

## TECHNICAL ARTICLES

# PHOSPHORUS SORPTION AND DESORPTION IN SEMIARID SOILS OF SENEGAL AMENDED WITH NATIVE SHRUB RESIDUES

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Incorporation of organic residues into soils can improve P availability to crops in P-fixing soils. Perennial shrubs are commonly found in farmers' fields in Senegal, but little is known about their potential to reduce P sorption. Consequently, the residues of the two dominant shrub species, *Guiera senegalensis* and *Piliostigma reticulatum* were amended to soils where each is found, the Dior (Rubric Arenosol) and the Deck/Dior (Mixed Haplic Ferric Lixisol), respectively, and compared with beef manure for P sorption characteristics. Amended soils (2% weight/weight) were incubated at 24 °C for 30 or 75 days. Phosphorus isotherms were constructed using the batch technique, and sorption parameters were derived by fitting the Langmuir and Freundlich equations. All organic amendments decreased P adsorption maxima and affinity constants and increased P in the equilibrium solution (equilibrium P concentration) compared with the control. The amount of P desorbed from soils was greater in amended soils than in unamended soils. Soils beneath shrub canopy had lower P sorption capacity than soils outside shrub canopy in *P. reticulatum*-associated soils, which was reversed in *G. senegalensis*-associated soils. All organic amendments significantly increased soil pH. The longer incubation period of 75 days, over the 30 days, enhanced the effect of organic amendments in reducing soil P sorption and decreased soil pH. Manure amendments induced the greatest reduction in soil sorption capacity and showed the highest desorption rate. These results indicate that the addition of locally available plant residues to soil at a high rate can reduce P sorption and should be included in nutrient management recommendations of deficient P-fixing Sahelian soils. (Soil Science 2008;173:669-682)

**Key words:** Organic residues, phosphorus, sorption, desorption, *G. senegalensis*, *P. reticulatum*.

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A common characteristic of highly weathered soils of the tropics is their ability to fix inorganic P (Pi). The colloidal component of these soils is dominated by hydrous oxides of Al and Fe onto which P is specifically adsorbed by ligand exchange (Parfitt, 1978). These geochemical processes are believed to control the solubility, and thus, the availability of soil P to plants (Sparks, 2003; Guppy et al., 2005). Effective P management in these soils requires a better understanding of their P sorption and desorption characteristics. Adsorption isotherms have been extensively used to characterize

Pi behavior in soils (Barrow, 1978). Parameters derived from such isotherms can be used as a guideline to predict P requirements of crops and P fertilizer management in soils (Fox and Kamprath, 1970; Sposito, 1982; Nwoke et al., 2003).

Addition of organic matter (OM) to soils has been reported to either increase or decrease P sorption by soils. However, the mechanism of OM interaction with P in soils is not fully understood (Haynes and Mokolobate, 2001; Guppy et al., 2005). Decreased P sorption after addition and mineralization of organic residue in soils (Singh and Jones, 1976; Bumaya and Naylor, 1988; Iyamuremye and Dick, 1996) has commonly been attributed to resulting organic acids and humic compounds that complex surface-bound Al and Fe oxides and/or P for sorption sites (Hue, 1991; Iyamuremye and Dick, 1996; Ohno and Crannell, 1996; Ohno and Erich, 1997; Haynes and Mokolobate, 2001). Other workers, however, found a positive correlation between soil OM and P sorption by soils (Brennan et al., 1994; Quang et al., 1996). Potential mechanisms that have been proposed are reactions of humic materials with the P-reactive compounds of Al and Fe and formation of new sorption sites (Lopez-Hernandez and Burnham, 1974), inhibition of crystallization of Al and Fe oxides by OM (Huang and Violante, 1986; Borggaard et al., 1990) or P immobilization in low-P residues (Singh and Jones, 1976).

Soils of Senegal are predominantly sandy and coated with Fe and/or Al oxides and hydroxides that are known to sorb Pi (Iyamuremye et al., 2000). The common, unmanaged, and largely unrecognized form of agroforestry is the presence of two dominant native shrubs, *Guiera senegalensis* J. F. Gmel. (Combretaceae) and *Piliostigma reticulatum* (DC.) Hochst (Leguminosae-Caesalpinioideae) in agroecosystems throughout the Sahel. Here, crops coexist with shrubs that are coppiced and burned at the beginning of each cropping season. These shrubs offer two important avenues for improving P availability

to associated crops. One is that they provide the largest source of OM in these systems (Lufafa et al., 2008), which if incorporated into soils could modify anion sorption capacity of soils (Iyamuremye and Dick, 1996). Second, the canopy and rhizosphere of woody species in semiarid ecosystems are associated with increased OM, nutrient content, and microbial activity (West, 1991; Van Miegroet et al., 2000) that could affect the geochemistry of P. However, there is virtually no information available on the potential impacts of shrub residue amendments relative to P dynamics in the Sahel.

Therefore, the objectives of this study were to determine the impact of shrub canopy and shrub residue amendments on P sorption characteristics of two major soils of Senegal, and how incubation period influences these processes.

MATERIALS AND METHODS

Soil and Shrub Residue Sampling

Soils were collected from two sites. The first site (Keur Mata Arame) is located in the northern region of the Peanut Basin in Senegal (14°45 N, 16°51 W, and 43 m above sea level). The soil is 95% sand, mainly constituted of materials from aeolian deposits, classified as Rubic Arenosol (FAO, 2006), locally referred to as a Dior soil (Badiane et al., 2000). *Guiera senegalensis* is the dominant shrub vegetation. The second site (Nioro du Rip) is located (13°45 N, 15°47 W) at 18 m above sea level. The soil is a Deck-Dior (Badiane et al., 2000) loamy-sand (fine-sandy, Mixed Haplic Ferric Lixisol [FAO, 2006]), a leached ferruginous tropical soil. The dominant shrub species at the site is *P. reticulatum*. Selected characteristics of these soils are given in Table 1.

Within each study site in farmers' fields, four shrubs with canopy diameter of approximately 2 m, which represents the average size of shrubs in farmers' fields (Lufafa et al., 2008), were randomly selected for soil and shrub biomass sampling. Each shrub was treated as a replicate. This spatial replication was maintained

TABLE 1  
Selected soil characteristics at the sites of study

Site	pH (H <sub>2</sub> O)	Organic C	Total N	Total P	Fe <sub>ox</sub>	Al <sub>ox</sub>
		-----%-----			g kg <sup>-1</sup> -----	
Nioro	6.1	0.45	0.021	0.084	7.23	3.07
KeurMata	5.3	0.29	0.019	0.093	6.64	2.05

for subsequent laboratory incubations. In January 2003, during the dry season, soil was collected from a 0- to 30-cm depth beneath (approximately 1 m radius from the shrub center) and outside the influence of shrub canopy (2- to 3-m distance from around the edge of canopy) using a coring device (10 cores of 2.5-cm diameter per sample). Root and litter fragments were removed followed by homogenization, air-drying, and sieving through a 2-mm screen before chemical analyses and laboratory incubation. Aboveground biomass of the four shrubs (four replicates) for each species was harvested and sorted into leaves and stems (branch diameter, <1 cm) and air-dried. A 500-g composite sample of each biomass component was ground to 0.25 mm and kept in sealed plastic bags and subsequently used in the soil amendment treatments.

