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The effect of C:P ratio of plant residues added to soils of contrasting phosphate sorption capacities on P uptake by *Panicum maximum* (Jacq.)

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Abstract

Reutilization of P from *Setaria sphacelata* residues having C:P ratios of 704:1, 227:1, and 77:1 was studied using a reverse ^{32}P-isotopic dilution technique in the greenhouse. Residues were incorporated into two highly weathered Malaysian soils (Ultisols and Oxisols) treated with five levels of inorganic P labeled with ^{32}P and cropped with *Panicum maximum* (Jacq.). Yield of dry matter, total P, and ^{32}P activity of Panicum was monitored through four cuttings spanning a period of approximately 13 weeks. Panicum yields and residue-P uptake were depressed by high and medium C:P ratio residues at the first cutting but recovered in subsequent cuttings. General adequacy of P concentrations in the affected tissue and its failure to respond to applied inorganic P among other factors suggest that the initial yield depression was not induced by P immobilization. The fractional percentage of P derived from residues increased with increasing P content of residues at all cuttings. Similarly, L-values were consistently greater on residue-treated soils. Residue P had greater effects on the soil with lower than on that with higher P-sorbing capacity. Changes in residue P uptake, L-values, and extractable P in soil between successive cuttings suggest a rapid release of a large amount of easily mineralizable residue P within the first 4 weeks, with the subsequent P release being much slower by comparison.

Introduction

Residues constitute a major fraction of a crop's total dry matter production and their management has important consequences for both soil conservation and the maintenance of soil physical characteristics. Crop residues also contain a significant proportion of the nutrients taken up by the crop and, when returned to the soil, contribute to the maintenance of soil fertility. Several studies have shown that such materials can be an important supply of phosphorus (P) to subsequent crops (Blair and Boland, 1978; Dalal, 1979; Friesen and Blair, 1988; Fuller et al., 1956; Till and Blair, 1978). The rate and extent of reutilization of P from crop residues can be influenced by a number of factors including the amount and type of residues, their carbon:P (C:P) ratio and the prevailing soil and climatic conditions (Dalal, 1977).

Soils of the tropics are diverse in both their chemical and physical properties. The phosphate sorption capacity is among the most frequently cited properties of 'tropical soils' and may range from the unremarkable to the extraordinary in soils containing substantial amounts of sesquioxidic or allophanic clay minerals. P released from plant residues added to soil has been found to be rapidly adsorbed onto clay surfaces (Friesen and Blair, 1988; White and Ayoub, 1983). Moreover, it has also been demonstrated (Hue, 1991; Singh and Jones, 1976) that the addition of organic residues to soil can influence its P sorption characteristics. The availability of released P to plants could, therefore, be influenced by the P sorption capacity of soil as well as the effect of the residues themselves on P sorption.

The object of this study was to examine the effects of C:P ratio and soil P sorption capacity on the recovery by plants of P from plant residues applied in combination with different levels of applied inorganic P (P_i) to two contrasting tropical soils. In addition, their effects on parameters of soil P availability during and after cropping were also examined.

Materials and methods

Soils

Two Malaysian soils with contrasting P-sorption capacities were used: Rengam series, a Typic Paleudult (sandy clay loam, isohyperthermic) derived from granite rock and having a low P-sorption capacity according to the method of Juo and Fox (1977), and Kuantan series, a Tropeptic Haplorthox (clayey, kaolinitic, isohyperthermic) derived from basalt and dolerite rocks and having a high P-sorption capacity. Soils were collected from sites that had received no previous fertilizer application. The top 0- to 40-cm layer was collected for the Rengam series while, for the Kuantan series, which had a high organic matter content, the 15- to 40-cm layer was collected so as to minimize the effect of native organic P mineralization. The soils were air-dried, ground, and sieved to <5 mm. Soil physical and chemical characteristics (Table 1) were determined according to procedures described in Page et al. (1982). Additionally, available organic P was calculated as the increase in inorganic P in $NaHCO_3$ extracts following H_2SO_4-H_2O_2 digestion of the evaporated extract (Bowman and Cole, 1978). Phosphorus adsorption isotherms were determined by the method of Fox and Kamprath (1970) and the standard P requirement was calculated as the amount of P sorbed by soil to attain an equilibrium solution P concentration of 0.2 mg kg^{-1} (Juo and Fox, 1977).

