

AN ABSTRACT OF THE DISSERTATION OF

Ekwe L. Dossa for the degree of Doctor of Philosophy in Soil Science presented on December 28, 2006.

Title: The Biogeochemistry of Nitrogen and Phosphorus Cycling in Native Shrub Ecosystems in Senegal

Abstract approved:

Richard P. Dick

Two native shrub species (*Piliostigma reticulatum* and *Guiera senegalensis*) are prominent vegetation components in farmers' fields in Senegal. However, their role in nutrient cycling and ecosystem function has largely been overlooked. A study including both laboratory and field experiments was conducted to evaluate potential biophysical interactions of the two shrub species with soils and crops in Senegal. Carbon (C), nitrogen (N) and phosphorus (P) mineralization potential of soils incubated with residues of the two shrubs species was studied in laboratory conditions. Additionally, the effect of shrub-residue amendment on P sorption by soils was examined. Under field conditions, the effect of presence or absence of shrubs on crop productivity and nutrient recycling in soil was investigated. Another study examined shrub species effect on spatial distribution of nutrients and P fractions.

Results showed shrub residues used as amendments immobilized N and P, which suggested these residues have limited value as immediate nutrient sources for crops. However, soils amended with shrub residues sorbed less P than unamended soils, indicating that when added to P-fixing soils, shrub residues could improve P availability to crops. In the absence of fertilization or when water was limiting, shrubs increased crop yield, likely through a combination of improved soil quality and water conditions associated with the shrub canopy and rhizosphere.

The presence of shrubs increased nutrient-use efficiency over sole crop systems. Shrubs were shown to create “islands of fertility” that had greater C, N and P concentrations under their canopies than in open areas. Shrubs differed in their ability to modify soil properties. *G. senegalensis* had higher soil C and N under its canopy and lower pH than *P. reticulatum*. Sequential extraction of P fractions showed that NaOH-P, most of which is organic P, was the dominant P fraction in the soils. These results showed that, in the Sahel, shrubs are important components of cropping systems that should be conserved and actively managed.

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The Biogeochemistry of Nitrogen and Phosphorus Cycling in Native Shrub
Ecosystems in Senegal

by
Ekwe L. Dossa

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Ekwe L. Dossa, Author

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CONTRIBUTION OF AUTHORS

Ekwe L Dossa conducted research, analyzed data and wrote each manuscript. Dr. Richard Dick assisted with research design, data analyses and reviewed each manuscript. Drs. Kouma Mamadou, Ibrahima Diedhiou, Fred Kizito, Modou Sene, Aminata Badiane and Ndiaye A. Samba were involved in research design and data collection for manuscript 1 and manuscript 2. Dr. John Baham was involved in research design, and review of manuscript 3. Dr. Jana Compton and Dr. Komi Assigbetse contributed to study design and were involved in data analysis of manuscript 4.

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The Biogeochemistry of Nitrogen and Phosphorus Cycling in Native Shrub Ecosystems in Senegal

CHAPTER 1

General Introduction

Senegal forms part of the Northern Guinean Savannah located in the transition zone between the Sahara desert to the North and the sub-humid savannas and woodlands to the South. Low and episodic rainfall, high solar radiation and strong winds are major climatic features of these semiarid ecosystems (Nicholson, 1989; Sivakumar et al., 1993). Natural resource degradation and desertification are major issues confronting most countries of sub-Saharan Africa (SSA). It is recognized that under low population pressure, land degradation and natural rehabilitation rates are balanced (Larson and Frisvold, 1996), which explains to some extent why such fragile ecosystems of SSA have survived for a long time. However, due mainly to increased human and livestock pressure, the natural regulating mechanisms are not able to cope with emerging problems (Dreschsel et al., 2001). Consequently, there is increasing soil degradation and decreasing ecosystem productivity in SSA. To alleviate soil degradation and to improve long-term sustainability of agroecosystems of SSA, farmer-centered practices compatible with natural resource preservation need to be promoted.

Under current rainfall regimes prevailing in SSA, nitrogen (N) and phosphorus (P) are recognized as the major elements that limit crop production (Schlecht et al., 2006). This nutrient limitation to crop productivity is aggravated by the physical characteristics of soils; they are very sandy, low in organic matter (OM) with a clay fraction constituted of low-activity clay with limited exchange and nutrient storage capacity (Bationo and Buerkert, 2001). While low N content of soils is linked to low soil organic matter, low P is generally attributed to geochemical control of P

availability by Al and Fe oxides, abundant in highly weathered soils (Parfitt, 1978). The low P availability may further limit C and thus N cycling in these ecosystems (Vitousek and Howarth, 1991).

Traditionally, farmers have coped with low nutrient soils in SSA by means of fallowing (Floret and Pontanier, 1993). Mechanisms contributing to soil fertility restoration during fallow include maintenance of a protective vegetation cover, replenishment of soil chemical composition through litter fall and decomposition, and increase of soil organic matter. However, recent increase in human and animal pressure on land led to suppression of fallow. Meanwhile, numerous studies have been conducted on management strategies to maintain productivity and/or improve fertility of soils. The limited rate of adoption owing to socio-economic constraints (Bationo et al., 1998) suggests that management strategies based on indigenous practices should be given priority in order to improve probability of impact at a landscape level.

In the semi-arid and sub-humid zones of West Africa, the traditional agroforestry referred to as “parklands” systems (Pullan, 1974; Sall, 1996) is an adaptative agricultural practice to environmental degradation. In such a cropping system, farmers allow selected trees to grow in crop fields. Trees in parklands reflect farmers’ basic needs including fuel wood, fodder, medicinal products but also soil fertility maintenance. Considerable attention has been devoted to the role of trees in parkland systems. For example, improved soil physicochemical properties and higher crop yields beneath the tree canopy compared to areas outside the canopy have been reported in *Faidherbia albida* parkland systems (Depommier et al., 1992). Similar but less remarkable effects are observed under other parkland trees such as *Cordia pinnata*, *Vitellaria paradoxa*, *Parkia biglobosa* (Kater et al., 1992; Samba, 1997).

One other important vegetative component in parklands in Senegal is the shrub components. Two native perennial species (*Guiera senegalensis* and *Piliostigma reticulatum*) dominate the shrub vegetation. Indigenous knowledge associates the shrubs with improved soil conditions and crop yields. However, there is virtually no information regarding the biophysical contribution of these shrubs to nutrient cycling and ecosystem function. Shrub invasion in arid and semiarid ecosystems has been

attributed to human-induced climatic and land use changes (Brown and Archer, 1989; Polley et al., 1994; Whitford, 2002). Shrubs also have been recognized to impart a spatial heterogeneity to nutrient distribution in arid and semiarid environments (Kieft et al., 1998). Several factors contribute to such patchiness. In areas subject to eolian erosion, shrubs maintain existing soil and trap wind-blown sediment and organic matter. By taking up nutrients and recycling them through litterfall and decomposition, shrubs contribute to a site-enrichment of their vicinity (Garner and Steinberger, 1989). As a result, higher C and N are commonly found under shrub canopy compared to soils in the open (Kieft et al., 1998). In addition, the shrub canopy and litter accumulated modify soil water and temperature, and create a favorable condition that benefits microbial activity (Gallardo and Schlesinger, 1995). These improved site conditions are also refuge to many small animals, which, by their excreta further enhance nutrient cycling under the shrubs (Whitford, 2002).

Nutrient cycling is an important process in the survival of semiarid ecosystem communities characterized by low soil quality (Vitousek, 1982), and decomposition and mineralization of litter are key components of the biogeochemical cycle of nutrients. In these ecosystems, water paucity exerts a significant limitation over the decomposition process. However, this is compensated by more active and extended activity of soil mesofauna and macrofauna, which are very active in litter comminution in arid environments (West, 1991). Moreover, common litter attributes that are known to control litter decomposition and nutrient mineralization in mexic environments may not necessarily apply in xeric environments. High wax, saponin and phenolics content characteristic of leaf of woody species in arid and semiarid environments exert significant influence over mineralization processes (Whitford, 2002). Particular to some arid environments is the photooxidation of lignin and complex molecules, which partly explains the relatively faster decomposition of OM reported in some arid ecosystems (Schaefer et al., 1985). Horizontal heterogeneity in nutrient distribution and hydrological properties associated with the presence of shrubs are distinctive features that may influence the overall rate of decomposition of litter and nutrient cycling in arid and semiarid environments.

By concentrating OM under their canopies, shrubs certainly influence cycling and availability of essential nutrients such as N and P. This is of a greater importance in semiarid sub-sahelian soils, mostly sandy with low cation exchange capacity. In absence of N fixation, OM acts as the primary source and sink of N within the soil-plant system. In highly weathered soils and P-limited soils as those of SSA, OM plays a crucial role in supplying most of soil solution P. Apart from P mineralized from OM, complexation reactions of organic acids released by the organic matter with Al and Fe, and competition from organic anions for sorption sites are major mechanisms that contribute to increased solution P (Iyamuremye and Dick, 1996). Consequently, it has been suggested that return of organic residues to soil would improve nutrient availability, particularly P, in nutrient deficient SSA soils.

With regard to their biophysical characteristics, shrublands in tropical environments have received little attention relative to their counterparts in temperate regions. The purpose of this thesis is to examine nutrient cycling, mainly N and P, and biogeochemical characteristics of *P. reticulatum* and *G. senegalensis* shrublands in semiarid Senegal. This thesis is composed of four main parts. Chapter 2 evaluates the potential of shrub residues to provide N and P to the crop. Nutrients mineralized in soils amended with shrub parts, manure, and unamended soils were compared in laboratory conditions. Chapter 3 compares in field conditions, crop productivity, N, P cycling and nutrient use efficiency in presence or absence of shrubs under different rates of mineral fertilizer. Chapter 4 assesses the geochemistry of P in soil incubated with various shrub residues. Phosphorus sorption and desorption were evaluated in a batch experiment method. Chapter 5 characterizes shrub-induced changes in spatial distribution and forms of nutrients. Nutrient patterns and the biogeochemical fractions of P were examined in a gradient across the shrub canopy. Inorganic and organic fractions of P were extracted and compared in soils beneath and outside shrub cover. Shrub species effect on these soil properties also was examined.

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CHAPTER 2

Carbon, nitrogen and phosphorus mineralization in soils incubated with native shrub residues in semiarid Senegal

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Abstract

Two native shrubs (*Piliostigma reticulatum* and *Guiera senegalensis*) are commonly found in farmers' fields in parkland systems in Senegal, but their role in nutrient cycling is not well understood. We investigated carbon (C), nitrogen (N) and phosphorus (P) mineralization of soils collected beneath and outside the canopy of *P. reticulatum* and *G. senegalensis*, which were amended with shrub leaf, shrub leaf+stem, and beef manure. Soils from each shrub species were incubated at 30°C for 118 days in two parallel incubations; CO₂ evolved, and mineral N, P leached from soils with a 0.01M CaCl₂ solution were monitored periodically. Cumulative CO₂ evolution for *P. reticulatum* leaf amendment was initially high but fell to levels similar to that of leaf+stem mixture by the end of the experiment. In contrast, *G. senegalensis* residues evolved CO₂ at similar rates throughout the incubation period. All soils amended with *P. reticulatum* and *G. senegalensis* residues immobilized N during the first 62 and 76 days of incubation, respectively, but later released inorganic N in solution. The addition of stem to leaf amendment in both shrub species resulted in net N immobilization throughout the 118 days of incubation. Manure significantly released inorganic P in solution but all the other amendments immobilized P. Cumulative C, N and P mineralized at the end of incubation were higher under canopy than outside canopy of shrubs, however, P in *G. senegalensis* soils showed an inverted trend. Our results suggest that none of these shrub residues would improve short-term nutrient availability to crops. Additional mineral fertilizer adjustment would be required for optimal crop yield when applying these shrub residues as mulch.

2.1. Introduction

In the arid and semiarid Sudano Sahelian zones, soils are inherently of low fertility (Bationo and Buerkert, 2001), and high agricultural and livestock pressure on lands with shortening fallows contribute to significant loss of organic matter and depletion of nutrient in these soils (Sanchez et al., 1997). Organic matter input to the soil in conjunction with optimal use of mineral fertilizer is expected to significantly improve crop productivity and restore soil fertility in these degraded agroecosystems (Woomer et al., 1994; Sanchez et al., 1997; Badiane et al., 2000; Sinaj et al., 2001; Tschakert et al., 2004).