#### Laboratory Analyses

Soil pH was determined with a glass electrode in 1:2.5 soil-water ratio. Total soil and plant C was determined by combustion on a LECO WR-12 C autoanalyzer (LECO Corp, St Joseph, MO). Total N in soils and organic residues was determined by Kjeldahl digestion. Total P in plant residue and soils was determined by a modified  $\text{Li}_2\text{SO}_4\text{-H}_2\text{SO}_4$  Kjeldahl procedure (Parkinson and Allen, 1975). Ammonium oxalate-extractable Fe ( $\text{Fe}_{\text{ox}}$ ) and Al ( $\text{Al}_{\text{ox}}$ ) were determined according to McKeague and Day (1966) on soil fractions less than 0.5 mm. Aluminum and Fe in extracts were determined on an inductively coupled argon plasma analyzer.

#### Experimental Design and Soil Incubation

Two separate experiments were done for each shrub, its associated soil as a split plot design with soil location treatments (beneath or outside shrub canopy) as main plot factors and residue amendments (leaf, leaf + stem, beef manure, or control of soil only) as the subplot factors. The relative mass of leaves and stems in the leaf + stem mixture was 40% and 60%, respectively. The manure was locally provided by the dairy farm at Oregon State University in Corvallis. There were four replications maintained from the field replication soil sampling of the four shrubs. Each shrub species was incubated with its associated soil, that is, *G. senegalensis* residues with soils from Site 1 and *P. reticulatum* residues with soils from Site 2. Leaf of *G. senegalensis* had 1.6% N and 0.1% P, whereas these concentrations in the stem mixture were

1.1% N and 0.04% P. In the *P. reticulatum* materials, N and P contents were, respectively, 1.8% and 0.1% in leaf and 0.8% and 0.045% in stem. Manure used in the amendment treatments had 1.8% N and 0.34% P contents.

Two sets of 30 g of soil mixed with 0.6 g of organic amendments were incubated at 24 °C for 30 or 75 days. Soil moisture was kept at approximately two-thirds field capacity by weighing the samples every week. At the end of the incubation, the soils were air-dried and kept at approximately 5 °C in the dark until they were analyzed.

#### Phosphorus Sorption

Two grams of each soil incubation treatment were placed in a 50-mL centrifuge tube and suspended in a 20-mL solution of 0.01 M  $\text{CaCl}_2$  containing 0, 0.2, 0.5, 1, 2.5, 5, 7.5, and 10  $\text{mg L}^{-1}$  of P. Two drops of chloroform were added to the samples to inhibit microbial growth. The samples were equilibrated in an end-over-end shaker at room temperature for 24 h and then centrifuged at 27,000g for 5 min, producing a clear supernatant. The supernatant was decanted and then analyzed for P using the colorimetric molybdenum-blue method (Murphy and Riley, 1962). Sorbed P was calculated using the difference between P in the initial solution and P in the equilibrium solution and mass of soil. Sorption isotherms were constructed by plotting sorbed P ( $\text{mg kg}^{-1}$  of P soil) against P in the equilibrium solution.

#### Phosphorus Desorption

Phosphorus desorption values were obtained by equilibrating 2 g of soil with 20 mL of a solution containing 10  $\text{mg L}^{-1}$  of P in a constant ionic strength background of 0.01 M  $\text{CaCl}_2$ . The pH of this initial equilibrium solution was immediately measured before P determination. The amount of P sorbed after a 24-h equilibration represented the initially adsorbed P. The P-saturated soils were subject to six sequential desorptions with 18.5 mL of 0.01 M  $\text{CaCl}_2$  equilibrated as in the sorption experiment, centrifuged and analyzed for soluble P. In calculating desorbed P, allowance was made for the 1.5-mL solution carried over from the previous desorption run (Fox and Kamprath, 1970; Sanyal et al., 1993). The differences between initially adsorbed P and P recovered in solution after desorption were considered as P retained on the soil in a relatively stable form.

### Model Fitting and Statistical Analysis

The sorption data were fitted to the following models using PROC NLIN (SAS Institute, 1999):

1) Langmuir equation

$$q = kbc / (1 + kc) \quad (1)$$

where  $q$  = sorbed P ( $\text{mg kg}^{-1}$  of P),  $b$  = adsorption maxima ( $\text{mg kg}^{-1}$  of P),  $k$  = parameter related to binding energy ( $\text{L mg}^{-1}$ ),  $c$  = P concentration in the equilibrium solution ( $\text{mg L}^{-1}$ )

2) Freundlich equation

$$q = KC^n \quad (2)$$

or modified Freundlich equation

$$q = KC^n + Q \quad (3)$$

where  $K$  and  $n$  are constants. The parameter  $n$  is hypothetically related to the distribution of sites with a given sorption energy.  $K$  is considered as an index of P sorbed in a solution having a final unit P concentration, which could be used to compare P sorption capacity of different soils (Sanyal et al., 1993).  $Q$  is the soil native exchangeable P (Barrow, 1978).

Soil parameters were analyzed using SAS PROC MIXED (SAS Institute, 1999). Tukey multiple comparison adjustment was used to determine pairwise differences among treatment. The coefficient of determination ( $R^2$ ) in the nonlinear regression was estimated as:

$$R^2 = 1 - (SS_{\text{residual}} / SS_{\text{total corrected}}) \quad (4)$$

Fitted sorption parameters were analyzed as a two-way nonlinear analysis of covariance

(Hinds and Milliken, 1987). In case of significant F test, models were compared for fitted parameters by computing a confidence interval about the difference of pairs of models (Hinds and Milliken, 1987).

## RESULTS AND DISCUSSION

### Equilibrium Solution pH

All organic amendments significantly increased equilibrium solution pH ( $P < 0.05$ ) relative to the control (Table 2). The increase was greater in soil outside shrub canopy than in soil beneath the canopy. In soils incubated for 30 days, leaf and leaf + stem-amended soils had comparable effects on soil pH, resulting in pH increase of 0.40 and 0.92 units, respectively, beneath and outside the shrub canopy in the *P. reticulatum*-associated soils. Manure produced the greatest soil pH increase of 1.05 units beneath the shrub canopy and 1.47 units outside the canopy. In the *G. senegalensis*-associated soils, compared with the *P. reticulatum* soils, the magnitude of pH increase was smaller in shrub residue-amended soils but greater when soil was amended with manure. The same pattern of pH increase after organic amendment addition was noticed for soils incubated for 75 days. However, pH values in all treatments were significantly lower than their counterparts in the 30-day incubation.

