentially Extracted)

The sequential fractionation procedure employed in this study separated soil P into six different fractions of varying availability (Table 1). The contents of sodium bicarbonate–extractable inorganic P_i ($NaHCO_3$-P_i) and organic P ($NaHCO_3$-P_o) ranged from 12.2 mg kg^{-1} to 25.7 mg kg^{-1} and from 15.2 mg kg^{-1} to 27.2 mg kg^{-1}, respectively. The wheat

Table 1
Effects of wheat residue management options (RMO) and supplementary nutrient inputs (SNI) on soil P fractions

Treatments		Soil P fractions (mg kg^{-1})					
		$NaHCO_3$-P		NaOH-P			
RMO	SNI	P_i	P_o[a]	P_i	P_o[a]	HCl-P	Res-P
Burning	Control	12.2	15.2	45.8	44.6	160.4	201.7
	Fertilizer	15.2	17.0	57.4	57.0	169.3	216.7
	FYM	20.4	22.4	48.3	63.3	165.8	209.0
	Mean	15.9	18.2	50.5	54.9	165.2	209.1
Incorporation	Control	15.7	17.1	44.8	63.7	160.7	216.7
	Fertilizer	18.9	19.7	56.2	78.7	182.8	225.0
	FYM	22.6	24.9	47.5	85.5	169.9	218.3
	Mean	19.1	20.6	49.5	76.0	171.1	220.0
Retention	Control	16.3	18.7	43.3	62.5	159.3	213.3
	Fertilizer	20.7	21.4	54.6	68.8	170.3	233.3
	FYM	25.8	27.2	46.7	75.9	168.7	216.7
	Mean	20.9	22.4	48.2	69.1	166.1	221.1
LSD ($P = 0.05$)	RMO	0.7	1.2	1.0	6.4	NS	NS
	SNI	0.7	0.7	1.6	5.2	NS	NS
	RMO × SNI	NS	NS	NS	NS	NS	NS

Notes. P_i, inorganic P; P_o, organic P; Res-P, residual P; and LSD, least significant difference ($P \leq 0.05$).

[a]Organic P (P_o) fractions in $NaHCO_3$ and NaOH extracts were calculated as the difference between P_i and total P in the respective extracts.

residue incorporation and retention significantly enhanced the $NaHCO_3$-P_i (by 3.2 and 5.0 mg kg^{-1}, respectively) and $NaHCO_3$-P_o (by 2.4 and 4.2 mg kg^{-1}, respectively) as compared to residue burning. The $NaHCO_3$-Pi and $NaHCO_3$-P_o are considered to correspond to the sorbed P forms and to the easily mineralizable P_o fractions (Chauhan, Stewart, and Paul 1981). The SNI, either as FYM or as fertilizer, increased both $NaHCO_3$-P_i and $NaHCO_3$-P_o fractions, with the increases being larger in FYM-treated plots. This result confirmed the findings of Gangnan and Simard (2003), who reported an increase in labile P fractions with the application of poultry litter, vegetable residues, and sheep manure. In another study, Vertisols under organic system had greater labile P ($NaHCO_3$-P_i and $NaHCO_3$-P_o) than the conventional rice fields, suggesting that organic systems sequestered P in these fractions (Linquist, Rurak, and Hill 2011). Labile forms of P, however, vary widely in dependence of experimental time. Seasonal climatic pattern and duration of experiment play a vital role in determining the labile fractions of P (Zamuner, Picone, and Diez 2012; Zhao et al. 2009). However, as the duration increases, fertilizer P may become less available, while soil-test P concentrations in manured soils remain unchanged. In some P-fixing soils, P from manure was more available than fertilizer P as the duration of incubation increased from 1 month to 9 months. It is postulated that the decomposition of manure resulted in concentrations of organic acids that effectively reduced P sorption to the soil and increased P availability (Laboski and Lamb 2003).

