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REGULAR ARTICLE

Spatial patterns of P fractions and chemical properties in soils of two native shrub communities in Senegal

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Abstract Two shrub species (*Piliostigma reticulatum* (D.C.) Hochst (Caesalpinioideae) and *Guiera senegalensis* J.F. Gmel (Combretaceae) are commonly found in farmers' fields at varying densities in semi-arid Senegal and throughout the Sahel where soils have chronically low phosphorus (P) availability. It seems plausible that shrub litter and the rhizospheres could influence P fractions and other chemical soil properties that affect crop productivity. Thus, a study was done at two sites, on the distribution of inorganic and organic soil P pools, organic C levels, and pH in soil beneath and outside the canopies of *P. reticulatum* and *G. senegalensis* (0-30 cm depth). Both sites had low total P ranging from 64 mg P kg^{-1} to 135 mg P kg^{-1}, and low extractable PO_4 (resin Pi) (1–6 mg P kg^{-1}) with P fractions dominated by NaOH-P. Organic P (Po) made up about 50% of total P, and most of the organic P (>60%) was found in the NaOH-P fractions. The labile P, particularly bicarb-Po was higher in soil beneath shrub canopies (8.4 mg P kg^{-1}), than outside the canopy (6.2 mg P kg^{-1}). Similarly, C, N and P to a lesser extent, were more concentrated beneath shrub canopies. *P. reticulatum* soil was dominated by the NaOH-Po fraction, whereas *G. senegalensis* had higher bicarb-Po at one of the study sites. An index of biologically available organic P (Bicarb-Po) / (Bicarb-Po+Bicar-Pi+Resin Pi) was >60% and indicates that biological processes represent an important part of P cycling in these shrub ecosystems. The differential ability of shrubs in modifying soil chemical properties under their canopies has major implications for biogeochemical cycling of nutrients and C in sandy soils of semi arid Sahelian ecosystems.

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Abbreviations

P_i	Inorganic P
P_o	Organic P
1R	One canopy radius
3R	Three canopy radiuses
2R	Two canopy radiuses

Introduction

Phosphorus (P) and nitrogen (N) are two major elements that limit crop productivity in arid and semiarid ecosystems (Tiessen 1995). Erratic distribution of low rainfall in these ecosystems makes water a critical resource that controls nutrient cycling and availability. Low levels of N in the Sahel are related to low net primary production and sandy soils with low potential to sequester carbon (C). Solution P in West African highly weathered soils is kept at low levels because of Al and Fe oxides reactions with P (Nwoke et al. 2003; Agbenin and Anumonye 2006; Dossa et al. 2008a).

Phosphorus supply to the soil solution for plant uptake is dependent upon the size of P pools that constitute soil P and their rates of hydrolysis and mineralization. Sorption processes at the soil mineral solution interface make it difficult to measure potentially mineralizable P pool (Bünemann et al. 2007). Alternatively, the sequential fractionation of soil P with increasingly stronger chemical extractants has been widely used to discriminate between P pools of different turnover rates in soils (Chang and Jackson 1957; Hedley et al. 1982; Tiessen and Moir 1993; Cross and Schlesinger 2001). This procedure has been successfully used to evaluate soil biological and geochemical processes in P cycling in various ecosystems (Hedley et al. 1982; Tiessen et al. 1984; Lajtha and Schlesinger 1988).

Organically bound P (Po) is an important P fraction for making P available to plants but is often overlooked for chemical P reactions. Its contribution to soil P increases along a weathering gradient from 20% to 90% (Stevenson and Cole 1999). Though total soil Po is generally considered to be not very dynamic (Stewart and Tiessen 1987), mineralization of only a small fraction of this pool can be important to meet crop P requirements (Harrison 1982). Although the labile fraction of soil Po can undergo a rapid turnover (Halm et al. 1972), especially in tropical ecosystems (Adepetu and Corey 1977); mineralization and immobilization reactions occur simultaneously in soils and result in minimal changes in the overall soil Po (Stewart and Tiessen 1987; Bünemann et al. 2007). Reports indicate that in P-limited soil ecosystems, Po mineralization may be the major source of soil solution Pi for the crop (Adepetu and Corey 1976; Beck and Sanchez 1994; Cross and Schlesinger 2001; Nwoke et al. 2003). In such P-deficient environments, tight biotic cycling of nutrients through plant litter assures conservation and availability of P in the plant-soil system (Vitousek 1984).

Arid and semiarid environments are characterized by spatial patchiness in their woody vegetation cover that may alter nutrient cycling. The spatial distribution of the shrubs has been related to hydrological characteristics that may favor establishment of woody species at certain places in the landscape (Cantón et al. 2004; Li et al. 2004). Shrubs in these environments represent distinct ecosystem units characterized by higher C and N, and improved microclimate and water availability under the shrub canopy (Schlesinger et al. 1996; Kieft et al. 1998; Van Miegroet et al. 2000; Kizito et al. 2007). These zones with better soil quality have intense biological activity and presumably faster nutrient cycling (West 1991; Gallardo and Schlesinger 1995). In addition, the shrub canopies can offer refuge to small animals, which by their excreta further enhance fertility build up and nutrient cycling beneath the shrubs (Whitford 2002). Shrubs in these ecosystems may further influence the spatial patterns of the soil biogeochemistry and other properties by the presence of the rhizosphere and litter inputs beneath the canopy zone. Hydraulic lift from deeper horizons and water redistribution in top soil layers is an intriguing property described with some shrub species that may alter nutrient mineralization (Caldwell et al. 1998; Kizito et al. 2007).These effects can be modified by plant species, soil type and environmental characteristics (Abrams et al. 1990).

Two native woody shrub species, *Piliostigma reticulatum* (D.C.) Hochst (Caesalpinioideae) and *Guiera senegalensis* J.F. Gmel (Combretaceae) are the dominant shrub species found in agroecosystems of Senegal (Lufafa et al. 2008) and throughout the Sahel.

Unlike shrublands of temperate arid environments, shrublands in the tropics have received less attention with regard to their biophysical characterization (Wezel et al. 2000). Since these two shrubs coexist with crops in farmers' fields, they could play an important role in cycling and availability of N and P to crops. Understanding the biogeochemistry of soils influenced by these shrubs is necessary to develop a foundation for managing this unrecognized resource for more productive and sustainable land-use.