The increase of pH in early stages of incubation after addition of organic residues has been attributed to ligand exchange reactions of organic acids from decomposing OM with Al and Fe OH that produce  $\text{OH}^-$  (Hoyt and

TABLE 2  
Effect of organic amendments on equilibrium solution pH in soils beneath and outside shrub canopy for 30- and 75-day incubation

Treatments	30-Day incubation		75-Day incubation	
	Beneath	Outside	Beneath	Outside
<i>Keur Mata (G. senegalensis)</i>				
Control	4.22 <sup>a</sup>	4.17 <sup>a</sup>	4.02 <sup>a</sup>	4.09 <sup>a</sup>
Leaf	4.27 <sup>a</sup>	4.35 <sup>a</sup>	4.26 <sup>b</sup>	4.29 <sup>b</sup>
Leaf + stem	4.38 <sup>a</sup>	4.88 <sup>b</sup>	4.27 <sup>b</sup>	4.44 <sup>c</sup>
Manure	5.96 <sup>b</sup>	6.05 <sup>c</sup>	5.75 <sup>c</sup>	5.84 <sup>d</sup>
<i>Nioro (P. reticulatum)</i>				
Control	5.26 <sup>a</sup>	4.63 <sup>a</sup>	5.14 <sup>a</sup>	4.45 <sup>a</sup>
Leaf	5.64 <sup>b</sup>	5.48 <sup>b</sup>	5.28 <sup>b</sup>	5.22 <sup>b</sup>
Leaf + stem	5.68 <sup>b</sup>	5.62 <sup>b</sup>	5.45 <sup>c</sup>	5.22 <sup>b</sup>
Manure	6.31 <sup>c</sup>	6.10 <sup>c</sup>	6.08 <sup>d</sup>	5.97 <sup>c</sup>

For each shrub and associated soil, values with same superscript letter within each column are not significantly different at  $P < 0.05$ .

Turner, 1975; Hue, 1992; Iyamuremye and Dick, 1996) or to proton-consuming decarboxylation reactions of organic-acid anions (Haynes and Mokolobate, 2001). However, such an effect is transient because pH can drop in the later stage of incubation because of the dynamics of organic components involved in the Al/Fe complexation reactions (Hoyt and Turner, 1975) and/or conversion of organic N to nitrate (Haynes and Mokolobate, 2001).

#### Phosphorus Sorption

Sorption isotherms after 30 days of incubation are shown in Fig. 1 for *P. reticulatum*- and *G. senegalensis*-associated soils. Soils amended with the different organic residues varied widely in their ability to sorb added Pi. The highest P sorption was observed with unamended soils, whereas manure-amended soils had the lowest.

At the highest concentration of added P ( $10 \text{ mg L}^{-1}$  of P), sorbed P was lower in all treatments beneath canopy of *P. reticulatum* compared with their counterparts outside the canopy (Figs. 1A, B). In *G. senegalensis*-associated soils, P sorption patterns were similar in soils beneath and outside shrub canopy (Figs. 1C, D). Leaf-amended soils sorbed less P than leaf + stem-amended soils except in soils outside the canopy of *P. reticulatum* (Fig. 1B). An extended incubation period of 75 days generally resulted in less P sorption by soils, particularly in the organic residue-amended soils (Fig. 2). The shape of the isotherms was basically the same for all treatments, depicting an L-type characteristic (Sparks, 2003).

Overestimation of inorganic P and, hence, underestimation of P sorption by soils with the ascorbic method could have occurred after

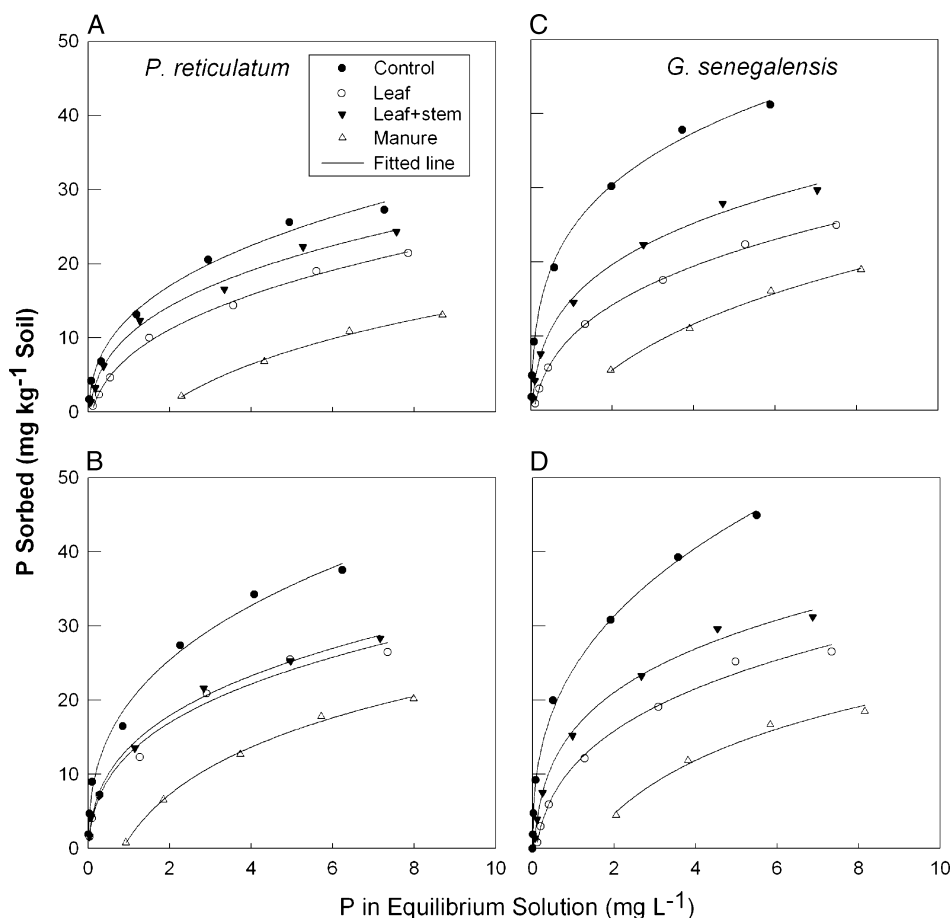


Fig. 1. P adsorption isotherms after a 30-day incubation of soils amended with *P. reticulatum* residues beneath (A) and outside shrub canopy (B) and soils amended with *G. senegalensis* residues beneath (C) and outside shrub canopy (D). Adsorption isotherms were fitted with equations  $q = Q + KC^n$  for manure and  $q = Q + KC^n$  for all other treatments.