The contents of NaOH-extractable P_i (NaOH-P_i) and P_o (NaOH-P_o) fractions ranged from 43.3 mg kg^{-1} to 57.4 mg kg^{-1} and from 44.6 mg kg^{-1} to 85.5 mg kg^{-1}, respectively (Table 1). The NaOH-P_i and NaOH-P_o fractions represent moderately labile P forms, that is, those held by chemisorption to iron (Fe) and aluminum (Al) components and associated with humic substances (O'Halloran, Stewart, and Kachanoski 1987). The mean NaOH-P_i content was greater in the residue burning plots than in residue incorporation and retention plots. This finding lends credence to the earlier report that burning of natural regrowth increased NaOH-P_i fractions when compared with mulching and incorporation (Kolawole, Eniola, and Tian 2004). It has been reported in that under positive P balances $NaHCO_3$-P_i would ultimately be converted to NaOH-P_i under long-term cropping with only inorganic P applications (Zhang and McKenzie 1997; Zhao et al. 2009). An increase in NaOH-P_i in fertilizer treatments over the control is obtained in the present experiment also under all RMO options. However, unlike NaOH-P_i, the NaOH-P_o fraction was significantly greater with residue incorporation and retention than with residue burning. On average, residue incorporation and retention had 38 and 26% more NaOH-P_o, respectively, than residue burning. Irrespective of RMOs, the nutrient input as fertilizer or FYM significantly increased NaOH-P_i and NaOH-P_o fractions over the control (no nutrient input). The fertilizer addition maintained greater values of NaOH-P_i, whereas the FYM application resulted in larger values of NaOH-P_o under all RMOs. Among all P fractions, the NaOH-P_o showed the largest increases due to residue incorporation or retention and nutrient input. This increase in soil NaOH-P_o could be the result of biological immobilization of soil P_i. Some of the soil P_i removed by wheat crops was probably converted to P_o in decomposed wheat crop residues in residue retention and incorporation treatments. Further, stimulated microbial activity in response to application of organic materials and incorporation of P into microbial biomass and its associated pool of metabolites (Khan and Joergensen 2009) might have resulted in buildup of P_o fraction in soil. Shafqat and Pierzynski (2010) also reported an increase in the moderately labile (NaOH-P_o) fraction of P by return of crop residue to soil surface. According to Schoenau, Stewart, and Bettany (1989), NaOH-P_o is associated with humic compounds and adsorbed to Al and Fe. Therefore, as the soil organic matter is increased with the application of residues and FYM, the capacity of the soil to retain P in the form of NaOH-P_o may also be increased.

Wheat RMO and SNI treatments did not affect less labile (HCl-P) and nonlabile recalcitrant P (residual-P) fractions (Table 1). The HCl-P fraction represents inorganic and organic P that is associated with primary and secondary calcium (Ca) minerals in soil. The residual P is a highly stable part of the total P pool in soil, which may be available to plants in the long-term only. Compared with labile and moderately labile forms, the HCl-P and residual-P (relatively nonlabile forms) contents were high and ranged from 160.4 mg kg^{-1} to 182.8 mg kg^{-1} and from 201.7 mg kg^{-1} to 233.3 mg kg^{-1}, respectively. These stable fractions are generally known to remain unaffected by application of organic inputs and fertilizers (Damodar Reddy, Subba Rao, and Takkar 1999a).

Phosphorus Adsorption

The P adsorption isotherms showing the relationship between P adsorbed (q) and equilibrium solution P concentration (Ce) for the soils under different residue management options and supplementary nutrient input sources are given in Figure 2. The P adsorption isotherms revealed that wheat residue retention or incorporation decreased P adsorption over the residue burning for all the three nutrient inputs. Consequently, greater values of equilibrium solution P concentrations were recorded for the soils under residue retention or