Our previous study (Dossa et al. 2008b) showed that *P. reticulatum* and *G. senegalensis* have contrasting litter decomposition patterns and higher organic matter beneath their canopies. We hypothesized that these shrubs behave as islands of biogeochemical intensity that should increase nutrient concentration and availability under their canopies. We further hypothesized that the intensity of nutrient concentration and the biogeochemistry of P is species-dependent. We were particularly interested in P relations because the prime agricultural soils of Senegal have very low soil solution P, and thus, an understanding of shrub interactions with P fractions could provide the basis to develop optimized crop-shrub system for improved P availability to crops. Therefore the objectives of this study were to determine the influence of *P. reticulatum* and *G. senegalensis* -canopies and rhizospheres on spatial distribution of: 1) soil C, N and P; and 2) soil inorganic and organic P fractions.

Materials and methods

Study sites and sampling design

The study area is the "Peanut Basin" of west central Senegal. Two sites were selected for soil sampling. The first site (Keur Matar Arame) is in the northern region of the Peanut Basin (14°45 N, 16°51 W, and 43 m above sea level), with mean annual precipitation of 450 mm and temperatures ranging from 20.3°C in December-January to 33.4°C in April–June. The soil is 95% sand, mainly constituted of materials from aeolian deposits with no distinct horizonation in the top 1 m layer, classified as Rubic Arenosol (FAO 2006), locally referred to as Dior soils (Badiane et al. 2000). They have low buffer and exchange capacity (Tschakert et al. 2004). *Guiera senegalensis* J.F. Gmel. (Combretaceae) is the dominant evergreen shrub vegetation, with average stand density of 240 shrubs ha^{-1} at this site (Kizito et al. 2006), which is representative of lower rainfall region of northern Senegal (~300−500 mm annually). Herbaceous vegetation in the interspace between shrub stands consists of annuals dominated by *Alysicarpus ovalifolius* (Schum.) J. Leonard, *Cenchrus biflorus* Roxb., *Dactylotenium aegyptium* (L.) Willd. *Eragrostis pilosa* (L.) P. Beauv. and *Merremia tridentata* (L.) Hall.

The second site (Nioro du Rip) is located (13°45 N, 15°47 W) at 18 m above sea level with mean annual precipitation of 750 mm distributed from July to September and mean air temperatures ranging from 20°C to 35.7°C. The soil is a Deck-Dior (Badiane et al. 2000) loamy-sand [fine-sandy, mixed Haplic Ferric Lixisol] (FAO 2006), a leached ferrugineous highly weathered tropical soil. The dominant shrub species at the site is *Piliostigma reticulatum* (DC.) Hochst (Caesalpinioideae), an evergreen species found at average density of 185 shrubs ha^{-1} (Kizito et al. 2006) and is representative of central Senegal with average rainfall of ~500–1,000 mm. Herbaceous annual vegetation in the inter-shrubs space is mainly dominated by *Cenchrus biflorus* Roxb., *Digitaria lecardii* (Pilg.) Stapf., *Eragrostis tremula* (Hochst & Steud), *Indigofera pulchra* Willd., *Mitracarpus villosus* (SW.) DC and *Stylosanthes fruticosa* (Retz.) Alston.

Within each study area there were two types of fields identified and each type had two, true landscape level replications. One field type (referred to as "*regional sole species comparison*") had nearly a 100% coverage of a single species that dominates in that region (in the northern site at Keur Matar Arame this was *G. senegalensis* and in the southern site at Nioro du Rip it was *P. reticulatum*). This allowed for a comparison between the northern and southern sites for the integrated effect of shrub species and soil type. The second field type at each site had both shrub species present in the same field at approximately equal densities (referred to as "*within site species comparison*"). This allowed for a direct comparison of the two species on the same soil type. Each field was approximately, 0.1 ha and each of the two landscape level replicated fields were>1 km from each other.

For the sole species fields, four shrubs were sampled per field which resulted in four shrubs×two field replicates or eight shrubs/southern or northern site. For the mixed species sites, two pairs of *P. reticulatum* and *G. senegalensis* (adjacent shrub stands separated by <2 m) were selected in each field at each site for soil sampling and this resulted in two shrub species×two field replicates or four shrubs total/species/northern or southern site.

The shrubs selected had a canopy size of approximately 2 m, which is representative of average shrub size in farmers' fields (Lufafa et al. 2008), and were free from the influence of neighboring shrubs. For each shrub, we established three sampling positions from the center of the shrub at distances of one canopy radius (1R), two canopy radiuses (2R), and three canopy radiuses (3R). In September 2005, soil was sampled at 0–30 cm depth at ten random locations at each radius distance around the shrub using a coring device of 2.5 cm diameter. During soil sampling, when a shrub was paired with the other species, the space between the two shrubs was excluded to avoid possible interferences. The samples (ten cores) were mixed as a single composite sample for each sampling position, air-dried at room temperature and sieved through a 2 mm screen prior to chemical analyses. The plots selected for this study had not been cultivated at least 2 years prior to soil sampling, and indigenous knowledge estimated shrub stands to be over 20 years of age at the time of sampling.

Laboratory analyses

Soil pH was determined with a glass electrode in 1:2.5 soil:water ratio. Organic carbon (C) and total nitrogen (N) were determined by combustion on a LECO CNS-2000 autoanalyzer (LECO Corp., St. Joseph, Missouri). No attempt was made to test the soil for carbonate as the 0–40 cm soils at the sites of our study are reported to have acidic reactions (pH <7) (Khouma 2000) and are known not to contain carbonates (person. communication, M. Sene 2009). Total phosphorus (P) was determined by a modified Kjeldahl Li_2SO_4-H_2SO_4 procedure (Parkinson and Allen 1975). Nitrate-N and ammonium-N in 1*M* KCl soil extract were determined respectively by the salicylate-nitroprusside, and the hydrazine-sulfanilamide methods (Mulvaney 1996). P extracted by the $NaHCO_3$+NH_4F method is defined as the plant-available P (Dabin 1967). Phosphorus extracts and digests were analyzed for orthophosphate by the molybdenum blue colorimetric method (Murphy and Riley 1962) after pH adjustment when necessary.