Residue management through agroforestry has been suggested as a promising technique to control soil degradation and sustain crop yield (Young, 1997; Lal, 2002) and at landscape levels can have much greater potential to provide significant organic carbon (C) inputs. In many countries, the most common agroforestry system is the parkland system where trees or woody shrubs are randomly allowed to grow in crop fields. Parkland systems of *Faidherbia albida* (Del. A. Chev.) and other species have been reported in West Africa (Samba, 1997) and extensively studied for their potential positive effects on soils and crop productivity (Young, 1997; Rhoades, 1997; Buresh and Tian, 1998) but with limited success of adoption by farmers (Rhoades, 1997; Buresh and Tian, 1998).

However, largely overlooked components of parkland systems in semi-arid sub-Saharan Africa are two native and dominant shrubs, *Piliostigma reticulatum* and *Guiera senegalensis*. These shrubs are commonly found in farmers' fields in Senegal (M. Sene and R. Dick, personal communication) but their role in nutrient cycling and ecosystem function is not well understood. Traditional management of these shrubs includes pruning at the soil surface and burning of shrub residues at the beginning of each cropping season (Diack et al., 2000). Non-thermal management of these organic materials holds potential to add organic matter to soils and thus improve soil quality and be a source of nutrients such as nitrogen (N) and sulfur which are partly lost during burning, or phosphorus (P) which is

geochemically controlled in many arid and semiarid soils (Cross and Schlesinger, 2001).

Litter decomposition and concomitant nutrient release is regulated by chemical composition of the litter (Oglesby and Fownes, 1992) as well as abiotic factors, mesofauna and microbial actions (Li et al., 2001). Although the C/N ratio or N-related indices of residues have often been found to be the major factors of decomposition processes (Jarvis et al., 1996; Kemp et al., 2003), they are not the only determinants. Other factors such as lignin, cellulose, polyphenolic and tannin content of the litter also affect nutrient release dynamics during decomposition (Palm and Sanchez, 1991; Bernhard-Reversat, 1998; Mafongoya and Nair, 1997).

Shrubs in arid and semi-arid environments create a spatial heterogeneity in resources, which affects nutrient cycling and redistribution (Van Miegroet et al., 2000). In these environments, soils beneath the canopy of shrubs have higher C and N than soils outside the canopy (Kieft et al., 1998). In addition, the improved water balance and microclimate under the shrub create a favorable environment for biological activity (Gallardo and Schlesinger 1995). The better soil quality under shrub canopy may further stimulate mineralization and cycling of nutrients (West, 1991). As a first step towards understanding the ecology and effective management of *G. senegalensis* and *P. reticulatum* that coexist in farmers' fields, the ability of residues (leaves and stems) to release nutrients needs to be investigated. Preliminary results on decomposition rate suggest that *P. reticulatum* might be a good material for mulch (Diack et al., 2000; Iyamuremye et al., 2000). However, there is very little information on the mechanisms of decomposition and nutrient release patterns of residues from *P. reticulatum* and *G. senegalensis* and how soil beneath shrub canopy may influence this process.

The objective of this study was to determine C, N and P mineralization potential of native shrubs residues (*P. reticulatum* and *G. senegalensis*) incubated with soils collected beneath and outside shrub canopy under laboratory conditions.

2.2. Materials and Methods

2.2.1. Study site

Soils used in the incubation study were collected from two sites. The first site (Keur Mata Arame) is located in the northern region of the Peanut Basin (14°45 N, 16°51 W, and 43 m above sea level). The mean annual precipitation is 450 mm. Temperatures range from 20.33°C in December-January to 33.4°C in April-June. The soil is 95% sand, mainly constituted of materials from eolian deposits, classified as leached ferric lixisol (FAO, 1991), locally referred to as a Dior soil (Badiane et al., 2000). *G. senegalensis* is the dominant shrub vegetation. Shrub stand density at the site is about 240 shrubs ha⁻¹. 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, 1991)], a leached ferruginous tropical soil. The dominant shrub species at the site is *P. reticulatum* with stand density of 185 shrubs ha⁻¹.

2.2.2. Soil, shrub materials sampling and experimental design

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 (A. Lufafa, personal communication), were randomly selected for soil and shrub biomass sampling. Each shrub was treated as a replicate. This spatial replication was maintained for subsequent laboratory incubations. In January 2003 during the dry season, soil was collected from a 0-30 cm depth at ten random locations beneath (approximately 1 m radius from the shrub stem) and outside the influence of shrub canopy (2-3 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 to pass a 2-mm screen prior to chemical analysis and laboratory incubation. The shrub residues were collected in January 2003 when shrubs were approximately 1.5 m tall. 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 until subsequently used in the soil amendment treatments.

The experimental design was a randomized 2 by 4 factorial design for each shrub type with two soil sources (beneath or outside the shrub canopy) and four residue treatments [leaf, leaf+stem in same proportion as found under field conditions, composted beef manure or control of soil only]. There were four replications maintained from the field replication soil sampling of the four shrubs. The residue treatments reflect possible management options of farmers. Leaf alone which represents the case where coppiced material is dried in the field and stems are stripped of leaf material and removed from fields for fencing or fuel; or when all coppiced materials are non-thermally managed and left in the fields (leaf+stem). Each shrub species was incubated with its associated soil, i.e., *G. senegalensis* residues with soils from site 1 and *P. reticulatum* residues with soils from site 2.

2.2.3. C, N and P mineralization

The C mineralization experiment was carried out according to the static method of Zibilske (1994). Fifty grams of soil were thoroughly mixed with 0.35 g of organic residues (leaf, leaf+stem of shrubs species and beef manure) and transferred into a 1 L glass jar. The relative mass of leaves and stems in the leaf+stem mixture was 40% and 60%, respectively. The rate of residues added to soils was selected to reflect typical field shrub residue rates. Soils were wetted to 2/3s field capacity and jars tightly closed and incubated at 30°C for 118 days. A hole drilled in the lid of the jar was fitted with a rubber septum to allow for gas sampling. Carbon dioxide (CO₂) evolved was sampled after 1, 2, 3, 7, 14, 21, 28, 35, 49, 63, 77, 91, 105 and 118 days and analyzed on a gas chromatograph; cumulative CO₂ was calculated for each sampling date as mg CO₂-C per g of soil. After each sampling, jars were opened and aerated for approximately one hour before resuming incubation, and soil moisture was adjusted gravimetrically.

The N and P mineralization study was conducted on the same soils and shrub residue as those used in the C mineralization study according to the Stanford and Smith (1972) method with a slight modification. Thirty grams of soil mixed with 0.21 g of organic amendment were transferred into a leaching tube with the bottom packed with a glass wool pad to retain the soil. A thin glass wool pad was placed over the soil to minimize dispersion during leaching. Initial N and P were removed by leaching dry soils mixed with the different amendments with 30 ml of 0.01 M CaCl₂ solution in three increments followed by 20 ml of a nutrient solution devoid of N and P (0.004 M CaCl₂; 0.002 M CaSO₄, 0.002 M MgSO₄, 0.0025 M K₂SO₄). Excess water was removed under vacuum (600 MPa). This leaching procedure was repeated at each sampling date. The tubes were capped with parafilm with a small hole in the center of the parafilm to ascertain adequate aeration, and incubated in the dark at 30°C for 118 days. Samples were leached after 10, 20, 34, 48, 62, 76, 90, 104 and 118 days. Mineral N in the leachates was analyzed as NO₃⁻-N and NH₄⁺-N by steam distillation (Bremner and Keeney, 1965), and ortho-P was determined by the colorimetric molybdenum-blue method (Murphy and Riley, 1962).

2.2.4. Soil and plant analysis

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, Missouri). Total N in soils and organic residues was determined by Kjeldahl digestion followed by steam distillation according to Bremner and Mulvaney (1982). Total P in plant residues and soils was determined by a modified Kjeldahl Li₂SO₄-H₂SO₄ procedure (Parkinson and Allen, 1975). Lignin, cellulose and hemicellulose were determined by the method of Goering and Van Soest (1970). For polyphenol determination, samples were hot-water extracted (Valachovic et al., 2004). Total polyphenol was determined in the diluted hot water extracts with the Folin-Ciocalteu reagent as described by Ohno and First (1998) using tannic acid as standards. Reactive polyphenols were estimated as the polyphenols precipitated by

shaking the diluted hot water extract samples with Sigma purified casein (Valachovic et al., 2004).

2.2.5. Kinetic models and statistics

Potentially mineralizable C, N, P and their mineralization kinetics were fitted with a single exponential model or a zero order model using SAS statistical package (SAS Institute, 1999). The exponential first order kinetics model was of the form:

$$X_m = X_0 [1 - \exp (-k_1t)] \quad (1)$$

where X_m = Cumulative amount of C,N or P mineralized, X_0 = potentially mineralizable C,N or P, k_1 = mineralization rate (day^{-1}) t = time of incubation (days).

The zero order model was as follows:

$$X_m = B_0 + k_2t \quad (2)$$

where B_0 is the intercept and k_2 the slope.

Statistical analysis was conducted separately for each shrub and associated soil. A pairwise t-test was performed to examine the influence of soil location (beneath and outside shrub canopy) on C, N and P mineralization. Organic residue incorporation effect was analyzed as a split-plot design using SAS PROC MIXED (SAS Institute, 1999), with soil location treatments (beneath or outside shrub canopy) as the main plot factor and residue amendments as the subplot factor. Blocking criterion was treated as random. Square root transformations were required to normalize variances for NO_3^- -N and NH_4^+ -N data. The ANOVA was performed on both original scale and square root transformed data. Although the residuals were improved, particularly for the analysis on day10, the P values were similar and conclusions were the same for analysis carried out on each sampling date. Therefore, P values from the original scale are reported in the results. Tukey multiple comparison adjustment was used to determine pairwise differences among treatments within each sampling date. Simple correlation procedure PROC CORR (SAS, 1999) was used to examine relationships between shrub residue quality and C, N mineralization rates.

2.3. Results

2.3.1. Chemical composition of soil and plant materials

Carbon, N and P contents of soils used in this experiment showed higher levels beneath the shrub canopy than outside the canopy, except P in the *G. senegalensis* soils, which had an inverse trend (Table 2.1). Nitrogen and P contents of leaf material was higher than the corresponding contents in leaf+stem mixture for both shrub species. Lignin content was similar in leaf and leaf+stem mixture of *P. reticulatum*, whereas *G. senegalensis* had higher lignin content in leaf+stem than in leaf materials (18.1% and 10.3% respectively) (Table 2.2). For all shrub residues, cellulose content was higher in leaf+stem mixtures than in leaf alone, but hemicellulose concentration was similar in all shrub parts. Total polyphenols content ranged from 3.9 to 7.3% and was lower in leaf than in leaf+stem residues of *G. senegalensis*, whereas in *P. reticulatum*, leaf+stem mixture had higher level of polyphenols than leaf material.

2.3.2. Carbon mineralization

Results of CO₂ evolution with time are shown in Fig. 2.1. A flush of CO₂ evolution occurred during the first week of incubation for all amended soils followed by a steady decrease in mineralization rates until the end of the incubation experiment. All amended soils released significantly more CO₂ than did the unamended soils ($P < 0.001$). In *P. reticulatum*-amended soils, leaf material had the highest CO₂ evolution from day 1 to day 90 of incubation whereas leaf+stem and manure-amended soils evolved CO₂ at similar rates until day 52 of incubation (Figs. 2.1A and 2.1B). Thereafter, manure and leaf treatments mineralized C at lower rates than leaf+stem amendment such that, by the end of the incubation, the order of cumulative CO₂ released was as follows, leaf = leaf+stem > manure > control. In *G. senegalensis*-amended soils, leaf, leaf+stem and manure evolved CO₂ at similar rates and had statistically equivalent cumulative CO₂ levels at the end of the incubation (Figs. 2.1C and 2.1D). Assuming no or negligible priming effect, net C mineralized at day 118 as a result of organic amendments varied from 55% of C added by manure to 81% of C added by leaf+stem in *P. reticulatum*-amended soils. For *G. senegalensis* residues, net

C mineralized accounted for 46% of the C added by manure and 59% of the C added by leaf+stem. For both shrub species, the patterns of C mineralization were similar in soils collected beneath and outside the shrub canopy but cumulative CO₂ evolved at the end of the incubation period was significantly higher ($P < 0.05$) in all treatments for soils beneath shrub canopy than their counterparts for soils outside the canopy.