Plant residues

Setaria (*Setaria sphacelata*) pasture cuttings of three different P contents (high, medium, and low C:P ratios) were used as residues. The residues were produced on field plots that had received 150, 300, and 2,000 kg ha^{-1} of P as triple superphosphate and were harvested after 7 weeks of regrowth after cutting. The harvested material was oven-dried at 60–65 °C and ground to pass through a 1-mm sieve. Chemical analyses of the Setaria residues are summarized in Table 2. Total N and P contents were determined in subsamples following H_2SO_4-H_2O_2 digestion. Carbon content was determined by the Walkley-Black method (Allison, 1965). Acid-soluble inorganic P was determined by shaking 1.00 g of ground samples (less than 0.5 mm) with 50 mL of 0.2 *N* H_2SO_4 for 2 hours, filtering, and measuring inorganic P in the filtrate (Jones and Bromfield, 1982). Acid-soluble organic P was calculated as the increase in inorganic P following H_2SO_4-H_2O_2 digestion of the filtrate.

P mineralization studies

The release (mineralization) of Setaria residue P and its availability for crop uptake was examined in a greenhouse experiment using *Panicum maxi-*

Table 1. Some physical and chemical properties of the Malaysian soils used in the experiment

Soil series	Particle size (%)		pH (H_2O)	Organic Carbon (%)	Total nitrogen (%)	Exchangeable cations (meq kg^{-1})				Total P (mg kg^{-1})	Total organic P (mg kg^{-1})	$NaHCO_3$-extractable P (mg kg^{-1})		Standard P requirements (mg kg^{-1})
	Sand	Clay				K	Ca	Mg	Al			Inorganic	Organic	
Rengam	69.5	20.6	5.6	1.6	0.14	0.7	1.9	1.5	3.5	118	48	1.5	8.6	105
Kuantan	13.6	69.9	4.7	3.5	0.28	0.8	0.8	0.7	5.9	3,295	501	31.4	24.7	665

Table 2. Chemical analyses of the Setaria residues applied to the soils

C:P ratio of plant residue	Total P (%)	Organic carbon (%)	Total N (%)	C:P ratio	C:N ratio	Acid-soluble P[a] Inorganic (%)	Organic (%)
High	0.072	50.7	1.40	704	36.2	71	6
Medium	0.212	48.2	1.06	227	45.5	40	12
Low	0.576	44.4	1.86	77	23.9	20	12

[a] Expressed as percent of total P.

mum (Jacq.) as a test crop. The experiment comprised a complete factorial of five levels of inorganic P, four plant residue P treatments (including a control), and two soil types in a completely randomized block design with four replications of each treatment. It was hypothesized that P uptake in regular sequential cuttings of Panicum would reflect changes in the availability of residue P due to continuing mineralization and its ability to substitute for applied inorganic P. The latter was labeled with ^{32}P to enable a distinction between the two P sources.

Three-kilogram portions of soil were mixed with lime at rates equivalent to 1.5 times the exchangeable Al content of each soil (0.44 g and 0.26 g $CaCO_3$ kg^{-1} soil for Kuantan and Rengam series, respectively) and incubated at approximately field moisture capacity for 2 weeks in PVC pots and then allowed to dry somewhat. Setaria residues were added to the limed soils at the rate of 100 g dry matter per pot and mixed thoroughly. The amounts of P added were 24, 71, and 192 mg kg^{-1} soil from the high, medium, and low C:P ratio residues, respectively.

Inorganic P rates were based on estimates of the standard P requirements of the two soils from adsorption isotherms (Fox and Kamprath, 1970) and a preliminary P rate experiment. An external P requirement of 0.2 mg kg^{-1} was assumed for Panicum and rates were chosen such that the highest provided optimal P requirements. These were applied immediately after residue incorporation as ^{32}P-labeled KH_2PO_4 at rates equivalent to 0, 18.75, 37.5, 75.0, and 150.0 mg P kg^{-1} Rengam soil and 0, 62.5, 125.0, 250.0, and 500.0 mg P kg^{-1} Kuantan soil in 60 mL of solution per pot together with basal nutrients and mixed thoroughly into the soil. Each pot received 4.03 MBq ^{32}P-phosphate. The ^{32}P in the inorganic P control pots was added in a solution containing 100 mg P mL^{-1} so as to prevent sorption of ^{32}P onto the walls of glassware used. This supplied a negligible amount of P (2 mg kg^{-1} soil) to the soil. The basal nutrients included 50 mg N kg^{-1} soil as $(NH_4)_2SO_4$, 50 mg K kg^{-1} soil as KCl, and 10 mg Zn kg^{-1} soil as $ZnSO_4 \cdot 7H_2O$.