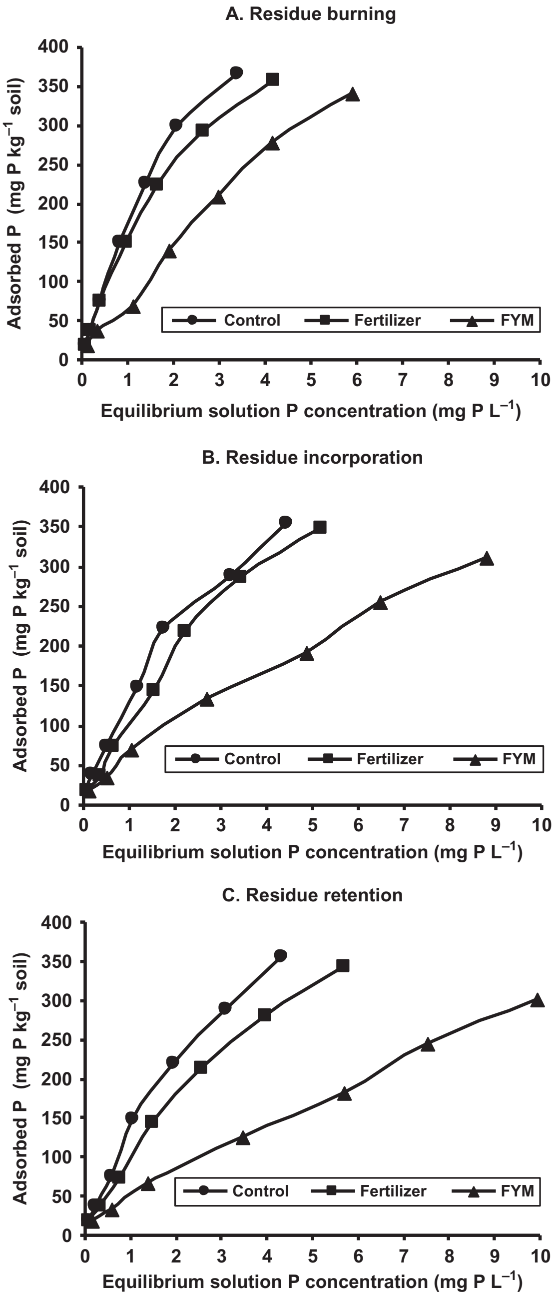

Figure 2. Phosphorus sorption isotherms as influenced by nutrient input sources under different residue management options. (A) Residue burning, (B) residue incorporation, and (C) residue retention.

incorporation than for those under residue burning. The nutrient input, particularly FYM, caused a lowering of P adsorption isotherms (inclining toward the X axis) as compared to the control (no nutrient input) in all the residue management options (Figure 2), indicating a marked decrease in P adsorbed and an increase in equilibrium solution P concentration. Minimum P adsorption occurred for the soil that received FYM in wheat residue retention plots followed closely by residue-incorporated plots. The decrease in P adsorption of the soil as a result of crop residues and/or FYM application could be attributed to competition between the phosphate ions and organic anions/acids produced from decomposition of organic materials for the same adsorption sites in soil (Iyamuremye and Dick 1996). Decomposition products from organic inputs also have been reported to form complexes with metal ions [Ca^{2+}, magnesium (Mg^{2+}), and Al^{3+} and Fe^{3+} that act as phosphate scavengers] and block the sorption sites in soils, thereby reducing P adsorption (Agbenin and Igbokwe 2006)

Phosphorus Adsorption Parameters and Maximum P Buffering Capacity

The P adsorption data of the soils under different wheat residue management options and nutrient input sources fitted well to the classical Langmuir equation, with highly significant R^2 values ranging from 0.970 to 0.994 (Table 2). The Langmuir P adsorption maxima (b) and bonding energy constant (k) derived from the Langmuir isotherms of P adsorption by soil varied widely among the wheat residue management options and nutrient input sources (Table 2). Residue retention and incorporation either alone or in combination with supplementary nutrient input decreased both b and k values as compared to residue burning. The greatest values of b (556.5 mg^{-1}) and k (0.57 mg^{-1}) were found for control plot soils under wheat residue burning, whereas the lowest b (401.45 mg^{-1}) and k (0.28 mg^{-1}) values were in the FYM-applied plots under wheat residue–retained plots. As b and k represent respectively P adsorption capacity and resistance to P release, the wheat residue and/or FYM-induced decreases in b and k values indicate a favorable effect on P availability in

Table 2
Phosphorus adsorption parameters of the soil as affected by wheat residue management options (RMO) and supplementary nutrient inputs (SNI)

Treatments		P adsorption parameters				
RMO	SNI	R^2	b (mg kg^{-1})	k (L mg^{-1})	MPBC (L kg^{-1})	SPR (mg kg^{-1})
Burning	Control	0.981**	556.5	0.57	317.0	56.9
	Fertilizer	0.989**	545.0	0.42	226.7	41.9
	FYM	0.993**	463.4	0.34	158.3	29.6
Incorporation	Control	0.971**	526.9	0.45	235.3	43.2
	Fertilizer	0.977**	499.5	0.38	187.7	34.9
	FYM	0.993**	404.5	0.30	122.1	23.0
Retention	Control	0.989**	501.2	0.43	215.2	39.6
	Fertilizer	0.970**	464.5	0.37	173.9	32.4
	FYM	0.994**	401.5	0.28	110.4	20.9

**Significant at 0.01 probability.

Notes. b, P adsorption maxima; k, bonding energy constant of P adsorption; MPBC, maximum P buffer capacity; and SPR, standard P requirement of soil (amount of adsorbed at a solution P concentration of 0.2 mg L^{-1}).

soil as evident from the increased labile and moderately labile P fractions under residue incorporation or retention. These results conform to the findings of Gupta et al. (2007), who reported an increase in P availability in soil after 4 years of rice straw incorporation.