Soil P fractionation

P fractions in soils were extracted using a modified sequential fractionation (Hedley et al. 1982; Tiessen and Moir 1993; Cross and Schlesinger 2001). The soils under the shrub canopy (1R) and furthest out of the canopy (3R) were compared for P fractions because they were most likely to show differences in P fractions influenced by shrub vegetation. A 2-g soil sample was placed in a 50 mL plastic centrifuge tube with 30 mL of deionized water and a 2.5 cm^2 anion exchange resin strip (AR-204UZR-4R Ionics) (Abrams and Jarrell 1992) previously saturated with HCO_3^- ions. The tubes were shaken for 16 h on a horizontal shaker. Phosphorus was desorbed from the resin strips by adding 20 mL of 0.5*M* HCl solution followed by shaking for 16 h (resin P). The water-soil suspension was centrifuged at 17, 500 rpm for 10 min at 0°C and the supernatant discarded. The soil residue was subsequently extracted with 30 mL of the following extractants: 0.5*M* $NaHCO_3$ (pH 8) for bicarbonate-P, 0.5*M* NaOH (hydroxide-P), 1*M* HCl (dHCl-P); and 15 mL of concentrated HCl (cHCl-P) according to Tiessen and Moir (1993). Prior to inorganic P determination, organic matter in the NaOH and cHCl extracts were precipitated with 0.9 *M* H_2SO_4 (Tiessen and Moir 1993) and 5*M* NaOH respectively. Organic matter precipitation in the $NaHCO_3$ extract was not successful; hence, inorganic P (P_i) in that extract was determined directly using a blank correction. For residual P, and total P in the bicarbonate, hydroxide and concentrated HCl extracts, aliquots of samples were digested with H_2SO_4-H_2O_2 (Parkinson and Allen 1975). Organic P (P_o) in these extracts was calculated as the difference between total P and P_i. In all extracts, pH was adjusted when necessary, and P was determined colorimetrically by the ascorbic acid method (Murphy and Riley 1962) on a spectrophotometer at 712 nm.

Interpretation of P fractions

The interpretation of P fractions varies somewhat among scientists (Cross and Schlesinger 1995). The resin-P extracts free P_i from the soil solution and bicarbonate P simulates plant root action and desorbs P from crystalline P compounds, sesquioxides, and carbonate (Tiessen and Moir 1993). Both resin-P and bicarbonate P are considered to be labile P pools. Hydroxide extractable P is thought to be associated with amorphous and some crystalline Al and Fe phosphates and hence constitutes a slow P pool relative to the resin and bicarbonate pools. Of lesser availability are the dHCl-P pool, which represent P extracted from calcium carbonate (Tiessen and Moir 1993), and the cHCl-P pool associated with P held in the interior of Fe and Al minerals and apatite (Cross and Schlesinger 2001). The concentrated HCl treatment is assumed to remove most of the residual P (Condron et al. 1990); hence un-extracted residual P obtained from the H_2SO_4-H_2O_2 digestion is most likely made of highly recalcitrant P such as occluded Fe- and Al-P of some highly weathered tropical soils (Tiessen et al. 1991).

Statistical analyses

Soil data for the *regional sole species comparison* was analyzed independently for each site using PROC GLM ANOVA (SAS Institute 1999) with sampling location and shrub replicate (nested within field) as factors in the model. Both data for the *regional sole species comparison* and the *within site species comparison* were consistent with a simpler model based on the fact that field effects were additive and sampling location as repeated measures satisfied the Huynh-Feldt condition and that there was no evidence of the need for a separate error term for testing species main effect. A computation of F ratio (MSE_{site1}/MSE_{site2}) on log-transformed data yielded a P value >0.25, which suggests that the data is reasonably consistent with the null hypothesis of MSE for site 1 and site 2 having the same expectations. Therefore, the *within site species comparison* samples were pooled for the two sites and analyzed as a simpler factorial design (PROC GLM, SAS Institute 1999) with site, species and sampling location as factors in the model. Shrubs of pairs (replicates) were nested within sampling field, which in turn was treated as random effect. Tukey's protected t-test was used for mean separation of soil P fractions.

For nutrients and pH, a factorial MANOVA test was performed to examine the overall effect of the different factors. This was followed by univariate factorial analyses and mean comparison by LSD at P <0.05.

Results

Soil organic C, N, P and pH

Soil total C, N and P were higher beneath the shrub canopy (1R) than outside the canopy (2R and 3R). This pattern occurred for the *regional sole species* comparison and the *within site species comparison*. To illustrate the pattern, the *within site species comparison* data are presented in Fig. 1. The MANOVA analysis revealed overall significant canopy and shrub species effects on soil characteristics (P <0.0001). Nutrients were generally more concentrated under shrub canopies (1R) of both species (Fig. 1). Soils at Keur Matar had higher total P but lower C and N than soils at Nioro. At both sites, concentrations of organic C, total N, total P and to a lesser extent ($NaHCO_3$+NH_4F)-P, were higher under shrub canopy and decreased linearly in a gradient outside the shrub canopy (Fig. 1). Inorganic N (NH_4^+-N and NO_3^--N) was highest under shrub canopy (1R) and lowest furthest out of the canopy (3R) in Nioro soils, but showed no consistent pattern in Keur Matar soils (Fig. 1). For the *regional sole species comparison*, NO_3^--N was detected at significantly (P <0.001) higher concentrations under shrub canopy (1R) than outside the canopy (2R, 3R) at both Keur Matar and Nioro sites (data not shown). Under *G. senegalensis*, pH values were acidic and increased in a gradient outside the canopy. In contrast, beneath *P. reticulatum*, there was a comparatively higher pH, which tended to decrease with increasing distance from the shrub center (Fig. 1).

Soil C/N, C/P and N/P ratios (Fig. 2) differed among sites, with site sampling locations, and were affected by shrub species. At Keur Matar, soil C/N ratio increased from shrub canopy (1R) to the 2R location but was lowest outside the influence of the shrub canopy (3R) while at Nioro, C/N ratio increased slightly (but not significantly) from shrub center to outside the canopy. The changes in C/P and N/P ratios showed a similar pattern and were significant only with *G. senegalensis* soils at Keur Matar (P <0.05), with highest ratios under the canopy (1R) while at Nioro, soil C/P and N/P ratios decreased from shrub center outside the canopy and were highest beneath *G. senegalensis* under the canopy (1R) (P <0.05). Mean soil C/N ratio was higher at Keur Matar than at Nioro site but C/P and N/P ratios were lower.