Soils were watered to near field moisture capacity and allowed to equilibrate for 1 day. One-month-old Panicum seedlings grown in a sand medium moistened to approximately field moisture capacity with Hoagland's solution (without P) were then transplanted at the rate of six seedlings per pot and were subsequently thinned to four seedlings per pot 1 week later. Plants were grown under ambient light and temperature conditions in a screenhouse. Neither fluctuate significantly at Serdang, Malaysia (3° N latitude, 102° E longitude). Pots were maintained at approximately field moisture capacity by watering once, twice, or thrice daily as required. The amount of water added was based on the weight loss of randomly selected pots. Two sidedressings, one of 50 mg N kg^{-1} soil as $(NH_4)_2SO_4$ and the second of 20 mg Mg kg^{-1} soil as $MgSO_4$ $7H_2O$ were applied in 60-mL solution at 18 and 26 days, respectively, after transplanting. At 29 days after transplanting, the Panicum tops were clipped at 7.5 cm above soil level, oven-dried at 60–65 °C and weighed to determine the dry-matter yield. The plants were allowed to regrow and were cut again after 21 days. This was continued for a total of four successive cuttings spanning a period of approximately 13 weeks. Following each cutting, except the last, 100 mg N kg^{-1} soil as $(NH_4)_2SO_4$, 100 mg K kg^{-1} soil as KCl, and 20 mg Mg kg^{-1}

soil as $MgSO_4\ 7H_2O$ were applied in 60-mL solution per pot.

Dried Panicum cuttings were ground to <1.0 mm and 250–500 mg subsamples digested with H_2SO_4-H_2O_2. Digests were analyzed for total P and for activity of ^{32}P by Cerenkov radiation in a liquid scintillation spectrometer. Radioactivity counts were corrected for background, for decay to the day of application of ^{32}P to soil, and for color quenching.

Calculations

The fraction of P in Panicum cuttings derived from ^{32}P-labeled inorganic P fertilizer (PdfF) was calculated according to Larsen (1952) as:

$$\mathrm{PdfF} = \frac{S_P^{-\mathrm{res}}}{S_F} \quad \text{or} \quad \frac{S_P^{+\mathrm{res}}}{S_F} \qquad (1)$$

where $S_P^{-\mathrm{res}}$ or $S_P^{+\mathrm{res}}$ are the specific ^{32}P activities of plants grown without and with residues, respectively, and S_F is the specific ^{32}P activity of the applied inorganic P.

Plant P derived from residues alone was calculated using isotopic dilution concepts described by Kucey and Bole (1984) and Thibaud et al. (1988). Thus,

$$\mathrm{PdfR} = 1 - \frac{S_P^{+\mathrm{res}}}{S_P^{-\mathrm{res}}} \qquad (2)$$

and

$$\mathrm{QdfR} = \mathrm{PdfR} \times Q_P^{+\mathrm{res}} \qquad (3)$$

where PdfR is the fraction of plant P derived from residues, and QdfR and $Q_P^{+\mathrm{res}}$ are the amounts of plant P derived from residues and the total plant P in plants grown with residues, respectively.

The labile pool of phosphate in the soil (L-value; Larsen, 1952) was calculated according to the equation:

$$\text{L-value} = \left(\frac{S_F}{S_P} - 1\right) \times F \qquad (4)$$

where F is the amount of inorganic phosphorus applied.

Results

Dry-matter yields of Panicum *cuttings*

Panicum responded to rates of inorganic P on both soils in the absence of incorporated Setaria residues, although the magnitude of the response diminished with successive cuttings (data not shown). Application of residues with high and medium C:P ratios depressed dry-matter yields at cutting 1 on both soils at all inorganic P rates although more severely on Rengam soil. With low C:P ratio residues, plants achieved maximal growth rates without the application of inorganic P. In subsequent cuttings, all plant residues either increased yields above the residue controls or had no significant effect.

Total P in Panicum *cuttings*

Depressed yields in the high and medium C:P ratio residue treatments with the first cutting also resulted in depressed levels of P uptake in those treatments, particularly in the Rengam soil (Fig. 1a). The effect was not significant in the Kuantan soil where yields were less depressed by these treatments (data not shown). However, in cuttings 2, 3, and 4, P uptake from the residue-treated soils was consistently equal to or higher than that from the untreated soils (Figs. 1b, 1c, and 1d). The effect was generally an upward displacement of the P uptake response curve; only in the third cutting from Rengam soil was a significant inorganic P × plant residue interaction observed.