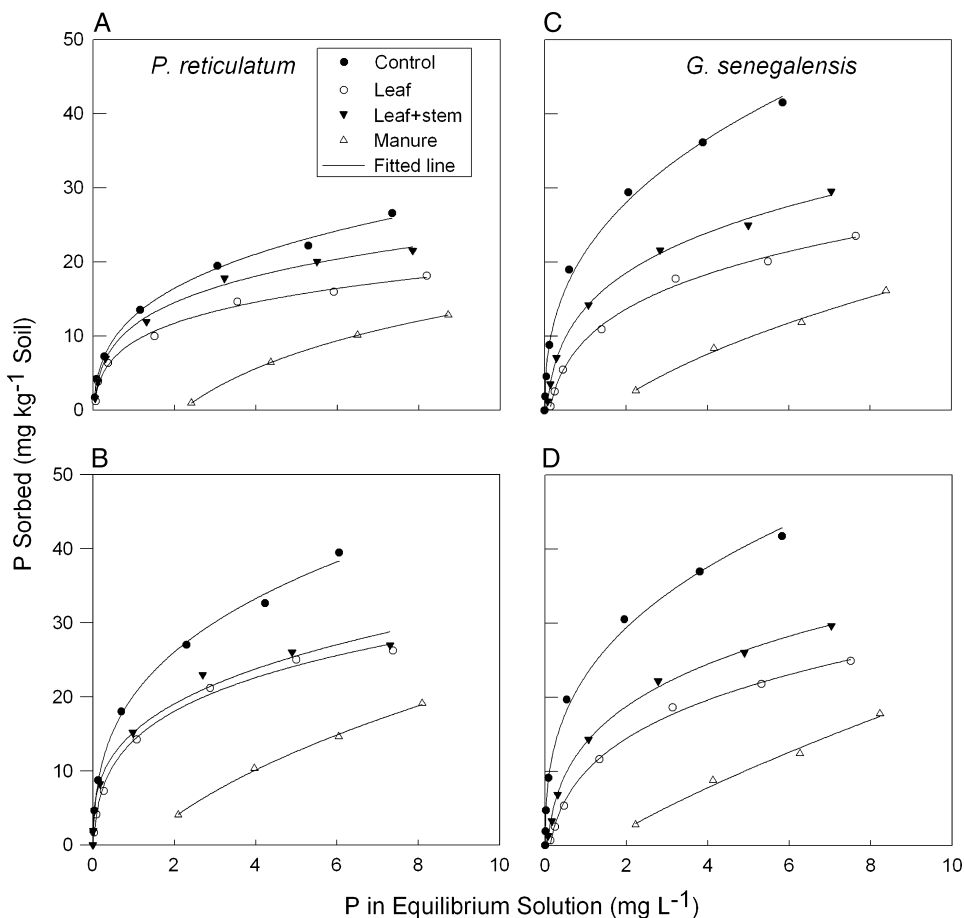


Fig. 2. P adsorption isotherms after a 75-day incubation of soils amended with *P. reticulatum* residues beneath (A) and outside shrub canopy (B) and soils amended with *G. senegalensis* residues beneath (C) and outside shrub canopy (D). Adsorption isotherms were fitted with equations  $q = Q + KC^n$  for manure and  $q = KC^n$  for all other treatments.

reaction of strong acid with labile organic P pool of the soil. However, this is not likely to be of major significance in these Sahelian soils, where the Murphy Riley is widely used in determination of  $P_i$  in routine soil analysis (M. Khouma, ISRA (Institut Senegalais de Recherches Agronomiques), Laboratoire National de Recherches sur les Productions Vegetales, Dakar, Senegal, personal communication, 2005).

Reduction of P sorption by organic amendments observed in the present study is consistent with results of previous research (Singh and Jones, 1976; Bumaya and Naylor, 1988; Iyamuremye et al., 1996). Major mechanisms of P sorption decrease by organic amendments include: (i) Al/Fe complex formation with organic acids and release of previously sorbed P (Iyamuremye and Dick, 1996); (ii) competitive inhibition of organic acids with P for sorption sites (Ohno and Crannell,

1996); and (iii) release of P from decomposing OM (Singh and Jones, 1976; Guppy et al., 2005).

Our results provided evidence that the P released from organic amendments reduced P sorption, as illustrated by the negative correlation between P sorption parameters and P leached from amended soils (see section below). These results, to some extent, support the contention of Guppy et al. (2005), who ascribed the decrease of P sorption by organic amendments mainly to P release from organic residues during decomposition. In our study, this P effect would likely be related to the water-soluble P of organic materials that is leachable from freshly amended soils (E. L. Dossa, M. Khouma, I. Diedhiou, M. Sene, F. Kizito, A.N. Badiane, S. A. N. Samba, and R. P. Dick, unpublished data) because P content less than 0.2% and C/P ratio greater than 340 of shrub residues in this



study would not be expected to cause net P mineralization (Singh and Jones, 1976; Sharpley and Smith, 1989; Stevenson and Cole, 1999).

Another possible mechanism for the effect of organic amendments to decrease in P sorption could be the blocking of sorption sites by organic acids and/or other decomposition products. This is supported by our observation that reduced P sorption paralleled a decrease in soil pH over the 75-day incubation. Indeed, the ability of organic acids to inhibit P sorption has been reported to increase with decreasing pH (Haynes and Mokolobate, 2001). The reduction of P sorption could also be attributed to the rise in pH after addition of organic residues to soils. Complexation of Al/Fe with inorganic ligands such as  $F^-$  and  $SO_4^{2-}$  has been reported (Iyamuremye and Dick, 1996). Such a reaction should not be ruled out in the case of manure-amended soils, which showed the lowest P sorption in our experiment.

#### Phosphorus-Fitting Parameters

In general, the Langmuir and Freundlich models fit the data well ( $R^2 > 0.97$ ). However, P

sorption of manure-amended soils was not well described by the Langmuir equation, whereas the Freundlich model provided a better fit for this amendment (Table 3).

Several reports have mentioned the adequacy of describing adsorption processes in soil with the Freundlich over a limited range of P concentrations (Barrow, 1978; Sanyal et al., 1993). Justification of such goodness of fit may be that, the Freundlich model, although being empirical, assumes that the binding affinity decreases as adsorption increases. Such an assumption is closer to reality and consistent with the adsorption process than that of constant binding energy, an underlying premise of the Langmuir model (Sparks, 2003). It is noteworthy that estimation of a third parameter ( $Q$ ) was necessary to fit the Freundlich model to manure-treated soil data. According to Barrow (1978), the Freundlich model gives a better fit when the soil labile P is included in the model. Indeed, all soil treatments compared in this experiment have very low native extractable P, except for manure-treated soils. This may explain why the simple Freundlich equation was well fitted for most of the data.