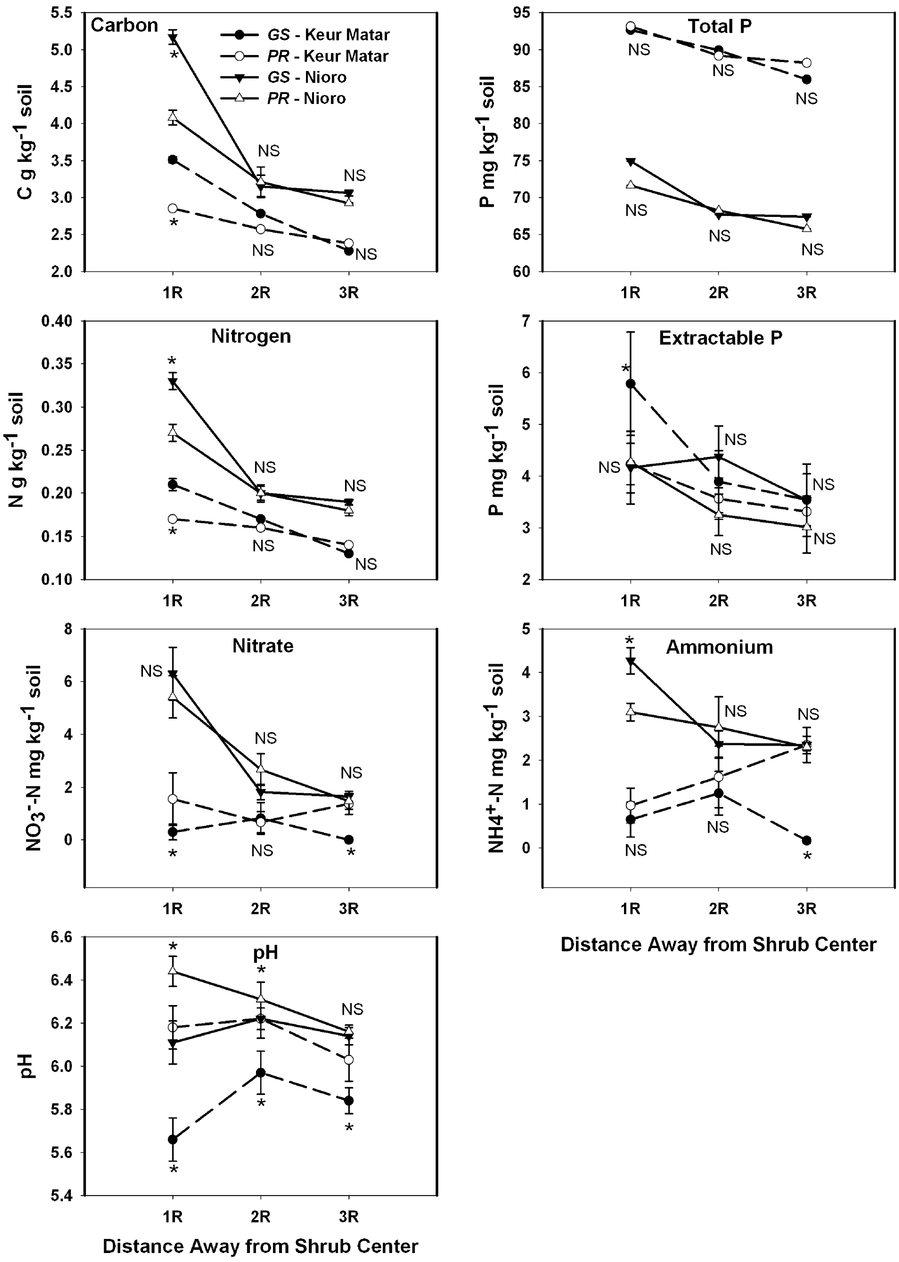


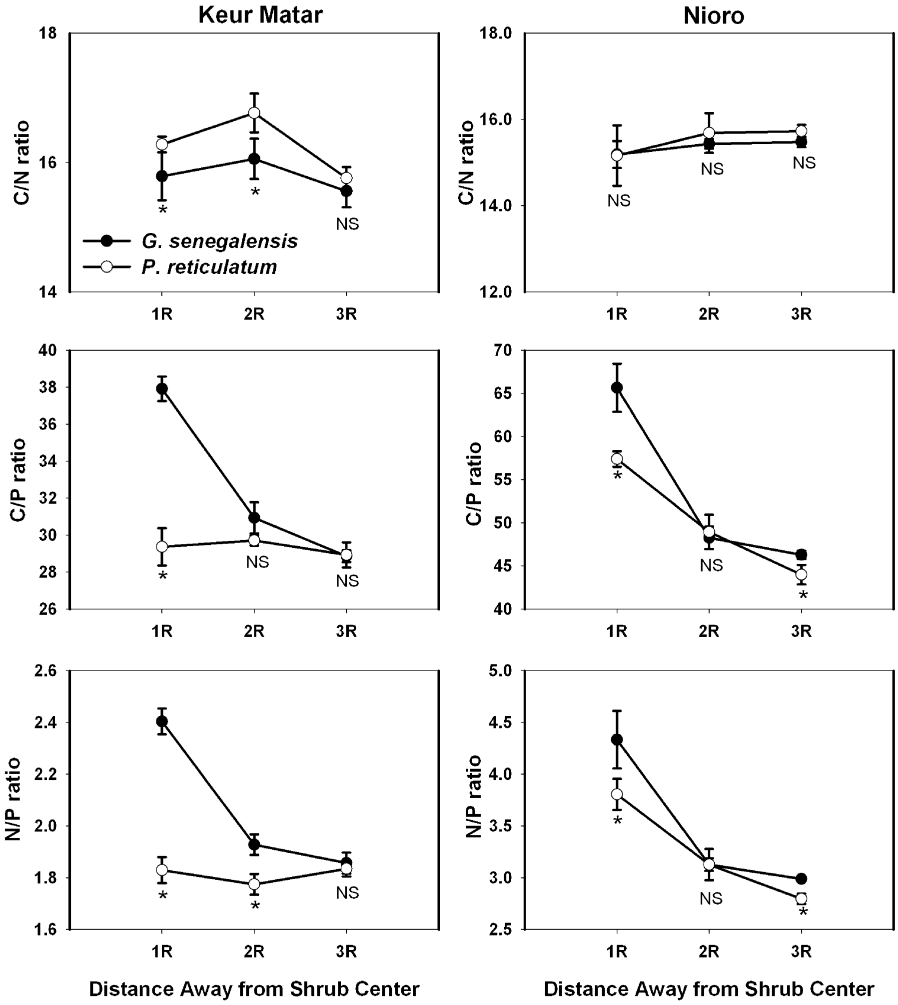
Fig. 1 Soil chemical characteristics at increasing distance from shrub center in soils under *G. senegalensis* and *P. reticulatum* at Keur Matar and Nioro sites. Bars indicate standard error on means. (**P* <0.05; NS, not significant; *GS*=*G. senegalensis*; *PR*=*P. reticulatum*)