Apart from cutting 1, total P uptake generally increased with increasing P concentration (decreasing C:P ratio) of the residue (Fig. 1). With the low C:P ratio residue, enhanced P uptake over and above the residue controls was greatest at the first cutting then generally decreased in successive cuttings; for the medium and high C:P ratio residues, P uptake in excess of the minus-residue treatments was greatest at cutting 3.

The effect of *Setaria* residues on cumulative P uptake (total of four cuttings) was significantly greater on the Rengam than the Kuantan series soil (Fig. 2). However, the effect was only significant for the lowest C:P ratio material. Up-

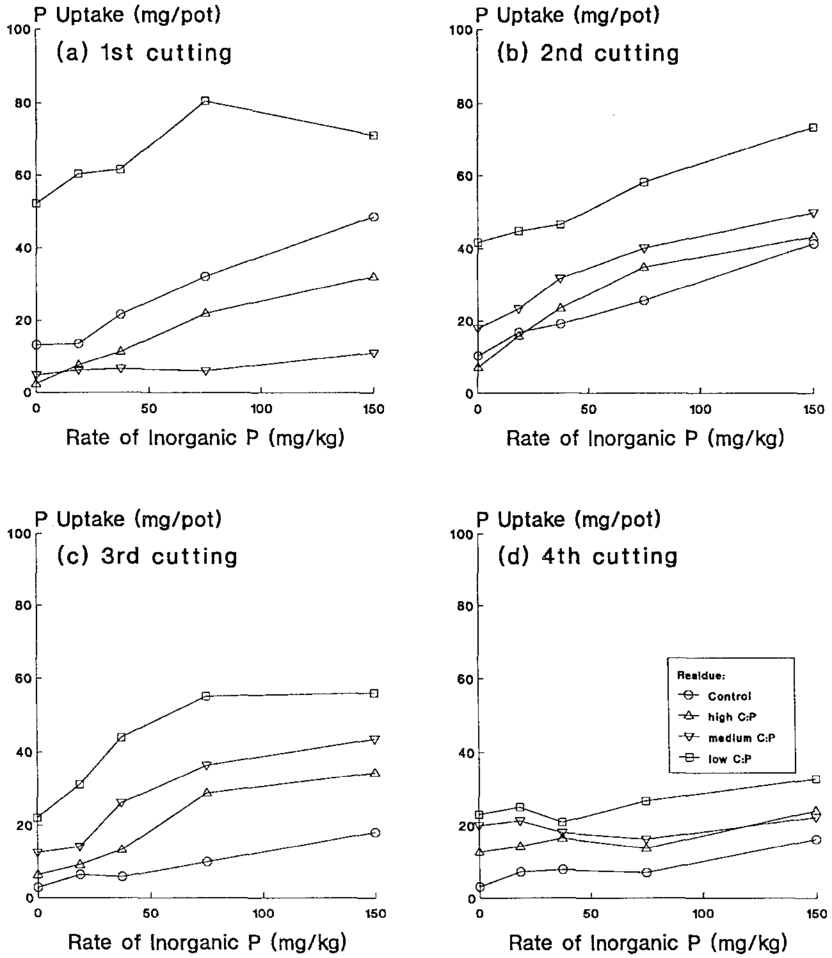

Fig. 1. Effect of inorganic P rate and Setaria residues as total P uptake by Panicum on Rengam soil during four cuttings.