2.3.3. Net N mineralization

Initial N leached from soils mixed with the different organic residues was relatively low (Table 2.3). In the *P. reticulatum* residue-amended soils, the initial inorganic N levels were comparable in all treatments. For *G. senegalensis* soils, leaf- and leaf+stem-amended soils had significantly higher ($P < 0.001$) levels of inorganic N than manure-amended soils and the control, and soils beneath the canopy had higher levels ($P < 0.05$) of inorganic N than soils outside shrub canopy. Inorganic N leached out of soils during the incubation period was mainly nitrate. Ammonium was detected only in leachates of the first week of incubation (data not shown).

Inorganic N leached from soils was highest for unamended soils throughout the incubation period in both the *P. reticulatum* (Figs. 2.2A and 2.2B) and the *G. senegalensis* residue-amended soils (Figs. 2.2C and 2.2D). Irrespective of soil location, all residue-amended soils immobilized N for some time during the experiment, and leaf+stem mixture showed the highest and longest immobilization.

In *P. reticulatum* residue-amended soils (Figs. 2.2A and 2.2B), net inorganic N mineralization occurred from day 62 in leaf and manure-amended soils while leaf+stem mixture exhibited N immobilization for the duration of the incubation. At the end of the experiment, amounts of cumulative N were lowest for leaf+stem ($P < 0.001$) and statistically identical for the other treatments although the control had higher cumulative N than manure and leaf-amended soils beneath the shrub canopy (Fig. 2.2A). In the *G. senegalensis* residue-amended soils, however, a more delayed net inorganic N release was observed from day 76 – day 90 with manure and leaf residue-treated soils while leaf+stem exhibited N immobilization for the entire duration of the experiment (Figs. 2.2C and 2.2D). In the *G. senegalensis* residue-

amended soils, cumulative N mineralized by the end of the incubation was in the order control = manure > leaf > leaf+stem ($P < 0.001$) in both soil beneath and outside shrub canopy.

In general, the control soils showed their highest mineralization rates at the beginning of the incubation followed by a steady decline and leveling off around day 34 - day 48. The inverse pattern was observed with amended soils, which had lowest rates in early stages of the experiment and a gradual rise as the incubation progressed (data not shown). At the end of the experiment, soils beneath canopy had higher cumulative inorganic N than soils outside the canopy ($P < 0.06$).

2.3.4. Net P mineralization

For both species, leaf material released high levels of P at time zero (Table 2.3) that were in the range of total P released by shrub residues over the incubation period. Manure-amended soils had the highest rate of P mineralization throughout the 118 day of incubation. In *P. reticulatum* soils, leaf-amended soils released the smallest amount of P in soil beneath canopy (Fig. 2.3A) and leaf+stem released slightly (but not significantly) more P than the control during the first 62 days of incubation. Outside shrub canopy, the different amendments resulted in levels of leached P similar to that of the control (Fig. 2.3B). Cumulative P at the end of the incubation period was higher in soils beneath shrub canopy than in soils from outside the canopy ($P < 0.01$). In the *G. senegalensis* soils, apart from manure-amended soils, all treatments immobilized P relative to the control (Figs. 2.3C and 2.3D). Leaf+stem tended to release less P than leaf treatment; however, these differences were not significant. As opposed to *P. reticulatum* residues-amended soils and to trends seen with C and N mineralization, soils from outside shrub canopy released more P than soils from beneath shrub canopy ($P < 0.01$).

2.3.5. Mineralization kinetics

The first-order kinetic model provided a good fit to C mineralization data with $R^2 > 97\%$ (Table 2.4). For *P. reticulatum* soils, the first-order rate constants varied

from 0.007 day⁻¹ for leaf+stem-amended soils outside shrub canopy to 0.034 day⁻¹ for leaf-amended soils beneath shrub canopy. In *G. senegalensis* soils, these rates fell in the range of 0.003 day⁻¹ for the control, to 0.013 day⁻¹ for leaf+stem-amended soils outside the canopy (Table 2.4).

For P mineralization modeling, all treatments in both *G. senegalensis* and *P. reticulatum* residue-amended soils fit the linear zero order model (data not shown). For *P. reticulatum* soils, P mineralization rates were higher for all treatments beneath shrub canopy compared to their counterparts outside shrub canopy. The zero-order rate constants ranged from 0.002 for leaf+stem outside shrub canopy to 0.075 for manure-amended soils beneath the shrub canopy. In *G. senegalensis* soils, kinetics of P mineralization in relation to soil location was reversed comparatively to trends seen with *P. reticulatum* soils. Soils from outside shrub canopy had the highest rates in all treatments with rate constant values between 0.015 and 0.05. Model fitting for N mineralization did not yield satisfactory results (low R² and lack of convergence, data not shown). However, the unamended soils fitted a first-order kinetics model with rate constants of 0.016 day⁻¹ and 0.007 day⁻¹ respectively beneath and outside the canopy of *P. reticulatum*. In the *G. senegalensis* soils, the kinetic rates were 0.009 day⁻¹ beneath canopy and 0.012 day⁻¹ outside shrub canopy.

2.4. Discussion

2.4.1. Residue source, type and C mineralization

We used CO₂ release during incubation to assess C mineralization of different residues added to soils. Rates reported in the present study may not reflect true rates occurring in field conditions owing to physical alteration of residues through grinding, incubation under optimal temperature and moisture conditions, restriction of decomposer community and disturbance of soil structure associated with laboratory incubation procedures (Diack et al., 2000; Li et al., 2001). Nonetheless, these standardized conditions are useful and provide meaningful information in comparing mineralization potential of litters of varying characteristics intended to be used as soil amendments (Li et al., 2001).

The pattern of C mineralization differed for the sources and type of residues used in this incubation study. A three-phase pattern was observed with leaf and manure amendments in the *P. reticulatum* soils. These segments of the mineralization curve are generally associated with varying C qualities. The flush observed in the first days of incubation may be associated with an increase in easily degradable compounds such as sugars, starch (Bernhard-Reversat, 1998) subsequent to disturbance, drying and wetting of soil (Jarvis et al., 1996) in establishing the incubation. Second- and third-stage decomposition phases represent increasingly difficult-to-degrade materials. The addition of stem material to leaf of *P. reticulatum* reduced the short term C mineralization rate and probably delayed the occurrence of the third segment of the curve, which did not appear for the duration of the experiment. However, by the end of the incubation, cumulative CO₂ evolution in leaf+stem-amended soils was slightly higher than that of leaf as a result of the higher C mineralization rate from day 49 of incubation. Diack et al. (2000) reported a higher decomposition rate of stem of *P. reticulatum* compared to leaf of the species, which they attributed to the high concentration of fructose in the stem. In *G. senegalensis* residue-amended soils, however, decomposition rates were similar for all organic residues added to soils.

Rates of CO₂ release at different stages of mineralization were correlated with different litter quality indices. The initial CO₂ rate was correlated with N content of residues ($r = 0.54$, $P < 0.001$) but also with lignin/N ratio ($r = -0.50$, $P < 0.003$) and cellulose ($r = -0.48$, $P < 0.004$). At later stages of C mineralization, reactive polyphenols ($r = 0.41$, $P < 0.01$) or (total polyphenols)/ N ($r = 0.41$, $P < 0.01$) best explained C mineralization rates (Table 2.5). While the effect of lignin and N contents of litter conforms to data from the literature (Melillo et al., 1982; Vanlauwe et al., 1996), the positive correlation of total polyphenols and (total polyphenols)/N ratio with C mineralization contradict observations by other authors that polyphenolic compounds inhibit decomposition (Palm and Sanchez, 1991; Constantinides and Fownes, 1993). However, Valachovic et al. (2004) reported a similar finding in a study on tree and woody species of the Pacific Northwest. Similarly, Bernhard-Reversat et al. (2003) observed a fast disappearance of soluble phenolic compounds in

eucalyptus leaf litter. This suggests that the effect of polyphenols on C decomposition is variable and may depend on plant species (Heal et al., 1978) and fraction of polyphenols involved.

Rates of C mineralization in this study are comparable to those of tropical woodland savanna species (Mtambanengwe and Kirchmann, 1995) but are higher than rates reported by Iyamuremye et al. (2000) in an incubation study in similar soil conditions. The lower incubation temperature used in the latter study (25°C versus 30°C in the present study) might partly explain these discrepancies.

Cumulative evolution of CO₂ in soil amended with the different residues was well described by a single exponential model ($R^2 > 96\%$) (Table 2.4). Many researchers, however, have fitted C mineralization data with a double exponential model to account for labile and stable pools of organic matter (Franzluebbers et al., 1994; Kaboneka et al., 1997). Such a model resulted in a poor fit to our data and/or generated parameter values that were out of range and were not meaningful in interpreting the CO₂ data.

2.4.2. Nitrogen and P mineralization

Nitrate was the dominant form of inorganic N leached out of soils during this incubation study, presumably as a result of soil pH (~6) and a possible rise of pH during incubation of amended soils (Diallo, 2005). At these pH values, activity of nitrifiers in soils might be important. These findings are in agreement with those of Iyamuremye et al. (2000) who found that NO₃⁻-N was the dominant form of N in soils incubated with various organic residues in Senegal.

All amended soils immobilized N but the length of the immobilization period varied for shrub-soil types. In *P. reticulatum* soils, net N mineralization occurred from day 62 of incubation while in *G. senegalensis* soils, it was delayed until day 76 - day 90. Mineralization and immobilization are concomitant reactions in soils during microbial decomposition of litter; the net effect reflects residue quality (Palm and Sanchez, 1991; Constantinides and Fownes, 1993; Lehmann et al., 1995; Schwendener et al., 2005).

Several litter characteristics explained differences in N mineralization rates observed throughout the incubation period. At day 10, rate of N mineralization was negatively correlated with lignin ($r = -0.36$, $P < 0.04$) and hemicellulose ($r = -0.34$, $P < 0.06$) while at advanced stages, rate of N mineralization was best correlated with initial N content of litter ($r = 0.57$, $P < 0.001$), and, to a lesser extent, with cellulose, C/N ratio, lignin/N ($r = -0.55$, $r = -0.53$, $r = -0.52$ respectively). These results follow findings of Vityakon and Dangthaisong (2005) who showed that N content of litter was the major determinant of N mineralization. The negative correlation of lignin/N with N mineralization rate has also been reported in other studies (Melillo et al., 1982; Maithani et al., 1998; Vityakon and Dangthaisong, 2005).

Our results indicate an inhibition of N mineralization by addition of stems to leaf materials probably owing to the high C/N and high lignin/N ratios of the leaf+stem mixture in the two shrub species. Similar results were obtained by Constantinides and Fownes (1993) who reported that stem material in green manure-amended soils reduced short-term N mineralization. As in other studies (Constantinides and Fownes, 1993; Mtambanengwe and Kirchmann, 1995; Iyamuremye et al., 2000), N mineralization was not successfully modeled in this incubation study and denotes the difficulty in fitting N mineralization pattern of residues undergoing immobilization.

Phosphorus mineralization followed a different pattern than was observed for N. For both *P. reticulatum* and *G. senegalensis* soils, manure-amended soils significantly released the highest P in solution ($P < 0.001$). All the other treatments immobilized P or had near zero P mineralization, with leaf+stem mixture in soils beneath canopy of *P. reticulatum* showing slightly higher solution P, which was not significantly different from the unamended soils in the first 34 days of incubation. However, when accounting for P leached from soils at day 0, cumulative P released with shrub leaf-amended soils ranged from 0.67 to 1.44 mg P kg⁻¹ and was always higher than total P leached from unamended soils (0.41 to 0.83 mg P kg⁻¹). Likewise, some tropical plant species litters have been associated with significant initial P release when they are incorporated to the soil (Kwabiah et al., 2003). Such a result

was explained by the relatively high water-soluble P content in the plant materials studied.

It is noteworthy that P measured in solution during this incubation experiment does not reflect the true residue P mineralization that would be associated with microbial decomposition alone. Rather, it represents the mineralized P in excess of that which is sorbed on surfaces of soil minerals or biologically immobilized (Sharpley and Smith, 1989; Iyamuremye et al., 2000). These results are expected based on the suggestion that residues with $C/P \leq 200$ would mineralize P while higher values of this ratio (≥ 300) would result in net immobilization (Sharpley and Smith, 1989; Stevenson and Cole, 1999). However, the near zero P mineralization of leaf+stem mixture with $C/P = 502$ in the *P. reticulatum* soils, although not significant, deviated from that rule and may be explained by the chemical composition of this particular material which interacted with the mineral soil either to desorb native soil P or to limit sorption of mineralized P from decomposing residues onto the mineral soil.