Soil P fractions

Data for the *regional sole species comparison* are presented in Table 1. Mean total P (calculated from the sum of individual P fractions) was 131 mg P kg $^{-1}$at Keur Matar, and 66 mg P kg $^{-1}$ at Nioro (Table 1). Soil Po fractions were a substantial proportion of total P, ranging from 36–50% of total P. Hydroxide extractable P was the major single soil P pool and accounted for approximately 38% of total P at both sites (Table 1). The second largest pool was the cHCl-P (23% of total P), and the smallest fraction was resin-P, which comprised 3.5% of total P at Keur Matar and 2.5% at Nioro. The dHCl-Pi represented 9% and 7.5% of total P at Keur Matar and Nioro respectively whereas residual-P accounted for 16–18% of total P at both sites.

Shrub canopy effects on soil P fractions were more pronounced at Keur Matar than Nioro. The bicarbonate Po pool was significantly higher (P <0.01) under shrub canopy (1R) than outside the canopy (3R) at both sites.

Fig. 2 Changes in C/N, C/P and N/P ratios at increasing distances from shrub center in soils under *G. senegalensis* and *P. reticulatum* at Keur Matar and Nioro sites. Bars indicate standard error on means. (*P <0.05; NS, not significant)



Additionally, resin-Pi and bicarb-Pi were significantly higher under shrub canopy than outside the canopy at Keur Matar (P <0.05) but identical at Nioro. Total P and soil Po were also higher under the canopy at Keur Matar. All other P fractions were distributed similarly between soil beneath and outside shrub canopy.

Apart from cHCl-P and dHCl-P pools, which were mainly inorganic P, all the other P fractions were dominated by organic P. At Keur Matar, 63% of NaOH-P was in organic form whereas at Nioro, Po represented about 80% of NaOH-P. Moreover, NaOH-Po accounted for most of soil organic P and represented 63–67% of total Po at Keur Matar and 61–64% of total Po at Nioro (Table 1).

Examination of the *within site species comparison* data revealed site and shrub species differences in P fractions. Most of the inorganic P fractions (NaOH-Pi, dHCl-P, cHCl-Pi) were higher in soils at Keur Matar than at Nioro (P <0.001), and so was total P (Table 2). At both sites, the NaOH-Po fraction was significantly greater (P <0.01) under the canopy of *P. reticulatum* than under *G. senegalensis*. However, the magnitude of this species difference in NaOH-Po between *P. reticulatum*- and *G. senegalensis*-canopy soils was 56% and 24% larger at Nioro and Keur Matar, respectively (Fig. 3). On the other hand, bicarbonate-Po content was higher under *G. senegalensis* at the Nioro site (Fig. 3). Species differences were not apparent for the other P fractions.

Discussion

Soil chemical properties

Soil properties differed between sites (see Tables 1 and 2). This was likely due to the natural variation that occurs within and among soil type. However, these differences varied according to the soil property. For example at Nioro on average, soil C, N and inorganic N contents were higher, but total P and available P levels were lower than at Keur Matar. A difference in mineralogy and/or pedogenic processes of the two soils may partially explain the differences in total P whereas higher clay content and higher rainfall regime at Nioro most likely contributed to differences in soil C and N between the sites. At Keur Matar the higher total P values with the *"regional sole species comparison*" (Table 1) relative to the "*within site species comparison*" (Table 2) may besides differences likely reflects recent management of the "r*egional sole species comparison*" fields which had been uncultivated for a longer period of time.

Beneath the shrub canopy (1R), concentrations of C, N, and P were higher than in bare soils outside the canopy (3R). Such a pattern of nutrient distribution commonly referred to as an "island of fertility" (Garner and Steinberger 1989) is well documented in various arid and semiarid ecosystems (Schlesinger et al. 1990; Wezel et al. 2000; Whitford 2002). Major mechanisms involved in the formation of fertile islands include biological and physical factors (Garner and Steinberger 1989) but their relative importance is not well understood. A physical property that may affect the specific spatial distribution is favorable hydrological sites that favor establishment of woody species in semi-arid environments (Cantón et al. 2004; Li et al. 2004). Physical processes such as accumulation of wind-blown materials and stemflow washing of dry-fall that collects on shrub foliage may initiate the fertile islands (Schlesinger et al. 1990; Whitford et al. 1997). Biological processes become important with time as plants take up greater amounts of nutrients and recycle them through litter deposition and decomposition (Schlesinger et al. 1990). One temporal issue is that the results reflect cumulative effects on the order of decades. We base this on anecdotal information from farmers and unpublished data from ring counts of *P. reticulatum* (I. Diedhiou, person. commun. 2009).