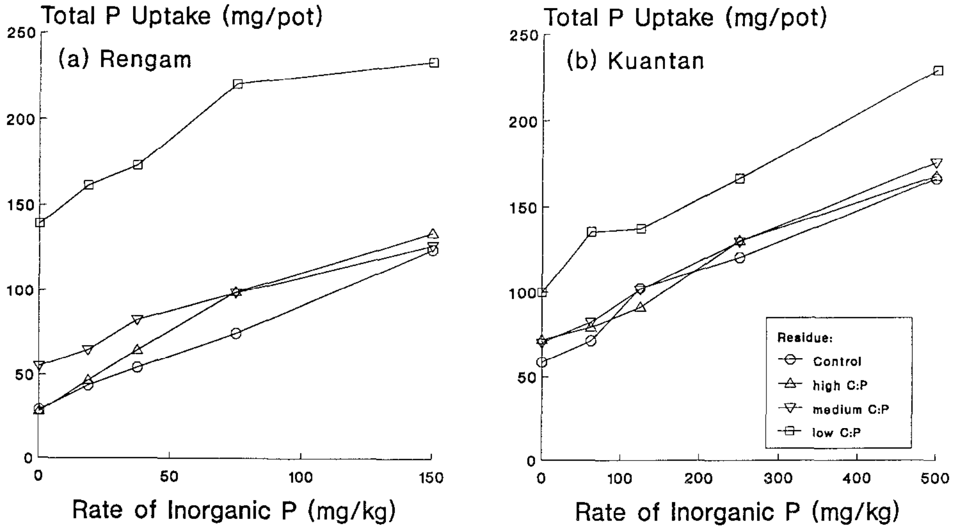

Fig. 2. Cumulative P uptake (four cuttings) as affected by Setaria residue C:P ratio and rate of applied inorganic P.

take of P from medium and high C:P ratio residues was marginally greater than the control from Rengam soil but without effect on the Kuantan soil.

Although the fraction of P in Panicum derived from residues (PdfR) decreased with increasing rates of inorganic P (data not shown), the quantity of P derived from residues (QdfR) was generally only weakly affected, declining slightly as P rates increased (Fig. 3). The effect was the same regardless of the C:P ratio of the residues. However, greater amounts of P were derived from the low C:P ratio material (high P concentration) while lesser amounts were derived from those with medium and low C:P ratios (Fig. 3, average of four cuttings). Averaged over P rates, QdfR declined at each successive cutting, especially for the low C:P ratio material (Fig. 4). The quantity of residue P in Panicum tops at any particular cutting was greater on Rengam soil than Kuantan soil by at least a factor of two. On the other hand, the *fraction* of P derived from residues (PdfR) was relatively constant between successive cuttings (Fig. 5, mean of P rates).

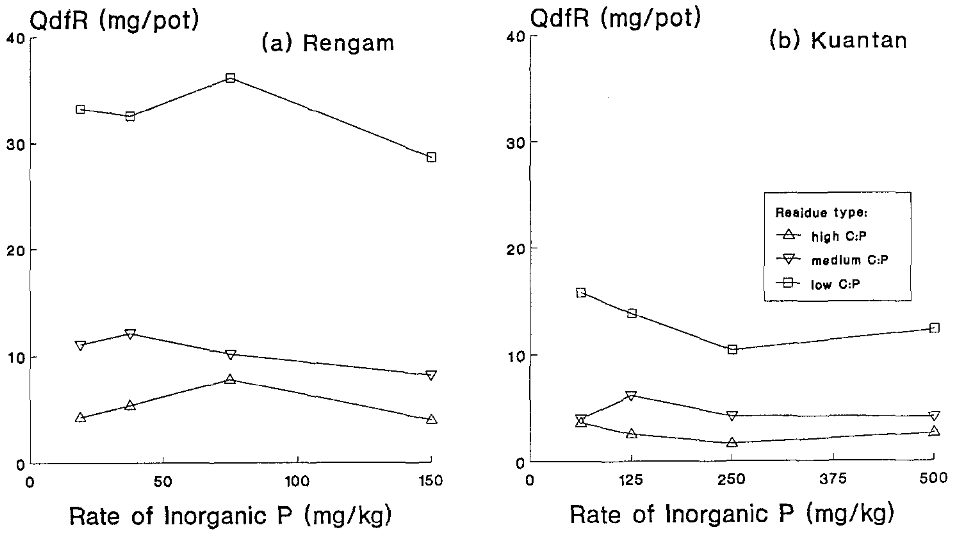

Fig. 3. Quantity of P derived from residues as influenced by inorganic P rates on two soils (average of four cuttings).