Our results are contrary to findings of Iyamuremye et al. (2000) who obtained net P mineralization with *P. reticulatum* leaves and stem incubated with soils collected from beneath and outside canopy of *Cordyla pinnata* tree species in Senegal. This difference in findings may be due to residue quality and soil type interactions. The greater P leaching from soils collected outside canopy of *G. senegalensis* than that from soils beneath the canopy was not expected. As seen in the *P. reticulatum* soils, we anticipated that more labile P would characterize soils from beneath shrub canopy because of the higher C and N and the more intense microbial activity usually associated with these soils in arid and semiarid environments (Gallardo and Schlesinger 1995; Kieft et al., 1998). Our results are similar to findings of Krämer and Green (1999) in a juniper microsite study, but are in contrast to other studies where higher P contents have been reported in soils beneath woody species canopies than outside the canopy (Samba, 1997; Iyamuremye et al., 2000). This trend with P mineralization in the *G. senegalensis* soils may be related to the slightly higher initial P content of soils collected outside the canopy (93 mg P kg^{-1}) compared to soils from beneath canopy (89 mg P kg^{-1}). In our study, one should not rule out the possibility

that animals deposit manure preferentially in the outer canopy of shrub when they graze on shrub foliage during the dry season. Moreover, soil excavation by burrowing rodents localized under shrub canopies is very common in the *G. senegalensis* site. Such a disturbance by animals referred to as “biopedturbation” has been reported as a major source of patchiness in arid systems (Whitford and Kay, 1999) and might have contributed to the trend seen with P.

2.5. Conclusions and Perspectives

In this incubation study, shrub residues showed different patterns of mineralization. Leaf residue of *P. reticulatum* evolved more cumulative CO₂ than leaf+stem mixture until day 76 of incubation but had similar cumulative CO₂ at the end of the incubation, whereas *G. senegalensis* residues evolved relatively less CO₂ and had similar rates of mineralization for the duration of the incubation. Regardless of the amendment or shrub species, soil beneath the canopies had greater C mineralization potential. This suggests there was greater microbial or active biomass inside than outside the canopy. All organic amendments showed some N immobilization. Release of N into the soil solution started from day 62 with *P. reticulatum* residues and later (day 76- day 90) with *G. senegalensis* residues. The addition of stem material to leaf resulted in N immobilization during the 118-day incubation. The different organic amendments did not prove to increase P level in soil leachates. These results suggest that shrub residues in the quality compared in this incubation study, when incorporated to soil, would not be effective in supplying the immediate nutrient needs of the crops. Our findings suggest that mineral fertilizer associated with organic amendment is needed to sustain optimal productivity in cropped Sahelian ecosystems (Woomer et al., 1994; Sanchez et al., 1997; Sinaj et al., 2001). Addition of these residues or organic matter may be important for reasons other than immediate nutrient supply. Increased soil organic matter would likely result in increased cation exchange capacity and, therefore, nutrient storage capabilities and improved soil structure for better water relations of these sandy soils. These ancillary properties could be important for optimal crop productivity. Given that some

treatments showed trends of net N release late in the course of the incubation, a study with a more prolonged incubation time alternating between dry and wet periods to reproduce field conditions would provide some useful insights on the long-term dynamics and mechanism of nutrient mineralization in soil amended with these shrub residues.

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Table 2.1. Selected characteristics of 0-30 cm-depth soils used in the incubation study (n = 4).

Soil location	Total C	Total N	Total P	pH
	-----g kg ⁻¹ -----	-----	mg kg ⁻¹	
	<u>Nioro (<i>P. reticulatum</i>)</u>			
Beneath canopy	5.77	0.21	0.86	6.4
Outside canopy	3.23	0.19	0.82	5.8
	<u>Keur Mata (<i>G. senegalensis</i>)</u>			
Beneath canopy	3.35	0.20	0.89	5.2
Outside canopy	2.51	0.18	0.93	5.4

Table 2.2. Initial chemistry of shrub residues, *G. senegalensis* (GS), *P. reticulatum* (PR) and manure (MAN) added to soils (n = 4).

		P	C	N	[†] LG	[‡] CL	[§] HM	[¶] PP	[#] RP	C:N	C:P	LG:N	PP: N	(PP+LG): N	RP: N
		mg g ⁻¹	-----%												
GS	Leaf	1.0	35.4	1.6	10.3	21.6	12.8	6.4	5.0	21	347	6.3	3.9	10.2	3
	Leaf + stem	0.64	33.3	1.3	18.1	45.2	13.3	3.9	3.6	26	520	14.2	3.1	17.3	2.8
PR	Leaf	1.0	35.2	1.8	13.1	19.8	13	5.3	4.2	20	348	7.4	3.0	10.4	2.4
	Leaf + stem	0.67	33.7	1.2	13.6	44.4	13.2	7.3	6.2	27	502	10.8	5.8	16.7	5
	Man	3.4	36.7	1.8	16.8	26.9	12.5	1.8	1.0	20	108	9.4	1.03	10.4	0.6

[†]LG, lignin

[‡]CL, cellulose

[§]HM, hemicellulose

[¶]PP, total polyphenols

[#]RP, reactive polyphenols

Table 2.3. Initial N and P leached from soils amended with the different organic residues. For each element, values in the same column having the same superscript letter are not statistically different at $P < 0.05$ ($n = 4$).

Treatments	<i>P. reticulatum</i>		<i>G. senegalensis</i>	
	beneath	outside	beneath	outside
	-----mg N kg ⁻¹ -----			
Control	4.9 ^a	4.4 ^a	3.9 ^b	2.4 ^b
Leaf	5.3 ^a	5.1 ^a	5.1 ^a	4.3 ^a
Leaf+stem	4.8 ^a	5.0 ^a	5.2 ^a	3.8 ^a
Manure	5.5 ^a	5.9 ^a	3.6 ^b	2.2 ^b
	-----mg P kg ⁻¹ -----			
Control	0.05 ^d	0.02 ^c	0.01 ^b	0.05 ^b
Leaf	0.90 ^a	0.70 ^a	0.20 ^a	0.17 ^a
Leaf+stem	0.58 ^b	0.42 ^b	0.13 ^a	0.14 ^a
Manure	0.28 ^c	0.20 ^c	0.20 ^a	0.12 ^a

Table 2.4. Parameter values for the first-order exponential model to describe C mineralization in *P. reticulatum* and *G. senegalensis* residue-amended soils beneath and outside shrub canopy. k = 1st order rate constant and C potential = potentially mineralizable C. Values in brackets represent the standard error on estimate.

Treatment	Beneath shrub canopy			Outside shrub canopy		
	C potential g kg ⁻¹	k day ⁻¹	R ²	C potential g kg ⁻¹	k day ⁻¹	R ²
<u>Nioro (<i>P. reticulatum</i>)</u>						
Control	0.34(0.02)	0.019 (0.002)	0.96	0.32 (0.03)	0.014 (0.002)	0.97
Leaf	2.15 (0.06)	0.034 (0.002)	0.98	2.09 (0.10)	0.024 (0.002)	0.97
Leaf+stem	3.01(0.20)	0.012 (0.001)	0.99	3.69(0.72)	0.007 (0.002)	0.97
Manure	2.00 (0.03)	0.020 (0.000)	0.99	2.09(0.08)	0.012 (0.000)	0.99
<u>Keur Mata (<i>G. senegalensis</i>)</u>						
Control	0.28 (0.04)	0.010 (0.002)	0.97	0.66 (0.37)	0.003 (0.002)	0.97
Leaf	1.96 (0.21)	0.012 (0.002)	0.97	1.74 (0.24)	0.011 (0.002)	0.96
Leaf+stem	2.58 (0.40)	0.009 (0.002)	0.97	1.78 (0.17)	0.013 (0.002)	0.97
Manure	1.95 (0.07)	0.012 (0.000)	0.99	1.63(0.09)	0.013 (0.001)	0.99

Table 2.5. Correlation of various residue characteristics with daily mineralization rate for C and N at beginning and end dates of incubation ($P < 0.01$).

Rate at day	N	[†] LG	[‡] PP	[§] RP	[¶] CL	[#] HM	C:N	LG:N	PP:N	(PP+LG):N	RP:N
<u>C mineralization</u>											
1	0.54	-0.37	ns	ns	-0.48	ns	-0.45	-0.50	ns	-0.45	ns
118	^{††} ns	ns	0.35	0.41	ns	ns	ns	ns	0.41	ns	0.41
<u>N mineralization</u>											
10	ns	-0.36	ns	ns	ns	-0.34	ns	ns	ns	ns	ns
90	0.60	ns	ns	ns	-0.55	-0.33	-0.57	-0.44	-0.34	-0.52	-0.40
118	0.57	-0.39	ns	ns	-0.55	-0.38	-0.53	-0.52	ns	-0.52	ns

[†]LG, %lignin

[‡]PP, %total polyphenols

[§]RP, %reactive polyphenols

[¶]CL, %cellulose

[#]HM, %hemicellulose

^{††}ns, not significant at $P < 0.01$

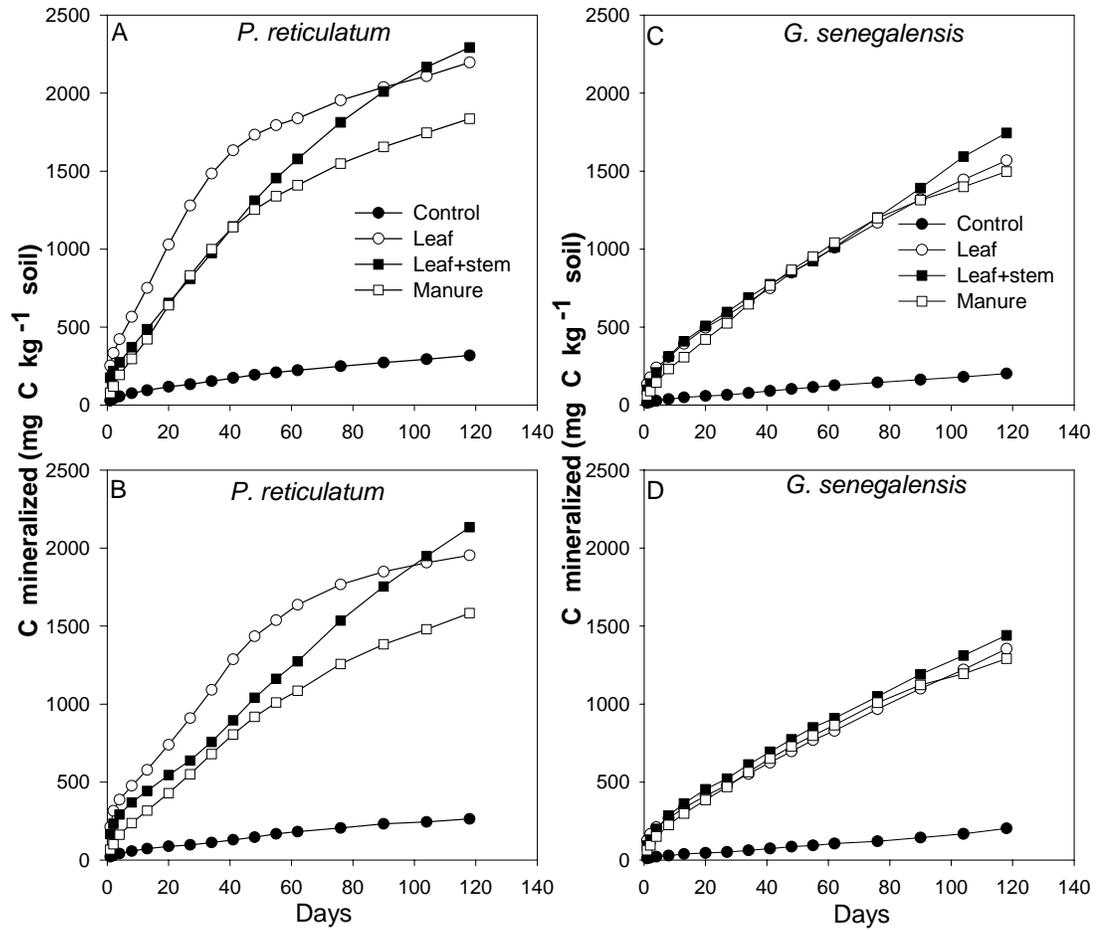


Figure 2.1. Cumulative CO₂ evolution beneath (A) and outside shrub canopy (B) in *P. reticulatum* residue-amended soils; and beneath (C) and outside (D) shrub canopy in *G. senegalensis* residue-amended soils.