TABLE 3  
Sorption parameters estimated from the Langmuir and Freundlich equations for the different soil amendments

Treatment	Location	30-Day incubation						75-Day incubation					
		Langmuir			Freundlich			Langmuir			Freundlich		
		$k^\dagger$	$b^\ddagger$	$R^2$	$K^\S$	$n$	$R^2$	$k$	$b$	$R^2$	$K$	$n$	$R^2$
Nioro ( <i>P. reticulatum</i> )													
Control	Beneath	0.64 <sup>a</sup>	32.8 <sup>b</sup>	0.99	12.2 <sup>b</sup>	0.43 <sup>bcd</sup>	0.99	0.94 <sup>a</sup>	27.9 <sup>b</sup>	0.99	11.9 <sup>cd</sup>	0.40 <sup>b</sup>	0.99
	Outside	0.82 <sup>a</sup>	43.9 <sup>a</sup>	0.98	19.1 <sup>a</sup>	0.39 <sup>d</sup>	0.98	1.15 <sup>a</sup>	41.2 <sup>a</sup>	0.98	19.0 <sup>a</sup>	0.40 <sup>b</sup>	0.98
Leaf	Beneath	0.31 <sup>b</sup>	29.7 <sup>b</sup>	0.99	6.9 <sup>d</sup>	0.57 <sup>b</sup>	0.99	1.08 <sup>a</sup>	18.8 <sup>c</sup>	0.99	8.4 <sup>e</sup>	0.38 <sup>b</sup>	0.99
	Outside	0.64 <sup>a</sup>	32.2 <sup>b</sup>	0.99	12.0 <sup>b</sup>	0.43 <sup>bcd</sup>	0.99	1.02 <sup>a</sup>	29.3 <sup>b</sup>	0.99	12.9 <sup>c</sup>	0.39 <sup>b</sup>	0.99
Leaf + stem	Beneath	0.57 <sup>a</sup>	28.9 <sup>b</sup>	0.99	9.7 <sup>c</sup>	0.47 <sup>bcd</sup>	0.99	1.07 <sup>a</sup>	23.3 <sup>bc</sup>	0.99	10.4 <sup>d</sup>	0.38 <sup>b</sup>	0.99
	Outside	0.74 <sup>a</sup>	32.6 <sup>b</sup>	0.99	12.8 <sup>b</sup>	0.42 <sup>cd</sup>	0.99	1.64 <sup>a</sup>	28.6 <sup>b</sup>	0.99	15.1 <sup>b</sup>	0.33 <sup>b</sup>	0.99
Manure	Beneath	NF <sup>¶</sup>	NF	NF	1.3 <sup>f</sup>	1.08 <sup>a</sup>	0.99	NF	NF	NF	0.9 <sup>f</sup>	1.27 <sup>a</sup>	0.99
	Outside	NF	NF	NF	3.8 <sup>e</sup>	0.84 <sup>a</sup>	0.99	NF	NF	NF	2.4 <sup>f</sup>	1.01 <sup>a</sup>	0.99
Keur Mata ( <i>G. senegalensis</i> )													
Control	Beneath	1.48 <sup>a</sup>	44.1 <sup>ab</sup>	0.99	22.4 <sup>a</sup>	0.37 <sup>c</sup>	0.99	1.28 <sup>a</sup>	44.3 <sup>a</sup>	0.99	21.1 <sup>a</sup>	0.40 <sup>c</sup>	0.99
	Outside	1.45 <sup>a</sup>	47.2 <sup>a</sup>	0.98	23.9 <sup>a</sup>	0.38 <sup>c</sup>	0.99	1.69 <sup>a</sup>	43.2 <sup>a</sup>	0.99	22.6 <sup>a</sup>	0.36 <sup>c</sup>	0.99
Leaf	Beneath	0.41 <sup>b</sup>	32.6 <sup>b</sup>	0.99	9.0 <sup>c</sup>	0.53 <sup>b</sup>	0.99	0.41 <sup>b</sup>	30.5 <sup>b</sup>	0.99	8.3 <sup>c</sup>	0.53 <sup>b</sup>	0.99
	Outside	0.41 <sup>b</sup>	35.9 <sup>b</sup>	0.99	9.9 <sup>c</sup>	0.54 <sup>b</sup>	0.99	0.40 <sup>b</sup>	32.9 <sup>b</sup>	0.99	8.8 <sup>c</sup>	0.54 <sup>b</sup>	0.99
Leaf + stem	Beneath	0.80 <sup>ab</sup>	34.4 <sup>b</sup>	0.99	13.6 <sup>b</sup>	0.43 <sup>b</sup>	0.99	0.69 <sup>b</sup>	33.8 <sup>b</sup>	0.99	12.2 <sup>b</sup>	0.47 <sup>b</sup>	0.99
	Outside	0.77 <sup>ab</sup>	36.9 <sup>b</sup>	0.99	14.1 <sup>b</sup>	0.45 <sup>b</sup>	0.99	0.65 <sup>b</sup>	35.2 <sup>b</sup>	0.99	12.3 <sup>b</sup>	0.48 <sup>b</sup>	0.99
Manure	Beneath	NF	NF	NF	3.5 <sup>d</sup>	0.81 <sup>a</sup>	0.99	NF	NF	NF	1.5 <sup>d</sup>	1.13 <sup>a</sup>	0.99
	Outside	NF	NF	NF	3.6 <sup>d</sup>	0.80 <sup>a</sup>	0.99	NF	NF	NF	1.4 <sup>d</sup>	1.21 <sup>a</sup>	0.99

For each shrub and associated soil, values with the same superscript letter within each column are not significantly different at  $P < 0.05$ .

<sup>†</sup> $k$ : binding affinity expressed in  $L\ kg^{-1}$ .

<sup>‡</sup> $b$ : adsorption maximum expressed in  $mg\ kg^{-1}$ .

<sup>§</sup> $K$ : Freundlich constant expressed in  $mg\ kg^{-1}$ .

<sup>¶</sup>NF: not fitted.

Organic amendments decreased predicted sorption capacity of soils. The predicted sorption maxima were low and ranged from 29 to 44 mg kg<sup>-1</sup> of P in the *P. reticulatum*-associated soils incubated for 30 days (Table 3). For the same incubation period in *G. senegalensis*-associated soils, the sorption maxima ranged from 32 to 47 mg kg<sup>-1</sup> of P. Generally, predicted P maxima were higher outside the shrub canopy than beneath the canopy, and P sorption maxima were greater in *G. senegalensis*-associated soils than in the *P. reticulatum*-associated ones (Table 3). A longer incubation time of 75 days resulted in a slight decrease in adsorption maxima in most treatments. The P affinity constant values predicted by the Langmuir equation were lowest in organic residue-amended soils except in *P. reticulatum* residue-amended soils in the 75-day incubation. The Freundlich *K* constant varied widely and had the same treatment ranking as the Langmuir adsorption maxima (Table 3).

Correlation analysis revealed a significant negative relationship between pH and various adsorption parameters, the strongest correlation being that with the adsorption maxima ( $r = -0.71$ ,  $P < 0.01$ ; Table 4). Soil organic C and

initially P leached from amended soils also were negatively correlated with sorption parameters. Decreasing P sorption with increasing pH has been attributed to electrostatic repulsion caused by increased OH<sup>-</sup> activity on the soil colloid (Nwoke et al., 2003) and reduction of Al activity (Iyamuremye et al., 1996). At the same time, the effect of OM amendments has commonly been linked to complexation reactions of Fe and Al and competition with P for sorption sites by organic acids (Iyamuremye and Dick, 1996).