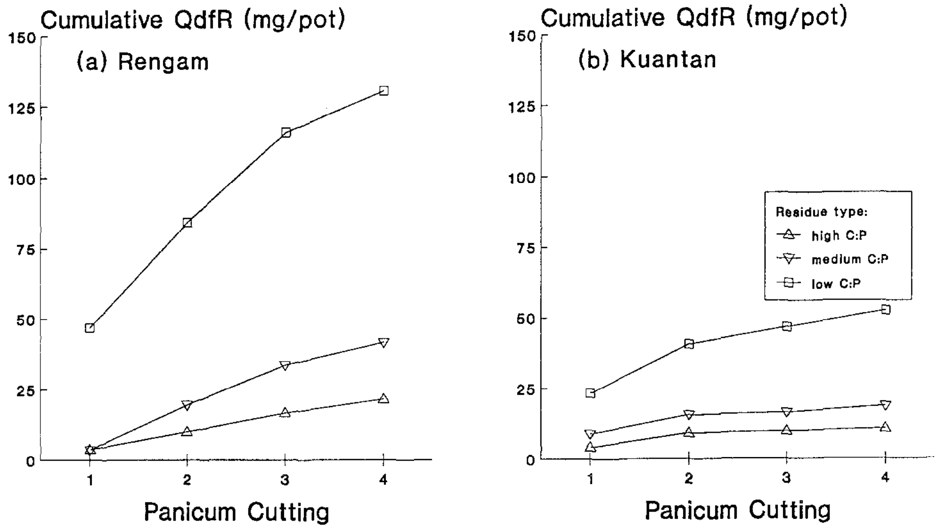

Fig. 4. Main effect of time (expressed as cutting number) on the quantity of P derived from Setaria residues on two soils.

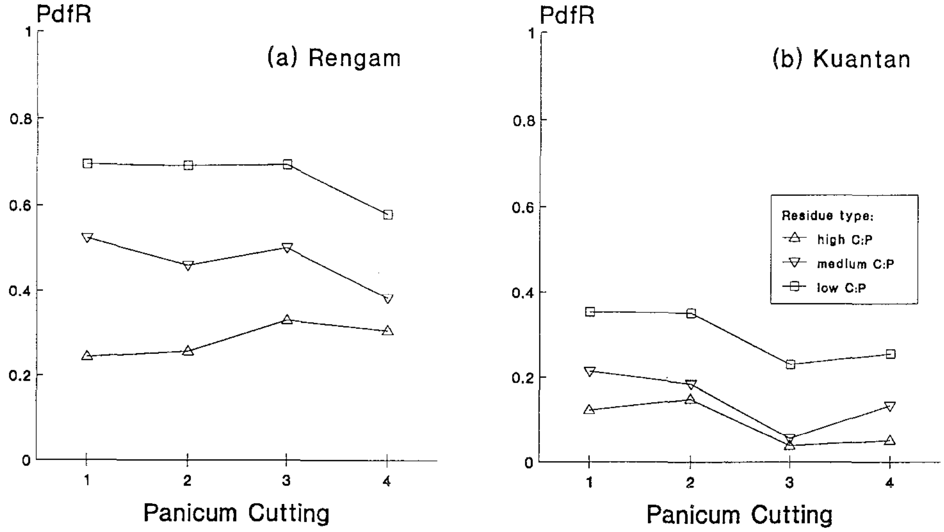

Fig. 5. Main effect of time (expressed as cutting number) on the fraction of P derived from Setaria residues on two soils.

Similarly, the fraction of P derived from fertilizer or soil also remained constant. As with the QdfR, the PdfR was approximately twice as great for the Rengam soil than the Kuantan soil, and the differences between different residues were also proportionately greater.

Available P

Bicarbonate extractable inorganic P (P_i) levels at the conclusion of the experiment (Table 3) were higher in the soils with incorporated residues than in those without and increased in the order: no residues ≤high C:P residues ≤medium C:P residues <low C:P residues. The increase in extractable P_i was comparable in the two soil series. In contrast, there was no significant effect of plant residues on the $NaHCO_3$-extractable organic P at the end of the experiment.

The effect of C:P ratio of residues and cropping on the L-value is shown in Table 4. L-values are averaged across all inorganic P rates since the residue treatment × P rate interaction was nonsignificant at all cuttings. Consistently higher L-values were observed in the residue treated soils compared with the controls. Moreover, the increase in L-values was higher with higher P content (lower C:P ratio) of the residues incorporated and the increase tended to be greater on the Rengam soil than on the Kuantan soil. Although the effect of inorganic P rates on L-values was significant at all cuttings, the effects were marginal and showed no consistent trend (data not shown).

Table 3. $NaHCO_3$-extractable inorganic P (P_i) and organic P (P_0) in soils at the conclusion of the experiment[a]

C:P ratio of residues	$NaHCO_3$-extractable P (mg kg^{-1})			
	Rengam Series		Kuantan Series	
	P_i	P_0	P_i	P_0
Control	4.60	9.96	44.08	33.52
High C:P	5.70	11.73	47.23	31.27
Medium C:P	10.29	11.80	52.15	29.20
Low C:P	24.29	13.08	64.23	30.01
$LSD_{0.05}$	6.61	4.94	6.61	4.94

[a] In the 0 mg kg^{-1} added inorganic P treatments only.