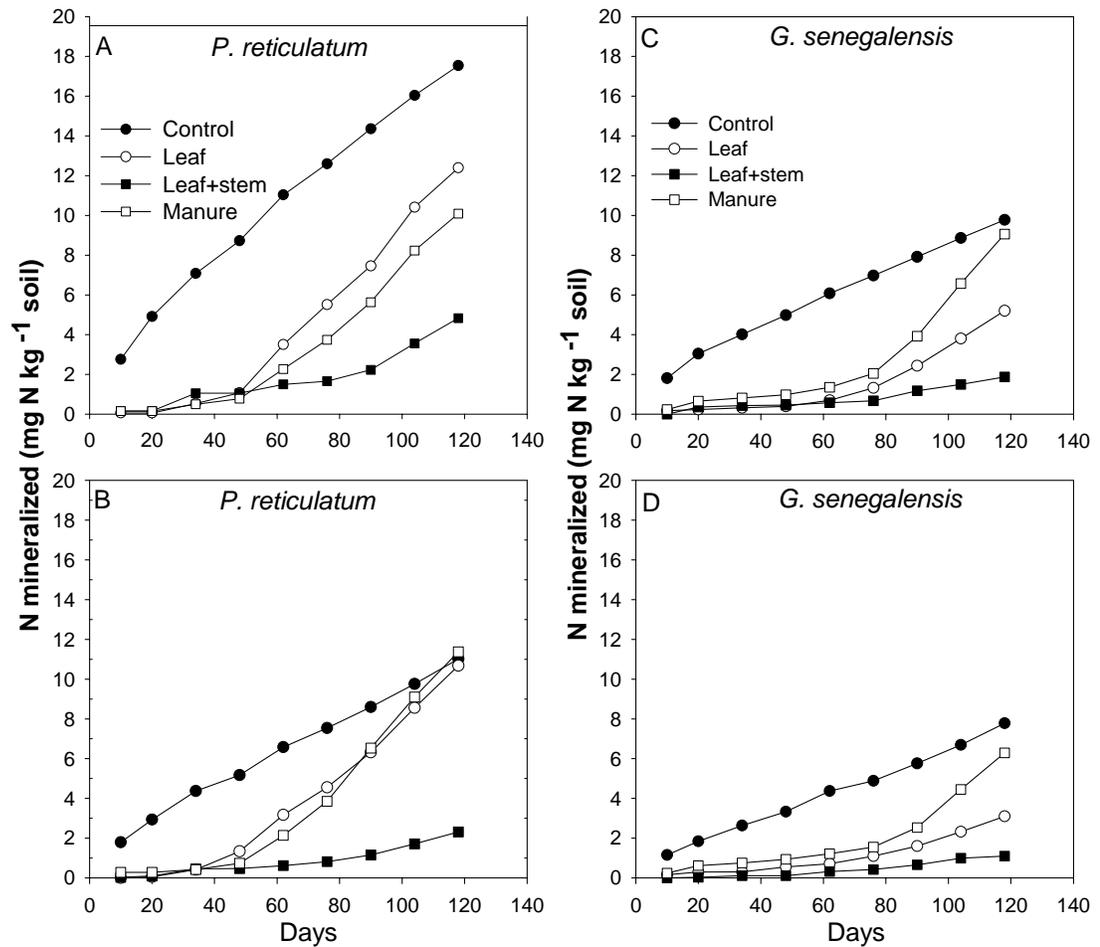


Figure 2.2. Cumulative N leached from soils beneath (A) and outside shrub canopy (B) in *P. reticulatum* residue-amended soils; and beneath (C) and outside (D) shrub canopy in *G. senegalensis* residue-amended soils.

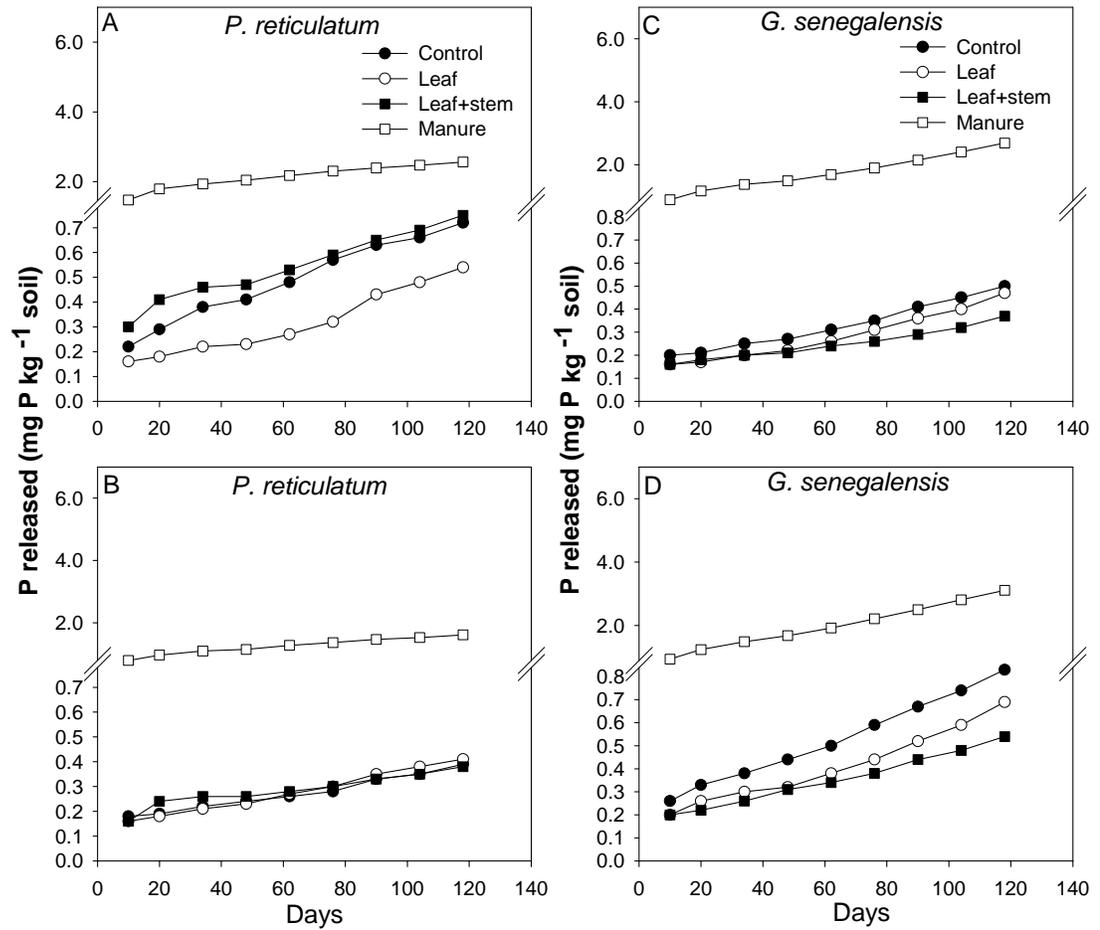


Figure 2.3. Cumulative P leached from soils beneath (A) and outside shrub canopy (B) in *P. reticulatum* residue-amended soils; and beneath (C) and outside (D) shrub canopy in *G. senegalensis* residue-amended soils.

CHAPTER 3**Crop productivity, nitrogen and phosphorus cycling in shrub-based cropping systems in semiarid Senegal**

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Abstract

Two perennial shrubs (*P. reticulatum* and *G. senegalensis*) form an important vegetation component of parkland systems in Senegal. However, their biophysical interactions with soil and crop are not well understood. Hence, a two-year study was conducted in 2004 and 2005 to investigate effects of the two shrub species at separate sites, on associated crop productivity and soil extractable N and P dynamics. A split-plot factorial design was used, with presence or absence of shrub as the main plot factor and fertilizer rates (0, 0.5, 1 and 1.5 times the recommended N P K fertilizer rate) as the sub-plot factor. Peanut in 2004 and pearl millet yields were significantly higher in plots with shrubs than in sole-crop plots. Millet biomass and N and P uptakes in biomass significantly increased with increasing fertilizer rate and were always higher in presence of shrubs, even in the absence of fertilizer. Contrary to P, mineral N in soils exhibited very rapid changes, reaching very low levels by the end of the growing season. Nutrient use efficiency was low in general but was improved in presence of shrubs. These results showed the importance of shrubs in optimizing crop productivity with or without commercial fertilizer. Shrubs component should be conserved to develop sustainable land use systems in these vulnerable semiarid ecosystems. Further research is needed to determine optimal densities and spatial arrangements of shrubs and associated crops. Because these shrubs are found throughout the Sahel in farmers' fields, the results have implication for the whole region.

3.1. Introduction

Agricultural systems in drylands of sub-Saharan Africa are considered vulnerable because of continuous degradation of soil quality and decline in soil productivity (Lal, 2002). Such a trend is partly explained by increased pressure on agricultural lands and overexploitation of woody resources (Tilander et al., 1995). In these low-input systems, it has been suggested that agroforestry, under proper management, could be an alternative to overcome land degradation and sustain ecosystem productivity (Young, 1989). Different land use options have been proposed to farmers (Kang et al., 1984; Budelman, 1988; Hagggar et al., 1991) but received limited rate of adoption due to soci-economic constraints (Rhoades, 1997; Bationo et al., 1998; Buresh and Tian, 1998). Ecosystem management technologies that build upon farmers' indigenous practices are most likely to have greater impact at landscape level.

A common traditional land use system in sub-Saharan Africa is the parkland agroforestry system where selected tree species are deliberately allowed to establish and grow in crop fields. Parkland systems of *Faidherbia albida*, *Cordyla pinnata* and other species have been reported in sub-Saharan Africa and extensively studied for their biophysical interactions with soil and crops (Dancette and Poulain, 1968; Tiedemann and Klemmedson, 1977; Depommier et al., 1992; Kater et al., 1992). However, a largely overlooked component of the parkland systems is the shrub vegetation.

Two native woody shrub species: *Piliostigma reticulatum* (DC) Hochst and *Guiera senegalensis* J.F. Gmel are commonly found interspersed under the trees in parklands in Senegal. Unlike trees, which are vulnerable to overexploitation (Tilander et al., 1995; Wezel, 2000) and have slow growth rates, these shrubs are adapted to yearly pruning. The shrubs are cut at the beginning of the growing season and subsequently pruned at each weeding during the cropping season. In sandy and low organic matter soils of Senegal, shrub biomass constitutes a major source of C addition to soils. However, little is known about the contribution of these shrubs to

ecosystem function and nutrient cycling. Previous recommendations of massive uprooting of shrubs were based on fear that shrubs may compete with the crops and reduce crop yield (Somarriba, 1988; Kater et al., 1992). However, a preliminary study in Niger in farmers' fields showed that millet near *G. senegalensis* had greater yields than when grown outside the influence of the shrub (Wezel, 2000). Other studies showed the potential of *P. reticulatum* residues to be used as mulch (Diack et al., 2000; Iyamuremye et al., 2000).

Trees or shrubs in farming systems may improve nutrient use efficiency, nutrient recycling and carbon sequestration in vegetative biomass and soil. It has been shown that trees exhibit higher nutrient use efficiency in low-fertility conditions than in nutrient-rich soils (Vitousek, 1982). In sandy soils of Senegal, application of mineral and/or organic fertilizer is required for optimal crop yield (Badiane et al., 2000). Shrubs in these cropping systems may better recycle part of applied nutrients while minimizing nutrient leaching losses.

There are no comprehensive studies of the native shrubs *P. reticulatum* and *G. senegalensis* relative to crop productivity and nutrient recycling in the Sahel. Therefore, the objectives of this study were to determine the influence of *P. reticulatum* and *G. senegalensis* on: 1) crop yield under varying rates of fertilizers; and 2) N and P recycling efficiency.

3.2. Materials and Methods

3.2.1. Study sites

The research took place at two sites in the Peanut Basin of Senegal in West Africa. Temporally and spatially variable rainfall characterizes the region. The climate is semiarid with most of the precipitation falling between July and October generally as intense short-duration showers. Millet (*Pennisetum glaucum* (L.) R. Br.) and peanut (*Arachis hypogaea* L.) are the two major crops.

The first experimental site (Keur Mata) is located 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. Cumulative annual rainfall at the site was 300 and 560 mm in 2004 and 2005 respectively. The soils are 95% sand, mainly constituted of materials from eolian deposits, classified as leached ferric lixisol (FAO, 1991), locally referred to as a Dior soils (Badiane et al., 2000). The top soils (0-10 cm) have organic matter content of 0.5%, total N and P contents of 0.15 g kg⁻¹ and 95 mg kg⁻¹ respectively, with mean pH of 5.5. They have low buffer and exchange capacity, and exchangeable bases of 0.9 cmol kg⁻¹ (Tschakert et al., 2004). *Guiera senegalensis* is the dominant shrub vegetation with shrub stand density of 240 shrubs ha⁻¹ (Kizito et al., 2006).