Several soil parameters showed shrub species dependency. The *G. senegalensis* soil was more acidic under the shrub canopy than outside. Conversely, *P. reticulatum* had a relatively higher pH under its canopy than outside. This differential shrub species effect on soil pH could be attributed to contrasting litter chemistry between the two shrub species. Organic acid anion content of litters (Brady and Weil

Table 1 Distribution of P fractions in the *regional sole species comparison* at Keur Matar and Nioro sites beneath (1R) and outside (3R) shrub canopy (n=8)

P fractions	Keur Matar			Nioro		
	1R mg P kg $^{-1}$ soil	3R	Prob.	1R mg P kg $^{-1}$ soil	3R	Prob.
Resin-P	5.5 (0.6)	4.1 (0.5)	P<0.003	1.5 (0.1)	2.2 (0.7)	NS
Bicarb-Pi	6.6 (0.6)	4.6 (0.4)	P<0.007	1.9 (0.2)	1.9 (0.6)	NS
Bicarb-Po	10.7 (1.3)	6.4 (1.4)	P<0.004	6.6 (1.6)	4.9 (1.4)	P<0.008
NaOH-Pi	17.5 (1.3)	18.1 (0.9)	[a]NS	4.9 (0.2)	5.6 (1.1)	NS
NaOH-Po	31.3 (4.1)	30.4 (4.3)	NS	20 (3.1)	18.8 (3.9)	NS
dHCl-Pi	11.6 (1.3)	11.3 (1.0)	NS	3.9 (1.9)	5.6 (1.6)	NS
cHCl-Pi	22.3 (1.1)	19.9 (1.6)	NS	9.1 (0.7)	8.9 (0.7)	NS
cHCl-Po	8.0 (1.6)	8.7 (1.4)	NS	6.2 (3.8)	5.5 (1.7)	NS
Residual-P	21.9 (1.9)	22.4 (1.1)	NS	11.9 (1.3)	11.3 (0.8)	NS
Total Po	50.0 (6.4)	45.5 (5.5)	P<0.05	32.8 (5.1)	29.1 (4.9)	NS
Total Pi	85.5 (6.3)	80.4 (4.2)	NS	33.3 (3.6)	35.6 (3.0)	NS
Total P	135.5 (8.6)	125.9 (5.2)	P<0.001	66.2 (6.9)	64.8 (4.9)	NS

Mean values and standard error in parenthesis

[a] NS=not significant

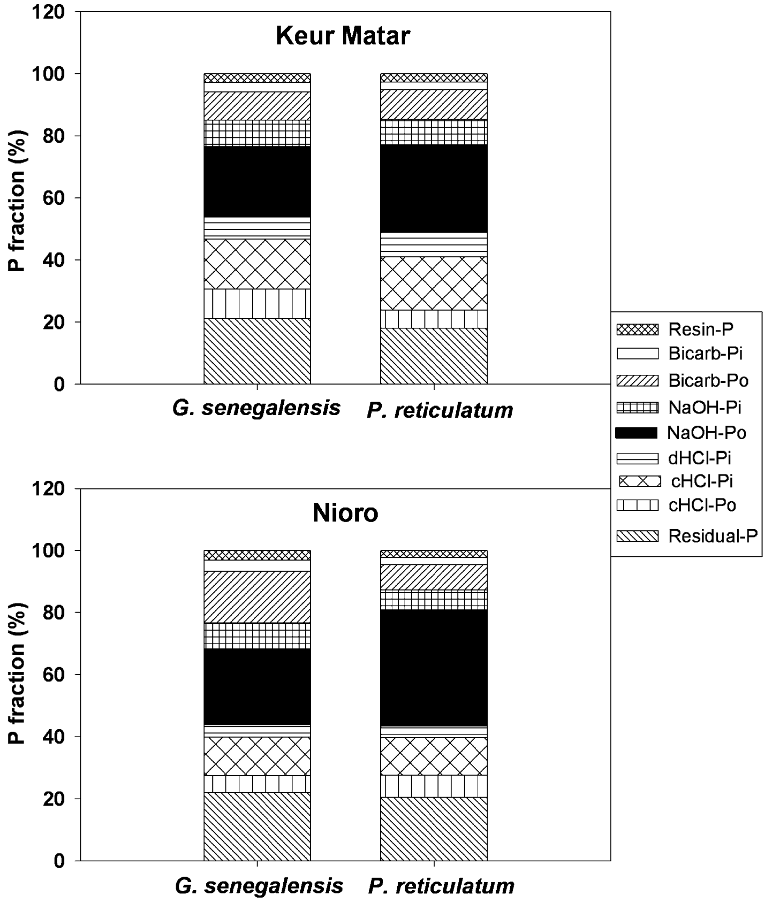
Table 2 Distribution of soil P fractions (mg P kg $^{-1}$ soil) by shrub species for the *within site species comparison* at Keur Matar and Nioro sites

Shrub species		Resin-P	Bicarb-Pi	Bicarb-Po	NaOH-Pi	NaOH-Po	dHCl-Pi	cHCl-Pi	cHCl-Po	Residual-P	Sum Po	Sum Pi	Total P
		Keur Matar											
G. senegalensis	[a]1R	2.5a	2.7a	8.2b	7.5a	20.3b	6.3a	14.4a	8.4a	18.9a	36.9a	52.3a	89.3a
		(0.8)	(0.6)	(2.0)	(1.4)	(1.8)	(1.0)	(0.4)	(6.3)	(2.4)	(6.9)	(2.4)	(7.7)
	3R	2.1a	2.1a	5.6c	7.2a	25.1a	6.2a	13.6a	5.1a	19.3a	35.8a	50.4a	86.2a
		(0.1)	(0.2)	(1.9)	(0.5)	(5.4)	(0.8)	(1.0)	(1.9)	(3.8)	(5.8)	(4.0)	(7.1)
P. reticulatum	1R	2.3a	2.2a	8.5b	7.3a	25.1a	6.9a	15.3a	5.3a	15.9ab	38.9a	50.1a	88.9a
		(0.2)	(0.1)	(3.8)	(0.8)	(3.4)	(1.1)	(2.0)	(0.9)	(1.6)	(2.5)	(2.3)	(4.5)
	3R	1.4ab	2.1a	8.3b	6.8ab	24.9a	6.8a	13.3a	6.8a	15.3ab	40.0a	45.8b	85.8a
		(0.2)	(0.4)	(2.7)	(0.6)	(4.4)	(0.7)	(0.8)	(1.4)	(2.0)	(7.8)	(2.0)	(6.3)
		Nioro											
G. senegalensis	1R	2.0ab	2.4ab	11.2a	5.8bc	16.5b	2.6b	8.4b	3.6a	14.9ab	31.3a	36.2c	67.5b
		(0.3)	(0.2)	(3.1)	(1.6)	(1.5)	(0.4)	(0.3)	(1.6)	(1.6)	(2.8)	(3.3)	(3.2)
	3R	1.0b	1.9b	7.3b	4.2c	23.4ab	1.7b	7.9b	4.2a	12.0b	35.0a	28.8d	63.8b
		(0.1)	(0.2)	(2.0)	(0.5)	(5.4)	(0.3)	(0.4)	(0.4)	(2.7)	(5.1)	(1.9)	(5.4)
P. reticulatum	1R	1.5ab	1.6b	5.4c	4.4c	25.1a	2.6b	8.1b	4.9a	13.7b	35.3a	31.8c	67.2b
		(0.2)	(0.2)	(0.6)	(0.6)	(3.1)	(0.5)	(0.5)	(3.1)	(1.5)	(4.8)	(1.3)	(4.1)
	3R	1.5ab	1.8b	4.8c	4.4c	22.8ab	2.3b	7.0b	6.9a	12.5b	34.5a	29.5c	64.0b
		(0.6)	(0.3)	(0.8)	(0.7)	(5.1)	(0.8)	(0.3)	(2.0)	(1.0)	(4.0)	(3.0)	(2.5)