Table 4. Effect of residue C:P ratio and cropping on L-values

C:P ratio of residue	L-values[a] (mg P g^{-1} soil)			
	Cutting 1	Cutting 2	Cutting 3	Cutting 4
Rengam Series				
Control	0.014	0.024	0.029	0.046
High	0.038	0.050	0.066	0.079
Medium	0.091	0.100	0.110	0.115
Low	0.203	0.218	0.233	0.200
$LSD_{0.05}$	0.029			
Kuantan Series				
Control	0.274	0.288	0.281	0.363
High	0.319	0.360	0.296	0.414
Medium	0.389	0.412	0.314	0.466
Low	0.520	0.546	0.422	0.579
$LSD_{0.05}$	0.039			

[a] Data averaged over all rates of added inorganic P.

Discussion

The overall effect of residue incorporation during the experiment was increased yields and total P uptake by Panicum from the Setaria residue-treated soils, irrespective of the C:P ratio of the residue. Although the depressed yields and consequentially diminished P uptake in some residue treatments at the first cutting suggests that P was immobilized during the early phase of the experiment, several observations suggest that this did not occur. First, yields of Panicum were depressed more on soils treated with the intermediate than with the high C:P ratio residue with which immobilization, and hence induced P deficiency, would be expected to be greater. Second, tissue P concentrations in the affected treatments were all well above critical sufficiency levels, suggesting that a nutrient other than P was limiting Panicum growth. Third, (in support of the preceding hypothesis) increasing rates of applied inorganic P did nothing to overcome the depressing effects of residue treatments.

Although total P uptake at the first cutting was depressed in the intermediate and high C:P ratio residue treatments, the observation that the fractional percentage and total quantity of P derived from residues (PdfR and QdfR, respectively) actually increased with decreasing C:P ratio (Table 5) is also consistent with mineralization of organic P from all materials in proportion to the quantities of easily mineralizable (acid soluble) P in them (Table 6). Since P uptake by plants from any source is dependent on factors that affect growth rate, PdfR probably reflects more accurately than QdfR the effect of

Table 5. Influence of residue C:P ratio on the fraction (PdfR) and quantity (QdfR) of P derived from residues in the first Panicum cutting[a]

C:P ratio of residue	Rengam soil		Kuantan soil	
	PdfR	QdfR (mg pot^{-1})	PdfR	QdfR (mg pot^{-1})
High	0.24	3.8	0.12	4.3
Medium	0.52	3.7	0.21	9.0
Low	0.70	46.8	0.35	23.5
$LSD_{0.05}$	0.08	4.5	0.06	4.2

[a] Main effect averaged over inorganic P rates.

Table 6. P added in residues to soils and percent recovery by Panicum

C:P ratio of residue	Amount of P added (mg P kg^{-1} soil)			Cumulative P recovery in Panicum[a] (% added)	
	Acid soluble		Total P	Kuantan soil	Rengam soil
	Inorganic	Organic			
High (704:1)	17	1	24	20	29
Medium (227:1)	28	8	71	9	20
Low (77:1)	38	23	192	9	23

[a] Main effect averaged over inorganic P rates.

residue P content (C:P ratio), soil P sorption capacity, and inorganic P rates on the availability of residue P to plants.

For any particular residue, PdfRs were generally at their highest at the first cutting then remained invariant or declined slightly (depending on the soil) in subsequent cuttings (Fig. 5). These trends indicate a rapid initial influx of P, probably from inorganic or easily mineralized pools (such as phosphate esters) in the residues. These pools, extractable in dilute acid, constituted 32 to 77% of the total P content of the residues (Table 2). Similar observations were reported by Friesen and Blair (1988) who used ^{32}P-labeled oat residues to trace release rates. They also observed apparently much slower rates of residue P release (presumably from more recalcitrant forms) after the initial influx, as evidenced by relatively constant PdfRs during the course of the experiment. Declining PdfRs at the later cuttings indicate declining rates of residue P mineralization.