We found a negative correlation between Fe<sub>ox</sub> and the Langmuir adsorption maxima ( $r = -0.55$ ,  $P < 0.05$ ), which stands in contrast to the widely established observation that exchangeable Fe and Al species fix phosphate in highly weathered soils (Parfitt, 1978). However, when the data for the two shrub species and associated soils were analyzed separately, significant positive correlations were obtained between sorbed P and Al<sub>ox</sub> ( $r = 0.79$ ,  $P < 0.05$ ) for *G. senegalensis*-associated soils and ( $r = 0.92$ ,  $P < 0.01$ ) for *P. reticulatum*-associated soils.

Regression of P sorbed on Fe<sub>ox</sub> and Al<sub>ox</sub> indicated that 85% and 62% of the variance in P sorption maxima were explained by Al<sub>ox</sub> contents of *P. reticulatum*- and *G. senegalensis*-associated

TABLE 4  
Pearson correlation coefficients between sorption parameters and selected soil characteristics

	Adsorption maxima	Freundlich <i>K</i>	Affinity constant ( <i>k</i> )
All soils			
pH	-0.71**	-0.55*	-0.49
Fe <sub>ox</sub> <sup>†</sup>	-0.55*	-0.43	-0.32
Al <sub>ox</sub> <sup>†</sup>	-0.36	-0.25	-0.33
C	-0.77***	-0.80***	-0.71**
Init P <sup>‡</sup>	-0.70**	-0.64**	-0.55*
Keur Mata soils ( <i>G. senegalensis</i> )			
pH	-0.37	-0.33	-0.33
Fe <sub>ox</sub>	0.37	0.21	0.17
Al <sub>ox</sub>	0.79*	0.60	0.53
C	-0.96**	-0.96**	-0.95*
Init P	-0.90**	-0.96**	-0.98***
Nioro soils ( <i>P. reticulatum</i> )			
pH	-0.96**	-0.88*	-0.62
Fe <sub>ox</sub>	0.25	0.09	-0.16
Al <sub>ox</sub>	0.92**	0.83*	0.59
C	-0.74	-0.71	-0.53
Init P	-0.71	-0.80*	-0.77

<sup>†</sup>Oxalate-extracted Fe and Al.

<sup>‡</sup>Initial inorganic P leached from amended soils.

\*Significant at  $P < 0.05$ .

\*\*Significant at  $P < 0.01$ .

\*\*\*Significant at  $P < 0.001$ .



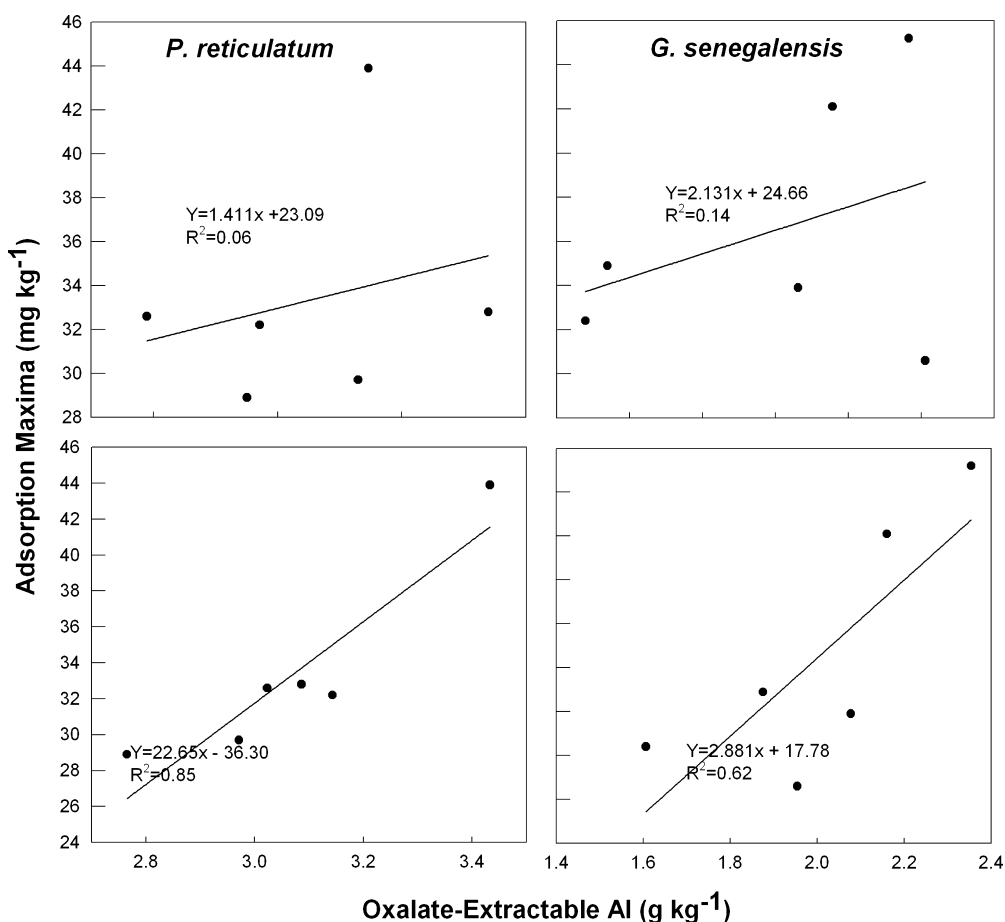


Fig. 3. Relationship of Fe<sub>ox</sub> (top) and Al<sub>ox</sub> (bottom) with P adsorption maxima as predicted by the Langmuir equation for *P. reticulatum*- and *G. senegalensis*-amended soils incubated for 30 days.

soils, respectively (Fig. 3). On the other hand, Fe<sub>ox</sub> showed no relationship with P sorption capacity of the soils investigated.

The range of P concentrations used in this sorption study is low compared with what is commonly reported in the literature but was deliberately chosen to approximate practical field conditions and to avoid P precipitation that may occur at high P concentrations (Barrow, 1978). Thus, the estimated Langmuir P adsorption maxima might be exceeded at adsorptive P concentrations higher than those used in the current experiment (Barrow, 1978). Sorption capacities of soils as determined in this study are low compared with other tropical soils (Iyamuremye et al., 1996). However, these values agree with those reported for some low P-fixing West African soils (Owusu-Bennoah and Acquaye, 1989; Nwoke et al., 2003).