Mean values and standard error in parenthesis. Values in column followed by the same letter are not significantly different at $P < 0.05$ ($n=4$)

[a] 1R=1 canopy radius, 3R=3 canopy radiuses away from shrub stem

Fig. 3 Proportion of P fractions relative to total P in soils beneath the canopy (1R) of *G. senegalensis* and *P. reticulatum* at Keur Matar and Nioro sites



2007) is known to determine the balance between proton production and consumption during decomposition (Haynes and Mokolobate 2001). Species with recalcitrant litter and slow decomposition rates cause greater production of organic acids and protons that acidify soil pH (Finzi et al. 1998). Residues of *G. senegalensis* do have a slow decomposition rate (Dossa et al. 2008b), which could partly explain the acidic pH beneath the canopy of the species. On the other hand, higher base cations uptake by *P. reticulatum* and return to soil of easily decomposable litter could be an additional process involved in creating the change in soil pH. Our results are similar to findings of Wezel et al. (2000) in semiarid Niger where greater acidification was associated with higher Al^{3+} and H^{+} and depleted Ca^{2+} levels under canopy of *G. senegalensis*. Low pH enhances the solubility of Al^{3+} and Fe^{3+}, which competes with base cations such as Ca^{2+} on the exchange complex (Finzi et al. 1998).

The higher soil organic C under *G. senegalensis* than *P. reticulatum* could be attributed in part to higher litter return and root biomass production of *G. senegalensis* relative to *P. reticulatum* (Dossa 2007). An additional mechanism is likely the slower decomposition rate of *G. senegalensis* residues because of its recalcitrant litter chemistry (Dossa et al. 2008b).

As expected, soil N content in these shrub ecosystems followed the same pattern as soil C and reflects stabilization of soil N through C-N bonds. Keur Matar soils have C and N contents comparable

Table 3 Bulk density of 0–30 cm soil beneath (1R) and outside shrub canopy (3R) at Keur Matar and Nioro

Soil location	Keur Matar g cm^{-3}	Nioro g cm^{-3}
1R	1.52	1.48
	(0.02)	(0.01)
3R	1.61	1.54
	(0.02)	(0.01)

Mean values with standard error of the mean in brackets (*n*=3) to those reported for soils in semiarid Niger (Wezel et al. 2000), but Nioro soils have higher C and N contents most likely as a result of higher rainfall regime and consequently greater net primary productivity. When these soil characteristics are expressed in terms of mass per unit area, the magnitude of the differences was greater but the trends were the same despite the lower bulk density values under the shrub canopy (1R) than outside the canopy (3R) (Table 3).

These spatial differences in nutrient concentration resulted in a species as well as sampling location effect for the C/N, C/P and N/P ratios (Fig. 2). The lower soil C/N ratios in Nioro soils than in soils at Keur Matar may indicate a greater N availability. The C/P ratio had roughly the same pattern as the N/P ratio and was wider beneath the canopy than outside the canopy, most likely as a result of the significant increase in organic matter under the shrub canopy. Indeed we found a strong and significant correlation between soil C and C/P ratio ($R=0.90$, $P<0.0001$), and soil C and C/N ratio ($R=0.87$, $P<0.0001$) (data not shown), suggesting that C content of soils was the major determinant of C/P and N/P ratios.

Shrub species effect on C and N distribution observed in the current study stands in contrast to results of Wezel et al. (2000) who showed higher C and N enrichment in soils beneath *P. reticulatum* than beneath *G. senegalensis*. Possible differences could be shrub age differences between the two studies, the independent nature of the sampling between studies (different soil types), and the poor representation of *P. reticulatum* ($n=5$) compared with *G. senegalensis* ($n=82$) in the study of Wezel et al. (2000). These authors partly explained differences in soil enrichment by contrasting size of the plants they sampled to represent the two shrub species (taller *G. senegalensis* versus smaller *P. reticulatum*). In our study, however, no such a physical difference was noticed between the two shrub species. Since soil type (especially clay content) can greatly affect the amount of organic matter, it can be difficult to isolate a species effect for the study of Wezel et al. (2000) as they had five *P. reticulatum* reps spread over wide geographic area. In contrast to our study where we had one site with side by side replicated comparisons of these two species on the same soil type.

Although there is always the possibility that the “island of fertility” effect was due to soil properties that were pre-existing to shrub establishment this seems highly unlikely. First, the soils are sandy and organic C rapidly decreases in the absence of vegetation or organic input because of the tropical environment. Second, the same pattern in soil characteristics observed in the *regional sole species comparison* was confirmed in the *within site species comparison* where the two shrubs species occurred side by side but differed significantly in the characteristics of the soil beneath their canopies. In an unpublished study where we removed shrubs – we found after 2–3 years total C and N level were rapidly declining to levels similar to soil not influenced by shrubs.