The increase in L-values in all residue-treated soils over the untreated control soils at all cuttings, including the first (Table 4), also indicates a release of residue P into the labile P pool in all cases. However, the increased L-values may alternatively be due to an effect of residue additions on the availability of native soil P. Bhat and Bouyer (1968) and Diatta and Fardeau (1979), who also observed increases in isotopically dilutable P following organic amendments to soil, hypothesized that the added organic matter may reduce P fixation and increase P mobility in soil. Organic acids are known to compete with phosphate for sorption sites on soil mineral surfaces (Gaur, 1969; Hue, 1991) and inorganic P desorbed from clay surfaces by soluble organic acids released from plant residues would dilute the ^{32}P applied to the soil with the inorganic P amendments in the same way as organic P mineralized from those residues. The large increases in L-values in relation to the amount of easily mineralizable P added in the residues (Table 6) suggests that such secondary effects were at least partly responsible for the increases in dilutable ^{32}P observed. Nevertheless, if one assumes (not unreasonably) that similar amounts of soluble organic acids were released from all three residues, then the progressive increases in L-values observed between the high medium, and low C:P ratio materials (Table 4) can only be attributed to P mineralized from the latter two materials. Mineralization therefore occurred at a medium C:P ratio (227:1, Table 2) somewhat greater than the critical level (200:1) above which residues are usually expected to cause immobilization (Dalal, 1977). Since, based on the depressed yield data at cutting 1, this medium C:P ratio material was the most probable candidate for immobilization, it is very likely mineralization also occurred from the high C:P ratio residue – as the L-value data indicate.

The very substantial effects of residues on L-values in both soils (Table 4), and on P uptake and yield response of Panicum (Figure 1) at the first cutting, indicate that significant releases of P from the residues occurred within 4 weeks of application. The general progressive increases in L-values in subsequent harvests suggest continuing (slow) release of residue P into the available P pool, although similar increases in the L-values of the residue-control treatments indicate mineralization of P from the native organic-P pool as well (Table 4).

Increasing levels of $NaHCO_3$-extractable inorganic P at the conclusion of the experiment (Table 3) also reflects increasing amounts of P released from residues with decreasing C:P ratios (increasing P concentrations). Similar amounts were recovered from this pool from both soils after cropping although cumulatively greater amounts were recovered in Panicum cuttings on Rengam soil (Fig. 4). Bicarbonate-extractable organic P was not significantly altered by residue treatment by the conclusion of cropping. Presumably, any initial effect was transitory in nature.

The effect of residues of all C:P ratios on total P uptake by Panicum and on the fractional percentage of P derived from residues (PdfR) was consistently greater on the lower sorptive capacity Rengam soil than on the more highly sorbing Kuantan soil. Cumulative recovery of residue P by Panicum over four cuttings was two to three times greater on the Rengam than on the Kuantan soil except for the high C:P residue (Table 6). Fertilizer P recovery was, on average, of a similar magnitude. Thus, diffusion of P released from Setaria residues to plant roots was evidently inhibited to a greater extent on the more highly buffered Kuantan soil. It has also been documented (Greaves and Webley, 1969; Smith, 1979) that sorption onto soil colloids of organic P released in the initial stages of decomposition may also inhibit its mineralization. However, the trend to greater increases in L-values due to residue incorporation on the more highly sorbing Kuantan soil (Table 4) does not support this possibility in the present study.

The combined results of, on one hand, an apparent absence of immobilization of inorganic P despite the addition of high C:P ratio organic residues to soil and, on the other hand, an apparent correspondence between P released from these residues and their acid-soluble P contents (inorganic P and phosphate esters), is consistent with the conceptual model of biochemical mineralization proposed by McGill and Cole (1981). Since phosphate esters are substrates for extra-cellular enzymes which catalyze phosphate release, the C:P ratio of the residue plays no role in this catalysis. In this sense the C:P ratio of residues is a very misleading criterion for predicting immobilization since inorganic and organically bound phosphate pools constitute different proportions of the total P content of residues. A more reliable indicator may be the ratio of C to some measure of C-bonded P.

Finally, although the rate of addition of residues to soil in this greenhouse study was substantially greater than would be realistically possible under field conditions, the relative recovery (by plants) was similar to that found in other studies (Blair and Bolland, 1968; Friesen and Blair, 1988) and demonstrates the important influence recycled P can have on crop nutrition. Furthermore, the competition for mineralized P between soil mineral surfaces and plant roots clearly favors adsorption processes although the results of this study suggest, and other reports have shown, that adsorption can be modified by organic acids also released from residues.

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