The second experimental site (Nioro) 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. Cumulative annual rainfall at the site was 740 mm in 2004 and 900 mm in 2005. The soil is a Deck-Dior (Badiane et al., 2000) loamy-sand [fine-sandy, mixed Haplic Ferric Lixisol (FAO, 1991)], a leached ferruginous tropical soil. Top soil (0-10 cm) has sand content >90%, organic matter of 0.6 % and total N of 0.21 g kg⁻¹. The surface soils have total P of 70 mg kg⁻¹, with mean pH of 6.2. The dominant shrub species at the site is *Piliostigma reticulatum*, found at density of approximately 185 shrubs ha⁻¹ (Kizito et al., 2006).

3.2.2 Experimental design and treatments

At both sites, a representative plot of approximately 0.5 ha with pre-existing shrubs was selected. The selected sites had been under continuous millet-peanut cultivation prior to the experiment. The experimental design at both locations was a split-plot with presence or absence of shrub as mainplot factors and fertilizer rates as the subplot factors in four replicates. In winter of 2003, main plots were established and shrubs from the minus shrub plots were hand removed when needed. Millet *Pennissetum glaucum* var Souna 3 was planted on all plots and fertilizer rate of 68.5 kg N, 15 kg P and 15 kg K ha⁻¹ applied uniformly to all treatments to allow plots to equilibrate for one year before initiation of the experiments. Main plot sizes were 46

m x 6 m at Keur Mata and 46 m x 4.5 m at Nioro. Subplot sizes were 10 m x 6 m and 10 m x 4.5 m at Keur Mata and Nioro, respectively.

In the summer of 2004, the experiments were initiated by imposing the subplot fertilizer treatments of 0, 0.5, 1 and 1.5 x recommended fertilizer rate. Crop sequences followed farmers' practices. In June 2004 at Nioro and in July 2004 at Keur Mata, peanut (*Arachis hypogaea* var 55-437) was planted 50 cm apart with a distance of 15 cm between rows. A single starter dose of 9 kg N, 30 kg P and 15 kg K ha⁻¹ was manually broadcast after peanut germination. Because of irregular germination of peanut at Nioro, plots were resown after fertilizer had been applied. During the second growing season, in June 2005, millet (*Pennisetum glaucum* var Souna 3) was planted at 1 m x 1 m distance with 4-6 seeds per hole. After germination, the plants were thinned to 1-2 plants per stand. A starter fertilizer rate of 22.5 kg N, 15 kg P and 15 kg K ha⁻¹ was applied at planting followed by 46 kg N ha⁻¹ as urea (split of 23 kg at two weeks and four weeks after planting). Weeding was mechanically conducted using a hoe adjusted to 5 cm depth, drawn by animal. Shrubs were periodically pruned according to farmers' practices to minimize competition for light between shrub and crops. The pruned biomass was chopped to approximately 1 cm length and surface-applied to the plot from which it was harvested. Crop residues, however, were removed from plots according to farmers' practices.

3.2.3. Soil, plant sampling and crop yield

Soil samples for chemical analyses were collected throughout the growing season in August, September and November in 2004 and in July, August, September and October in 2005. For each sampling date, 10 to 16 soil cores (2.5 cm) per subplot were randomly taken at 5 cm depth along the diagonals of within the inner two thirds of each subplot. The cores were homogenized air-dried and sieved to pass a 2 mm sieve and a 200 g-sample was kept in a sealed plastic bag under room temperature for further chemical analyses.

At harvest the border row all around each subplot was omitted. Entire peanut plants were mechanically removed from plots and sun-dried for 4-5 days after which

Pods were separated from the aboveground biomass. Millet grain yield was determined by harvesting ears from entire subplots. Ears were sun-dried and resulted in water content of <10% and shelled to yield dry millet grain per subplot. At Keur Mata, when significant granivorous bird damage was noticed, millet grain yield in affected subplots was corrected by using a shelling ratio (weight of grain)/(weight of empty ear) derived from unaffected millet plants from the same plot. The aboveground biomass of millet (leaf + stalk) was cut at the soil surface and fresh weight was recorded. Composite samples of approximately 500 g were taken for water content determination in an oven at 65°C until constant weight. The samples were kept in sealed plastic bags for further chemical analyses.

Shrub aboveground biomass was harvested at the beginning of each cropping season and sorted into leaf and stem components and fresh weight was taken. Subsequently, fresh weight of shrub biomass was recorded at each pruning date during the growing season. For each biomass component, a composite sample of approximately 500g was taken for water content determination in an oven at 65°C and kept for subsequent chemical analyses.

3.2.4. Laboratory analyses

Soil inorganic P was extracted by the $\text{NaHCO}_3 + \text{NH}_4\text{F}$ method buffered to pH 8.5 (Dabin, 1967). Ammonium-N and nitrate-N in 1 M KCl soil extract were determined respectively by the salicylate-nitroprusside, and the hydrazine-sulfanilamide methods (Mulvaney, 1996). Plant tissues were digested for total N and P using a modified Kjeldahl $\text{Li}_2\text{SO}_4\text{-H}_2\text{SO}_4$ procedure (Parkinson and Allen, 1975). Nitrogen in the digest was determined by the salicylate-nitroprusside procedure (Mulvaney, 1996). P in extracts and digests were analyzed for orthophosphate by the molybdenum blue colorimetric method (Murphy and Riley, 1962) after pH adjustment, when necessary, using a 5 M NaOH solution. In the $(\text{NaHCO}_3 + \text{NH}_4\text{F})\text{-P}$ determination (Dabin, 1967), interference of F^- with color formation was prevented using a 0.8 M H_3BO_3 solution.

3.2.5. Statistical analysis

Statistical analysis of the data was performed using PROC MIXED for a split-plot design (SAS Institute, 1999). Within each year, soil extractable N and P data for the different sampling dates were analyzed as repeated measures in time (SAS Institute, 1999). Fertilizer effect on shrub biomass and N, P uptakes in biomass was analyzed as a randomized-complete-blocks design (PROC GLM, SAS Institute, 1999). Tukey multiple comparison adjustment was used to determine pairwise differences among treatments. Alternately, means were compared by LSD at $P < 0.05$ (Little and Hills, 1978).

3.3. Results and Discussion

3.3.1 Crop yields

At Keur Mata in the 2004 season, peanut yield varied from 79 to 203 kg ha⁻¹ (Table 3.1). Plots with shrubs had significantly higher peanut yield than plots without shrubs ($P < 0.1$). This difference in yield was consistent at all fertilizer levels. There was no fertilizer effect on peanut yield but the interaction shrub x fertilizer was significant. During the second cropping season in 2005, millet grain yield ranged from 111 to 604 kg ha⁻¹ and was higher in plots with shrub ($P < 0.003$), but also increased with increasing fertilizer rate ($P < 0.0001$). There was no significant shrub x fertilizer interaction.

At Nioro, crop yields showed a pattern similar to Keur Mata for both 2004 and 2005 cropping seasons, except that millet grain yield tended to level off at the highest fertilizer rate (Table 3.2). Yield levels were generally higher at Nioro than at Keur Mata. Peanut yield ranged from 461 to 699 kg ha⁻¹ and was significantly higher in presence of shrubs ($P < 0.005$). In the 2005 season, fertilizer significantly increased millet grain yield ($P < 0.0001$).

Our fertilizer results showed a direct relationship between fertilizer rate and crop yield. This linear response of millet grain yield to fertilizer in Sahelian agroecosystems is well established (Bationo et al., 1993) and would be expected on the sandy soils of the present study. While yield levels obtained in 2005 are within the

expected yield range for each site (Dancette, 1978; van Duivenbooden and Cissé, 1993), values of peanut in 2004 fell below long-term averages due to a rainfall deficit, especially at Keur Mata. The lack of response to fertilizer in 2004 could be attributed in part to the limited rainfall. The disturbance in uprooting and replanting peanut at Nioro might have affected crop fertilizer relations. Fertilizer effect on crop yield was more apparent in 2005 when water was not limiting to crop growth (M. Sene, personal communication). The higher crop yield in plots with shrubs than in sole crop plots is consistent with report of higher millet yield around coppiced and uncoppiced *G. senegalensis* shrubs in Niger (Wezel, 2000). This improved yield in presence of shrubs could have resulted from several different mechanisms. When no fertilizer was applied, the higher crop yield in plots with shrubs may have been due to better plant nutrition, which follows the idea of “islands of fertility” creation by woody species in semiarid environments (West, 1991; Kieft et al., 1998). Indeed, as we report in the section below, in absence of fertilizer, shrub-crop association caused an increase in N and P uptake by crops. However, even when N and P deficiencies were supposedly removed by applying 1.5 times the recommended fertilizer rate, shrubs still significantly increased crop yield. In this case, shrubs could have improved crop-soil water relations.

The positive crop response in presence of shrubs even in dry year (season of 2004) suggests that shrubs were not competing with the crop for water resources. Supporting evidence for this hypothesis includes findings of Kizito et al. (2006) who showed a significantly higher soil moisture profile in millet-shrub intercrop plots than in sole millet plots for the same shrub species at the same study sites. Moreover, shrubs in semiarid environments have been postulated to perform water redistribution that could be vital for the survival of crops in periods of water deficit (Richards and Caldwell, 1987; Kizito et al., 2006).

In 2005, yields were not limited by water as rainfall and soil moisture levels were maintained at more than adequate levels for millet production (M. Sene, personal communication). This would suggest there might be other factors beyond nutrients and water relations that enable shrubs to improve growth of associated crop. This

could be better soil quality as evidenced by higher organic matter levels beneath shrubs and/or beneficial microorganisms harbored by shrub rhizospheres that assist crops (e.g. phytohormones). Additionally, at zero fertility levels shrubs may facilitate free-living N fixing microorganisms.

3.3.2. Dry matter, N and P uptakes

3.3.2.1. Crops

Peanut dry matter production (aboveground biomass) is reported for Niro site only because of severe defoliation of peanut plants at Keur Mata due to a severe locust invasion in 2004. Shrub presence had a significant effect on crop biomass production ($P < 0.05$); the effect of fertilizer was less significant ($P < 0.1$). Peanut biomass was lowest for sole peanut plots receiving no fertilizer and highest in plots with shrubs receiving the highest fertilizer rate (Fig. 3.1A). Nitrogen and P uptake showed a similar relationship to biomass data. Total crop N uptake approximately ranged from 20 to 30 kg N ha⁻¹ whereas P uptake varied from 1.5 to 2.8 kg P ha⁻¹ (Figs 3.1B and 3.1C). These biomass and nutrient uptake values are presumably underestimates for 2004 because of plant residues losses due to defoliation by grass grasshoppers.

In 2005 at Keur Mata, millet aboveground biomass ranged from 638 to 3,340 kg ha⁻¹ and showed a clear response to fertilizer rates (Fig. 3.2A). In addition, greater millet dry mass was obtained in the presence of shrubs. The magnitude of the difference between plots with shrubs and plots without shrubs was greatest at the highest fertilizer rate (Fig. 3.2A). Interestingly, even in the absence of fertilizer, shrub caused a ~3-fold increase in millet biomass. Similarly, N and P uptakes in millet biomass were lowest in unfertilized sole millet plots (5.5 kg N and 2.8 kg P ha⁻¹) and highest in millet-shrub intercropped plots receiving the highest rate of fertilizer (22.2 kg N and 8.7 kg P ha⁻¹) (Figs. 3.2B and 3.2C).

In 2005 at Niro, millet biomass, N, and P uptake had the same pattern as that at Keur Mata with respect to shrub and fertilizer effects (Fig. 3.3). However, biomass

and N uptake levels were comparatively higher at all fertilizer rates (Figs 3.3A and 3.3B); conversely, P uptake in biomass was lower at Nioro than at Keur Mata (Fig. 3.3C).

3.3.2.2. *Shrubs*

At Nioro, biomass of *P. reticulatum* as well as N and P uptakes by shrub showed no apparent response to fertilizer for both the 2004 and 2005 seasons (Table 3.3). Likewise, at Keur Mata, *G. senegalensis* biomass and nutrient uptakes were not related to fertilizer rates, although, except for the recommended fertilizer rate, biomass production and N, P uptakes were lowest in unfertilized plots and highest in plots receiving the highest rate of fertilizer (Table 3.4).