Soil P fractions

Soils in our study have low total P compared with other tropical soils (Cross and Schlesinger 1995; Agbenin and Anumonye 2006), reflecting their highly weathered and low nutrient-level nature. These soils are in this respect similar to other West African soils (Nwoke et al. 2003; Kolawole et al. 2003). Total P was significantly ($P<0.0001$) higher in soils at Keur Matar than in soils at Nioro. Organic P represented approximately 40% and 50% of total P in Keur Matar and Nioro soils respectively. These proportions are similar to those reported for Brazilian Ferralsols and northern Guinean savanna soils of Nigeria (Lehmann et al. 2001; Agbenin and Anumonye 2006), and are consistent with the model that proportion of Po in soil increases along a weathering gradient (Cross and Schlesinger 1995; Stevenson and Cole 1999). The average percentage of residual P (17%) is considerably lower than values of >70% reported by Agbenin and Anumonye (2006), and suggests a relatively rapid cycling of P in our shrub ecosystems as indicated by the high proportion of (resin-P+bicarb-P+NaOH-Po) relative to total P (Table 1). However, the range of Resin-P (1–6 mg P kg^{-1}) is very low compared with critical ion-exchange resin membrane P of 13–19 mg P kg^{-1} proposed by Mallarino and Atia (2005) for optimal corn yield, and suggests acute P deficiency in soils of our study.

Under the shrub canopy (1R), the bicarb-Po fraction was significantly higher than in soils outside the canopy (3R) (Table 1). Such a difference probably reflects an intense dynamic of P under the shrub canopy owing to the greater C and N content, and high microbial activity that characterize soils under shrub canopy in arid and semiarid ecosystems (West 1991; Gallardo and Schlesinger 1995). The bicarb-Po is recognized as a Po fraction easily accessible to microbes, which contributes to immediate P need for plants (Hedley et al. 1982). This P fraction has been positively correlated with phosphatase activity, which controls Po mineralization in soils (Halm et al. 1972). Therefore the higher levels of this fraction under shrub canopy illustrate the ability of these shrubs to cycle and maintain biologically active P.

The largest P pool, represented by NaOH-P, is consistent with reported values of P fractions for other tropical soils (Lehmann et al. 2001; Solomon et al. 2002; Nwoke et al. 2003; Araújo et al. 2004). This P pool, which represents the inorganic and organic phosphates sorbed to amorphous and crystalline Fe and Al minerals, was more important in soils at Nioro than Keur Matar. This difference is most likely due to the greater abundance of Fe/Al that characterizes soils at Nioro as a result of its highly weathered nature (M Sene, personal communication).

The majority of Po was in the NaOH-Po fraction, which made up >50% of the total Po (Tables 1 and 2). Hydroxide-Po is generally considered as a slow release Po pool involved in intermediate to long-term P transformations. However, studies have shown it to be a source of P for plants in P-limited ecosystems (Adepetu and Corey 1976; Adepetu and Corey 1977; Stewart and Tiessen 1987; Beck and Sanchez 1994; Cross and Schlesinger 2001; Kolawole et al. 2003), and an indicator of P availability in highly weathered tropical soils (Beck and Sanchez 1994; Maroko et al. 1999). Biological turnover of Po depends on microbial activity, which tends to be limited by low and erratic moisture regimes of arid and semiarid environments (Whitford 2002).

The shrub species effect on P fractions was relatively small but significant. At the Nioro site, NaOH-Po was 52% higher under *P. reticulatum* than soil outside the canopy while soil under the canopy of *G. senegalensis* had 107% more bicarb-Po pool than soil outside the influence of the canopy. Plant species effect on P fractions has been shown to be influenced by soil properties (Chen et al. 2003). These results are indicative of contrasting P dynamics between the two shrub species. Under periodic pruning, *G. senegalensis* was shown to produce greater annual biomass than *P. reticulatum* but similar litter P content (Dossa 2007). Presumably, the intensified P cycling through *G. senegalensis* biomass may be driving conversion of P from intermediate or slow pools, most likely the NaOH-Po pool, to a more labile P pool. In soils of low labile P, as is the case in this study, microbes may use the NaOH-Po and convert it into a more plant-accessible form during biomass turnover (Chauhan et al. 1981).

The *within site species* effect was most striking in Nioro soils, which had lower total P and lower extractable P than Keur Mata soils. Phosphorus transformation in P-limited soils may also be related to the amount and composition of exudate secretion by roots (Marschner 2002; Chen et al. 2003; Agbenin and Anumonye 2006), which might differ between the two shrub species. The large proportion of organic P (40–50%) suggests that biological and geochemical processes are equally important in P cycling processes in soils of this study. Cross and Schlesinger (1995) proposed the ratio of (Bicarb-Po) / (Bicarb-Po+Bicar-Pi+Resin Pi) as an index of Po that can be mineralized through biological processes. In this study, the average values of 62% under shrub canopy and 59% outside shrub canopy are higher than values of this index reported for various soil orders with the exception of highly weathered Oxisols (Cross and Schlesinger 1995).

Conclusions and perspectives

The soils of our study had low total P reserves and were dominated by the NaOH-P fraction with organic P representing about half of the total P. The biologically available P index (Bicarb-Po) / (Bicarb-Po+Bicar-Pi+Resin Pi) was about 60%, suggesting high potential for biological P cycling in soils of these shrub ecosystems. However, the low resin-P and ($NaHCO_3$+NH_4F)-extractable P suggests acute P deficiency in soils of this study. Shrub species had a differential canopy effect with soils under the canopy of *G. senegalensis* having higher nutrient contents but lower pH levels than their counterparts under *P. reticulatum*. This pH effect may offset plant available forms of nutrients for *G. senegalensis* canopy soils.

The results provide further evidence that shrubs in semiarid environments create islands of fertility by concentrating nutrients and organic P pools under their canopies. Despite the extensive anthropogenic disturbance and wind/water erosion of the Sahel, we conclude that the presence of shrubs are a critical buffer for maintaining soil quality and control P cycling in these agroecosystems. Further research on microbial activity in relation to nutrient turnover would provide more insight on the ways these shrub species recycle nutrients and affect soil properties beneath their canopies.

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