#### Equilibrium P Concentration and Buffering Capacity

Equilibrium buffering capacity of soils (EBC) and equilibrium P concentration (EPC) derived from P isotherms may provide useful information on P fertilizer requirement for optimal plant growth (Hartikainen, 1991). These parameters were derived from quantity/intensity (Q/I) plots for the different soil amendments using the lowest P concentrations of the sorption study. At these concentrations, the relationship between P sorbed or desorbed and P in equilibrium solution is nearly linear. An illustration of the Q/I plot is presented in Fig. 4. From these graphs, EPC was derived as the value of solution P concentration at zero sorption, whereas the slope of the line gave an index of the EBC (Hartikainen, 1991; Kpomblekou and Tabatabai, 1997). These

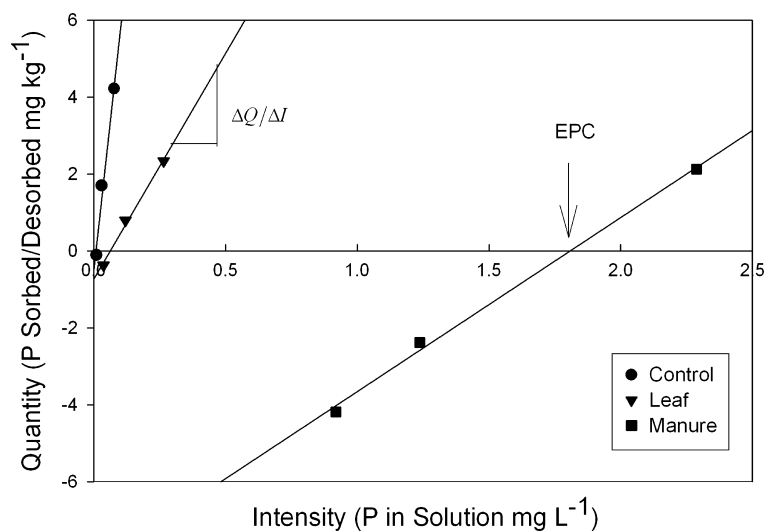


Fig. 4. The Q/I plot for soil beneath the canopy of *P. reticulatum* incubated for 30 days.

parameters are recorded in Table 5 for the whole data set.

Equilibrium buffer capacity values were lowest for manure-amended soils and highest for the control, ranging from 5.22 to 62.03 L kg<sup>-1</sup> beneath the shrub canopy and from 9.93 to 156.76 L kg<sup>-1</sup> outside the canopy. The *G. senegalensis*-associated soils had comparatively higher EBC values than *P. reticulatum*-associated soils, but the ranking was the same for the different treatments. The control had EBC of 225 L kg<sup>-1</sup> beneath the canopy and 207 L kg<sup>-1</sup> outside the canopy. These values dropped to 10 L kg<sup>-1</sup> with manure amendment. Apart from manure-amended soils, which had EPC values between 0.84 and 1.37 mg L<sup>-1</sup>, EPC values derived for the different treatments were low (<0.1 mg L<sup>-1</sup>) and were lowest for unamended soils.

In general, a prolonged incubation period (75 days) reduced the EBC in all samples except the leaf + stem amendment in the *P. reticulatum* soils (data not shown). Based on the average EPC of 0.2 mg L<sup>-1</sup> of P that is considered to be a critical solution P threshold for near maximum plant growth (Fox and Kamprath, 1970), one could infer from the above results that manure would provide solution P at levels to support optimal crop production in soils of this study. Although shrub leaf added to soil may improve P availability to the crop, the level of soil solution P would most likely be suboptimal for adequate plant growth in the absence of fertilization. The variation in standard P requirements of the soils corresponded to the adsorption maxima that ranged from 1.73 to 10.62 mg kg<sup>-1</sup> of P and was slightly higher in *P.*

TABLE 5  
The EPC, EBC, and standard P requirement of soils incubated for 30 days

Treatment	Location	Nioro ( <i>P. reticulatum</i> )			Keur Mata ( <i>G. senegalensis</i> )		
		EPC, mg L <sup>-1</sup>	EBC, L kg <sup>-1</sup>	P <sub>0.2</sub> <sup>†</sup> , mg kg <sup>-1</sup>	EPC, mg L <sup>-1</sup>	EBC, L kg <sup>-1</sup>	P <sub>0.2</sub> , mg kg <sup>-1</sup>
Control	Beneath	0.01	62.0	3.7	0.01	224.9	10.1
	Outside	0.00	156.7	6.2	0.00	207.6	10.6
Leaf	Beneath	0.06	11.7	1.7	0.08	22.7	2.5
	Outside	0.02	55.1	3.7	0.08	24.4	2.7
Leaf + stem	Beneath	0.01	20.1	2.9	0.02	51.8	4.8
	Outside	0.01	64.4	4.2	0.03	47.7	4.9
Manure	Beneath	1.82	5.2	—	1.19	8.9	—
	Outside	0.84	9.9	—	1.37	6.9	—

<sup>†</sup>P sorbed at equilibrium solution concentration of 0.2 mg L<sup>-1</sup> of P.