At both sites, shrub biomass yield was higher in the 2005 season than in 2004, presumably because of the better rainfall conditions in 2005. Shrub fertilizer relationship was most likely confounded by the variability in shrub size and shrub number per subplot at the beginning of the experiment. When shrub biomass and nutrient in shrub biomass were normalized on a single shrub basis, there was a quasi-linear and positive relationship between shrub biomass and N, P uptakes and fertilizer rate for *G. senegalensis* (Fig. 3.4) but not for *P. reticulatum* (data not shown).

3.3.3. *Carbon sequestration and nutrient use efficiency*

The agronomic efficiency of applied fertilizer in terms of carbon sequestration and nutrient recycled in aboveground biomass was determined from the slope of a linear model fitted to the data. Carbon estimates were based on the assumption that millet and shrub aboveground residues contained 40% C. The fits and corresponding regression equations are shown in Figs. 3.5 and 3.6 at Keur Mata and Nioro sites respectively. In general, total biomass C, N and P increased with increasing fertilizer rate. At Keur Mata, in the *G. senegalensis*-millet association, C sequestration per unit (kg) of N applied was 10.2 kg C ha⁻¹ as compared to 7.5 kg C ha⁻¹ in sole millet plots (Fig. 3.5A). The amount of C sequestered per unit of P applied was approximately 5-fold that per unit of N (Fig. 3.5B). Gains in N and P uptakes in biomass were 0.27 and

0.22 kg ha⁻¹ respectively in plots with shrubs and were approximately three times greater than corresponding values in sole millet plots (Figs. 3.5C and 3.5D). At Nioro, gains in C sequestration and N uptake per unit of applied fertilizer were higher than the counterparts at Keur Mata (Figs. 3.6A, 3.6B and 3.6C), but total P uptake in shrub-crop plots was lower than that at Keur Mata (Fig. 3.6D).

Low nutrient use efficiencies observed in the current study are consistent with previous research (Christianson et al., 1990; Christianson and Vlek, 1991). The much lower N use efficiency at Keur Mata than at Nioro may be explained by more intense N losses, presumably through leaching. Keur Mata soils are sandier and have relatively lower OM content compared to soils at Nioro. Additionally, active nitrification seems to be a major N transformation process in soils at Keur Mata during the growing season (S. Diedhiou, personal communication). Low P use efficiencies at both sites suggest possible P immobilization in microbial biomass and/or sorption reactions of P with the mineral soil. Hence, (NaHCO₃ + NH₄F)-extracted P most likely overestimated soil solution P that was actually taken up by crops (see section below).

3.3.4. Dynamics of soil extractable N and P

For soil mineral N analysis, nitrate and ammonium were pooled because their levels in soils were low and generally near detection limits. In 2004 at both Keur Mata and Nioro, N content of soils decreased throughout the growing season but exhibited a rise in concentration at the end of season (Fig. 3.7). Soil mineral N content was not affected by fertilizer rate, but was significantly higher ($P < 0.05$) in plots with shrubs than in sole millet plots. In 2005, mineral N content of soils dropped rapidly to lower levels than in 2004 and showed significant shrub and fertilizer rate effects ($P < 0.05$). Soils at Keur Mata showed a rise in N content at the end of season whereas soils at Nioro exhibited a steady decrease in their N concentrations (Fig. 3.8).

Extractable soil P in 2004 steadily increased in soils at Keur Mata but showed a decrease and then a rise in concentration at end of season at Nioro (Fig. 3.9). Extractable P content of soils was not affected by presence of shrubs but significantly varied with the different fertilizer rates ($P < 0.01$), the highest and lowest soil P

contents generally corresponded to highest and lowest fertilizer rates respectively. In 2005, soil P at both sites showed an initial increase up to August and a subsequent decrease until the end of season. The drop in concentration was more pronounced at Nioro than at Keur Mata (Fig. 3.10).

These results showed strong seasonal patterns of mineral N in the sandy soils of this study. The decrease in nutrient content may reflect microbial and crop uptakes, but also nutrient loss through leaching or runoff, particularly in the case of N. These results point out the need to avoid high mineral N rate and to split N application in soil conditions of the present study to reduce potential N leaching and to improve N use efficiency. The lower drop in N levels in 2005 (rainfall above average) than in the dry year of 2004 supports this hypothesis.

The increase in soil extractable N and P contents at end of season clearly evidenced in the dry year of 2004 may partly be attributed to release of nutrients from microbial death (Brookes et al., 1982). A similar result was reported by Magid and Nielsen (1992) in a study of inorganic P dynamics in sandy soils. The authors attributed negative correlation between inorganic P and soil moisture to physical changes in soils rather than biological turnover. Indeed, dehydration of soils subsequent to air-drying has been shown to affect P desorption properties of soils (Barrow and Shaw, 1980; Haynes and Swift, 1985). Such drying and wetting processes likely occurred toward the end of season in soil conditions of our study.

3.4. Conclusions and Perspectives

The presence of shrubs influenced intercropped peanut and millet productivity and mineral N content of soils throughout the growing period. In both dry and wet years, crop yield was higher in plots with shrubs than without shrubs. Under optimal rainfall conditions, fertilizer as high as 1.5 x recommended rate was effective in increasing both crop yield and crop and shrub biomass. Generally, mineral N content of soils decreased rapidly to very low levels near the end of the growing season, which may explain the poor N use efficiency in the sandy soils. In these soil conditions, split applications of N fertilizer appear as a practice that would reduce nutrient loss and

improve nutrient use efficiency. Within this framework, slow-release N fertilizer has been suggested as an alternative to improve N use efficiency in West African soils (Christianson and Vlek, 1991). The low P use efficiency observed in this study indicates that mechanisms such as sorption processes may prevent P from being easily accessible to the crop, and/or that the ($\text{NaHCO}_3 + \text{NH}_4\text{F}$) extraction method may have overestimated soil P that was actually taken up by the crops. The greater potential for carbon sequestration shown in plots with shrubs provides an opportunity to store C and reduce greenhouse gas carbon dioxide emission (Lal, 2002).

Our results showed conclusively that shrubs as managed in the present study are non-competitive and significantly improved N and P use efficiency for millet. Such an attribute is important with respect to nutrient cycling and land use sustainability in semiarid ecosystems. The results suggest that shrubs should be recognized as an important component of cropping systems in the Sahel. Further research is needed to confirm these results throughout the Sahel and to determine optimal shrub-crop densities and spatial distributions.

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Table 3.1. Crop yield as affected by presence or absence of shrub (*G. senegalensis*), and fertilizer rate at Keur Mata. Values within columns followed by the same superscript letter are not significantly different at $P < 0.05$.

†Rate	2004 season (<i>Arachis hypogaea</i>)				2005 season (<i>Pennisetum glaucum</i>)			
	Shrub	No shrub	P > t	Mean	Shrub	No shrub	P > t	Mean
	----- kg ha ⁻¹ -----				----- kg ha ⁻¹ -----			
0	190	79	0.019	134 ^a	218	111	0.208	164 ^c
0.5	135	103	0.420	119 ^a	359	148	0.015	253 ^{bc}
1	153	116	0.383	134 ^a	422	278	0.091	350 ^b
1.5	203	91	0.025	147 ^a	604	503	0.224	553 ^a
Mean	170 ^a	97 ^b			400 ^a	260 ^b		

†Rate values are x recommended fertilizer rate = 9 kg N, 30 kg P and 15 kg K ha⁻¹ in 2004; and 68.5 kg N, 15 kg P and 15 kg K ha⁻¹ in 2005.

Table 3.2. Crop yield as affected by presence or absence of shrub (*P. reticulatum*), and fertilizer rate at Nioro. Values within columns followed by the same superscript letter are not significantly different at $P < 0.05$.

†Rate	2004 season (<i>Arachis hypogaea</i>)				2005 season (<i>Pennisetum glaucum</i>)			
	Shrub	No shrub	P > t	Mean	Shrub	No shrub	P > t	Mean
	----- kg ha ⁻¹ -----				----- kg ha ⁻¹ -----			
0	697	637	0.310	667 ^a	854	651	0.183	752 ^d
0.5	639	551	0.351	595 ^a	1304	1072	0.104	1188 ^c
1	699	461	0.006	580 ^a	1563	1492	0.612	1527 ^b
1.5	606	522	0.133	564 ^a	1678	1869	0.200	1773 ^a
Mean	660 ^a	543 ^b			1350 ^a	1271 ^a		

†Rate values are x recommended fertilizer rate = 9 kg N, 30 kg P and 15 kg K ha⁻¹ in 2004; and 68.5 kg N, 15 kg P and 15 kg K ha⁻¹ in 2005.

Table 3.3. Biomass and nutrient uptake (kg ha⁻¹) of *P. reticulatum* as affected by fertilization rate at Niroo.

†Fertilizer rate	Leaf			Stem			Leaf+stem			Total		
	Mass	N	P	Mass	N	P	Mass	N	P	Mass	N	P
<u>Season of 2004</u>												
0	-	-	-	-	-	-	1099	30.2	2.9	1099	30.2	2.9
0.5	-	-	-	-	-	-	813	20.7	2.1	813	20.7	2.1
1	-	-	-	-	-	-	772	18.1	2.0	772	18.1	2.0
1.5	-	-	-	-	-	-	806	19.7	2.0	806	19.7	2.0
<u>Season of 2005</u>												
0	597	12.3	0.9	320	4.0	0.4	483	14.5	1.5	1400	30.9	2.7
0.5	509	9.9	0.8	338	3.7	0.4	312	10.1	1.0	1158	23.7	2.1
1	545	12.1	0.9	350	4.5	0.4	408	12.6	1.3	1303	29.3	2.6
1.5	572	10.9	0.8	444	4.7	0.5	409	11.8	1.2	1425	27.4	2.5

†rate values are x recommended fertilizer rate = 9 kg N, 30 kg P and 15 kg K ha⁻¹ in 2004; and 68.5 kg N, 15 kg P and 15 kg K ha⁻¹ in 2005.

Table 3.4. Biomass and nutrient uptake (kg ha⁻¹) of *G. senegalensis* as affected by fertilization rate at Keur Mata.

Fertilizer (x RD [†])	Leaf			Stem			Leaf+stem			Total		
	Mass	N	P	Mass	N	P	Mass	N	P	Mass	N	P
<u>Season of 2004</u>												
0	577	10.2	0.7	574	5.6	0.5	628	15.5	1.3	1781	31.3	2.5
0.5	804	14.8	0.1	687	7.7	0.7	1026	25.2	2.0	2518	47.6	3.6
1	516	8.9	0.6	502	5.3	0.5	594	14.7	1.2	1613	29.1	2.3
1.5	1147	21.0	1.4	894	9.0	0.8	1240	31.8	2.6	3284	61.9	4.8
<u>Season of 2005</u>												
0	1161	21.4	1.7	985	7.7	0.8	224	5.4	0.6	2370	34.5	3.0
0.5	1529	27.7	2.1	1663	13.9	1.3	362	8.2	0.9	3555	49.8	4.3
1	1063	19.0	1.3	957	8.6	0.8	244	5.0	0.5	2265	32.7	2.7
1.5	1771	33.5	2.4	1760	13.9	1.4	461	9.5	1.2	3993	57.0	4.9

[†]rate values are x recommended fertilizer rate = 9 kg N, 30 kg P and 15 kg K ha⁻¹ in 2004; and 68.5 kg N, 15 kg P and 15 kg K ha⁻¹ in 2005.