The maximum P buffer capacity (MPBC) of soil under wheat residue retention or incorporation was strikingly less than that under residue burning (Table 2). The soil from the control plot under residue burning, which had greater adsorption maxima (b) and bonding energy (k) values, also showed the greatest MPBC value (317.0 L kg^{-1}), whereas FYM plus wheat residue retention treatment resulted in the lowest MPBC (110.4 L kg^{-1}). It may be noted here that the soils with lower MPBC would need smaller P application rates than the soils with greater MPBC for maintaining a desired P concentration in soil solution (Damodar Reddy, Subba Rao, and Singh 2001). Input of organic C through crop residues and FYM to the soils results in greater microbial populations and more P assimilation into the microbial cells. Upon microbial turnover, a significant proportion of this organic P released becomes part of the labile organic P ($NaHCO_3$-Po) fraction in the soils (Wang et al. 2006). In addition to microbes, the availability of nutrients in soils also depends on cultivated crops (Schiemenz and Löbermann 2010). The implication of this result is that the residue incorporation or retention coupled with FYM addition can cut down the P requirement of soybean–wheat system for maintaining adequate P supply in this soil.

Standard Phosphorus Requirement (SPR)

Amount of P adsorbed at 0.2 mg L^{-1} equilibrium solution P concentration is generally accepted as standard P requirement (SPR) of a soil for optimum crop yield. Fox and Kamprath (1970) reported that yield obtained at 0.2 mg P L^{-1} solution concentration was optimum in a wide range of soils. In the present study, the SPR of soil showed wide variation depending upon the wheat residue management practice and supplemental nutrient input (Table 2). On average, the SPR of soil under different residue management options followed the order residue burning > residue incorporation > residue retention. Among nutrient input sources, the SPR values followed the order control > fertilizer > FYM. The SPR was greatest (56.9 mg kg^{-1}) for the control plot of residue burning treatment and reduced by 2.7 times to 20.9 mg kg^{-1} estimated for the soil that received the FYM under wheat residue retention. The wheat residue and FYM induced reduction in SPR of soil also indicate that the added organic material had improved P availability in soil as evident from the increases in labile P ($NaHCO_3$-P_i and $NaHCO_3$-P_o) and moderately labile organic P (NaOH-P_o) fractions for the plots receiving FYM under residue incorporation or retention (Table 1).

Correlation of P Fractions with P Adsorption Parameters and P Uptake

Correlation coefficients for the relationship of different P fractions with P adsorption parameters and P uptake by soybean crop (5th year and 5-year mean) are presented in Table 3. The $NaHCO_3$-P_i, $NaHCO_3$-P_0, and NaOH-P_o fractions had highly significant negative correlation with P adsorption parameters (b, k, MPBC, and SPR) while showing highly significant positive correlation with P uptake by soybean crop. The relationship of P uptake with soil P test parameters, however, is dependent on experimental time of soil sampling. There may be a decrease in the readily available soil P directly after crop harvest. However, in long-time P experiments, crop cultivation can result in high levels of bioavailable P in the soil (Eichler-Löbermann et al. 2008). The other P fractions, particularly

Table 3
Correlation coefficients (r) for the relationships of soil P fractions with P adsorption parameters and P uptake by soybean crop

	P adsorption parameters				P uptake by soybean	
Soil P fractions	b	k	MPBC	SPR	5th year	5-yr mean
$NaHCO_3$-P_i	−0.962**	−0.950**	−0.966**	−0.970**	0.888**	0.847**
$NaHCO_3$-P_o	−0.984**	−0.929**	−0.950**	−0.957**	0.870**	0.834**
NaOH-P_i	0.138^{ns}	-0.156^{ns}	-0.092^{ns}	-0.079^{ns}	0.356^{ns}	0.398^{ns}
NaOH-P_o	−0.802**	−0.848**	−0.860**	−0.859**	0.807**	0.793*
HCl-P	-0.279^{ns}	-0.478^{ns}	-0.445^{ns}	-0.438^{ns}	0.666^{ns}	0.701*
Residual-P	-0.325^{ns}	-0.479^{ns}	-0.471^{ns}	-0.459^{ns}	0.449^{ns}	0.448^{ns}

**Significant at 0.01 probability.
*Significant at 0.05 probability.
Notes. ns, not significant; b, P adsorption maxima; k, bonding energy constant of P adsorption; MPBC, maximum P buffer capacity; and SPR, standard P requirement of soil.

NaOH-P_i, and residual P, were not significantly correlated with P adsorption parameters and soybean P uptake.

Conclusions

The results of this study demonstrate that the incorporation or surface retention of wheat residue on long-term basis has the potential to improve soil P fertility by increasing labile ($NaHCO_3$-P_i and P_o) and moderately labile (NaOH-P_o) P fractions and reducing P adsorption capacity of soil in comparison to residue burning. Beneficial effect of residue incorporation/retention on soil P fertility was further enhanced with the supplementary nutrient input, especially as farmyard manure. It is concluded that the continuous incorporation or surface retention of wheat residue along with FYM as supplementary nutrient input was an effective strategy alternative to the current practice of residue burning for improving soil fertility and P use efficiency under a soybean–wheat system.

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