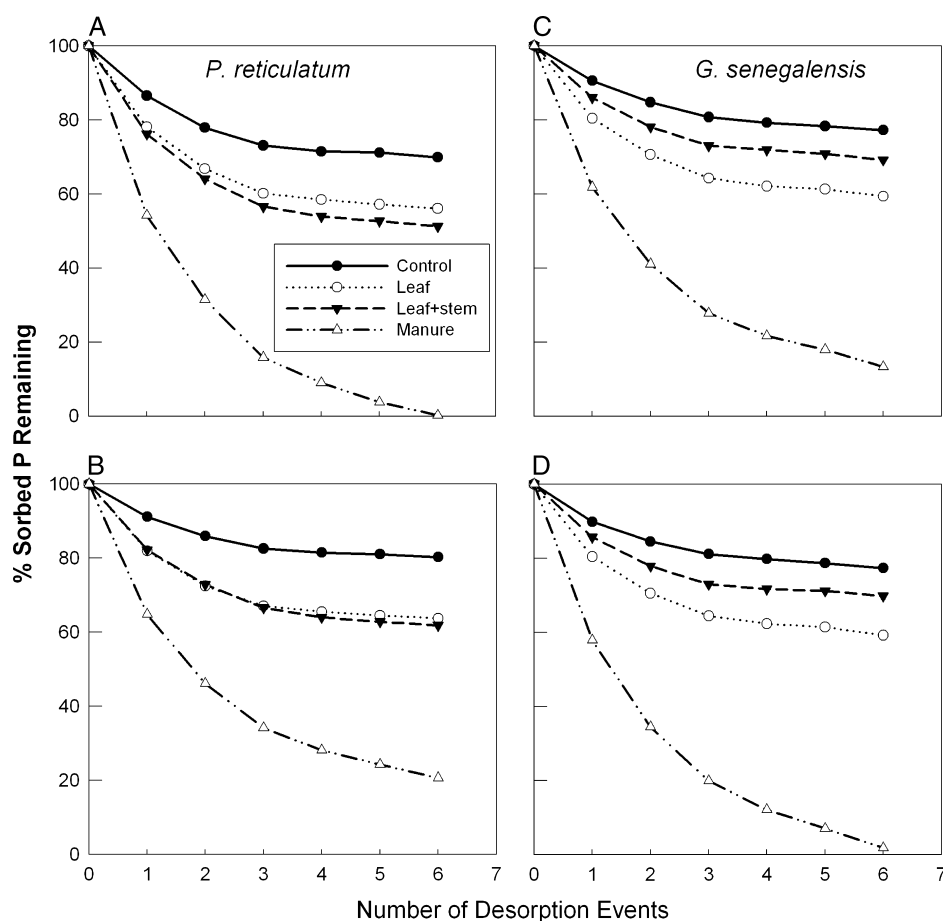


Fig. 5. Percentage of sorbed P remaining after sequential desorptions ( $n = 6$ ) in 0.01 M  $\text{CaCl}_2$  solution for *P. reticulatum* residue-amended soils beneath (A) and outside shrub canopy (B) and *G. senegalensis* residue-amended soils beneath (C) and outside shrub canopy (D). Incubation period is 30 days.

*reticulatum*-amended soils than in *G. senegalensis*-amended ones (Table 5).

#### Phosphorus Desorption

In the *P. reticulatum*-associated soils, most of the desorbed P (>90%) was obtained by third extraction for the 30-day incubation (Fig. 5). At the end of the desorption series, the amount of P released into solution was 30% of the initially sorbed P for the control. Those of leaf and leaf + stem were 44% and 48%, respectively, whereas manure-amended soils desorbed 98% of the initially sorbed P. Soils outside the canopy showed a decrease in the amount of P desorbed, which was 18% for the control and 78% for manure-amended soils. The faster and greater desorption of P in manure-amended soils corroborates with the results of Le Mare (1982),

who suggested that P sorbed to OM-associated Al and Fe was readily exchangeable.

The desorption pattern was the same in the *G. senegalensis*-associated soils; however, the total amount of P desorbed relative to the initially fixed P was smaller and ranged from 20% with the control to 86% with manure-amended soils beneath shrub canopy. A higher amount of P was desorbed in soil outside than beneath the canopy of *G. senegalensis*. An extended incubation time of 75 days generally resulted in slightly more P desorption (data not shown).

Except for the highest solution P, which corresponds to the highest P sorbed onto soils in both sorption and desorption processes, for any given solution P concentration, P sorbed during desorption was always higher than that during sorption. This hysteresis illustrated in Fig. 6 has been reported in many sorption studies (Barrow,

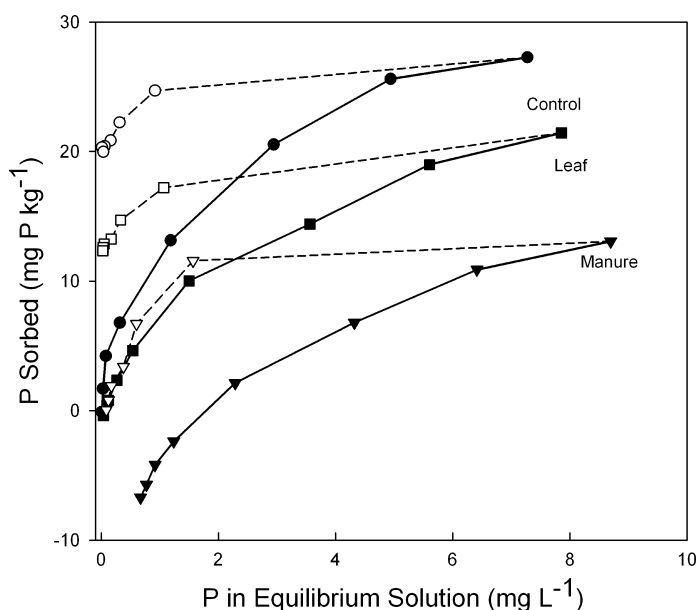


Fig. 6. Compared P isotherms during sorption (solid line) and desorption (broken line) for soils beneath the canopy of *P. reticulatum* incubated for 30 days.

1983; Sanyal et al., 1993; Dubus and Becquer, 2001). This reflects either the irreversibility of adsorption reaction or some kinetic disparity between sorption and desorption processes at the solid/liquid interface of soil. Some authors postulated that sorbed P might undergo further transformations that would increase its affinity to the mineral soil (Bolan et al., 1985; Sanyal et al., 1993). Conversely, Hingston et al. (1974) viewed kinetic irreversibility as a shift of desorbable monodentate forms of sorbed P to bidentate forms, which are quite irreversible. However, Barrow (1983) argued that recovery of sorbed P is possible under low surface activity if sufficient time is allowed for the reaction to come to completion. It is worth noting that the shaking time of 24 h used in the desorption process in this study might have been too short for the reaction to come to an equilibrium.

#### CONCLUSIONS AND PERSPECTIVES

The results of this study showed that all organic amendments used in this study decreased P sorption capacity of soils. Over the range of P concentrations used, manure-amended soils showed the greatest reduction in P sorption and the highest equilibrium solution P concentration. Manure released higher amounts of P in solution and at a faster rate than did the other amendments. Generally, the decrease in P sorption was greater beneath the shrub canopy than outside the can-

opy. A prolonged incubation time of 75 days resulted in slightly less P sorption and more EPC than when soils were incubated for 30 days.

The results suggest that manure is superior to shrub biomass in reducing P sorption, but at landscape levels in rural Senegal, the actual amount of animal manure is low (using Badiane et al., 2000, results in estimates of  $0.048 \text{ kg ha}^{-1} \text{ yr}^{-1}$  of C when distributed across all fields of a typical village in the row cropping region of Senegal). In contrast, Lufafa et al. (2008) showed that with existing densities, *P. reticulatum* and *G. senegalensis* would provide aboveground biomass C (if not burned) of approximately 5 and 3.5 times greater, respectively, than the amount of C inputs of manure when applied to all cropped fields of a village. Consequently, a more practical strategy to provide significant organic inputs to reduce P sorption could be from nonthermal management of aboveground residues—indeed, we have evidence that shrub densities could be increased more than three times the current densities observed by Lufafa et al. (2008) that actually results in elevated crop productivity (E. L. Dossa, M. Khouma, I. Diedhiou, M. Sene, F. Kizito, A. N. Badiane, S. A. N. Samba, A. Lufafa, S. Sire, and R. P. Dick, unpublished data, 2008).

Although field scale P cycling studies are needed on shrub-crop systems, results of this laboratory study would suggest that nonthermal

management and incorporation of shrub residues would be desirable in reducing P sorption—thus increasing the availability of native P and P added in fertilizers for crop uptake and efficiency (Haynes and Mokolobate, 2001). Additional research is needed to determine optimal and non-competitive shrub densities that maximize biomass production that could be used to decrease P sorption and improve soil quality.

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