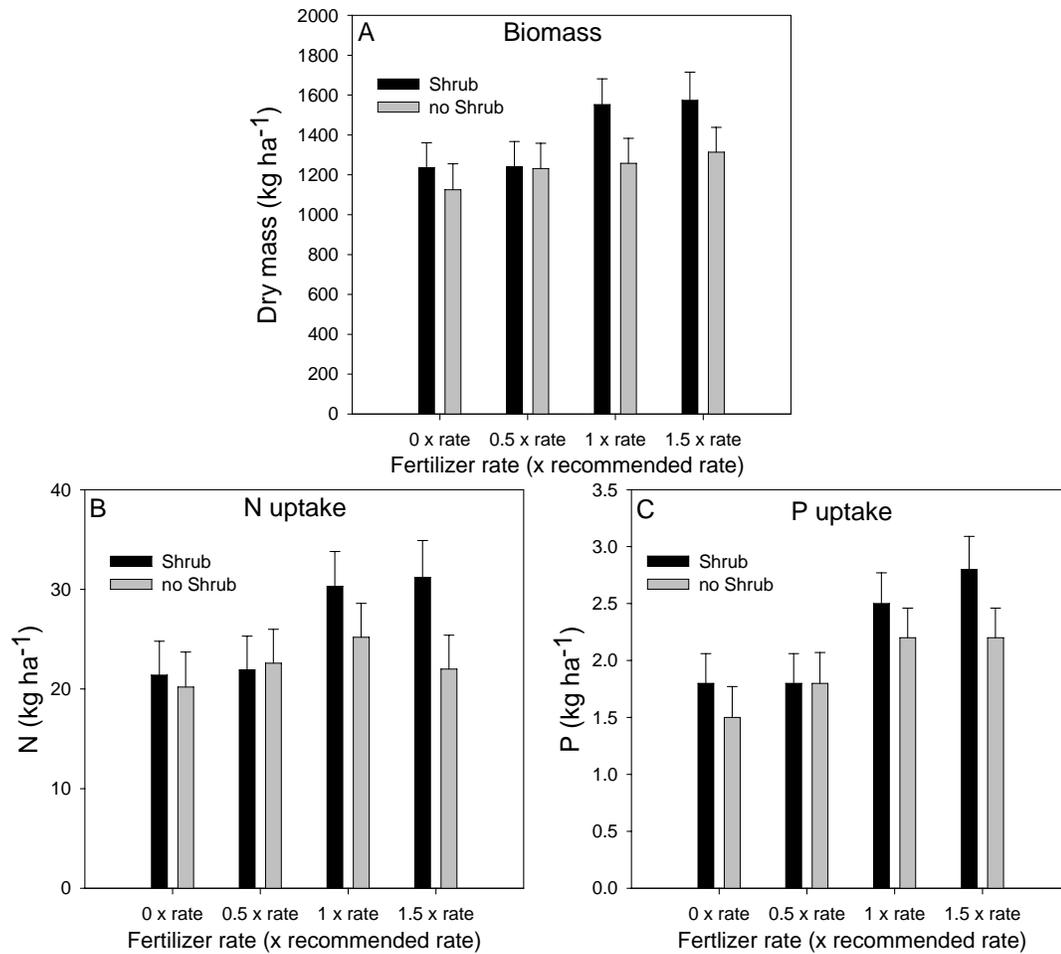


Figure 3.1. Peanut biomass (A), N (B) and P uptake (C) as affected by presence of shrub (*P. reticulatum*) and fertilizer rate in 2004 (Niro).

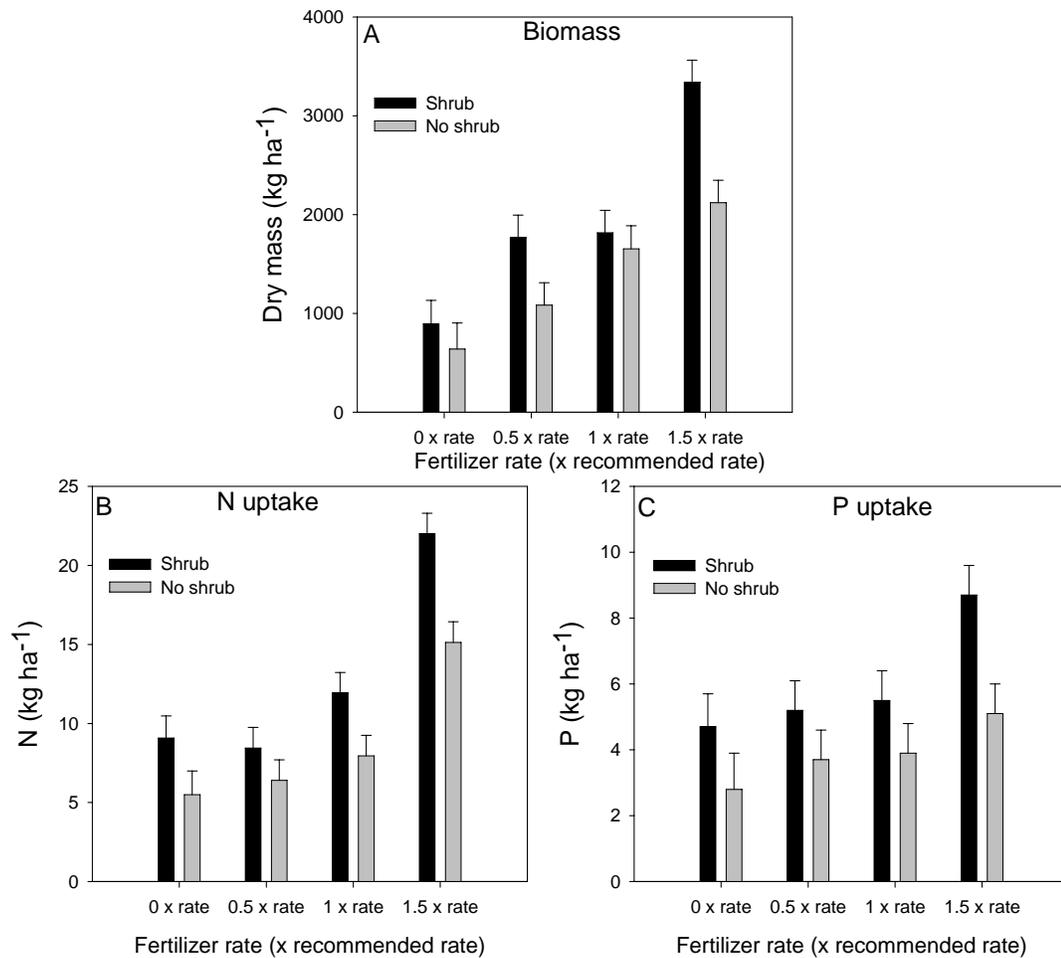


Figure 3.2. Pearl millet biomass (A), N (B) and P uptake (C) as affected by presence of shrub (*G. senegalensis*) and fertilizer rate in 2005 (Keur Mata).

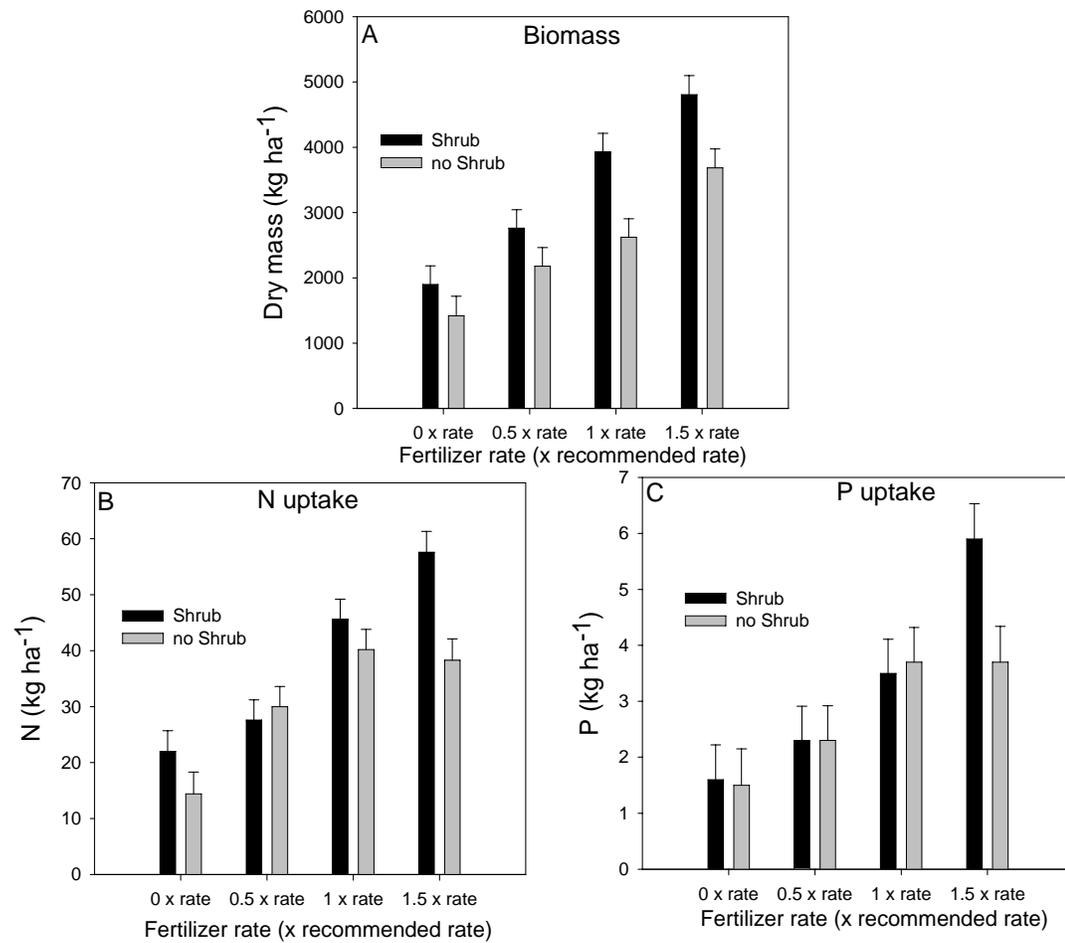


Figure 3.3. Pearl millet biomass (A), N (B) and P uptake (C) as affected by presence of shrub (*P. reticulatum*) and fertilizer rate in 2005 (Nioro).

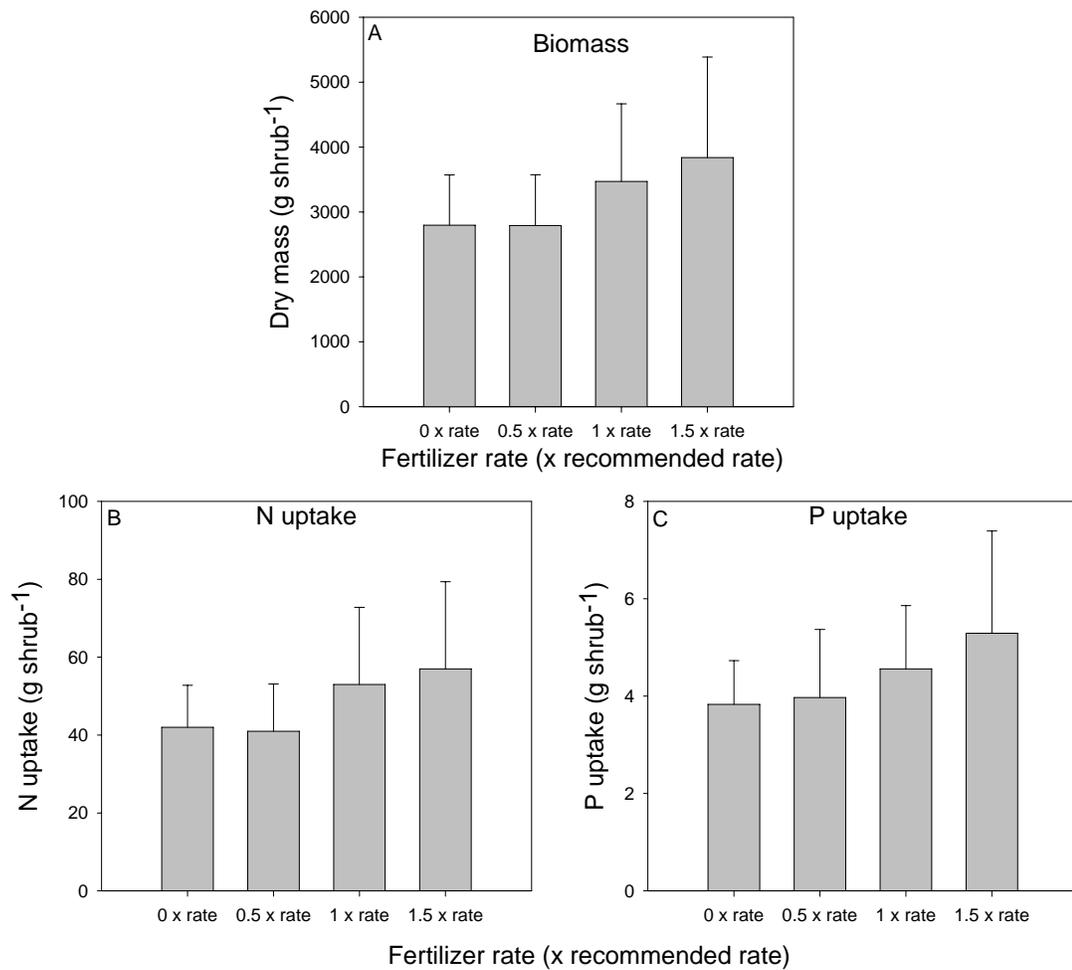


Figure 3.4. Normalized *G. senegalensis* biomass growth (A), nitrogen uptake (B) and phosphorus uptake (C) as affected by fertilizer rate at Keur Mata. Data are from 2005 season.

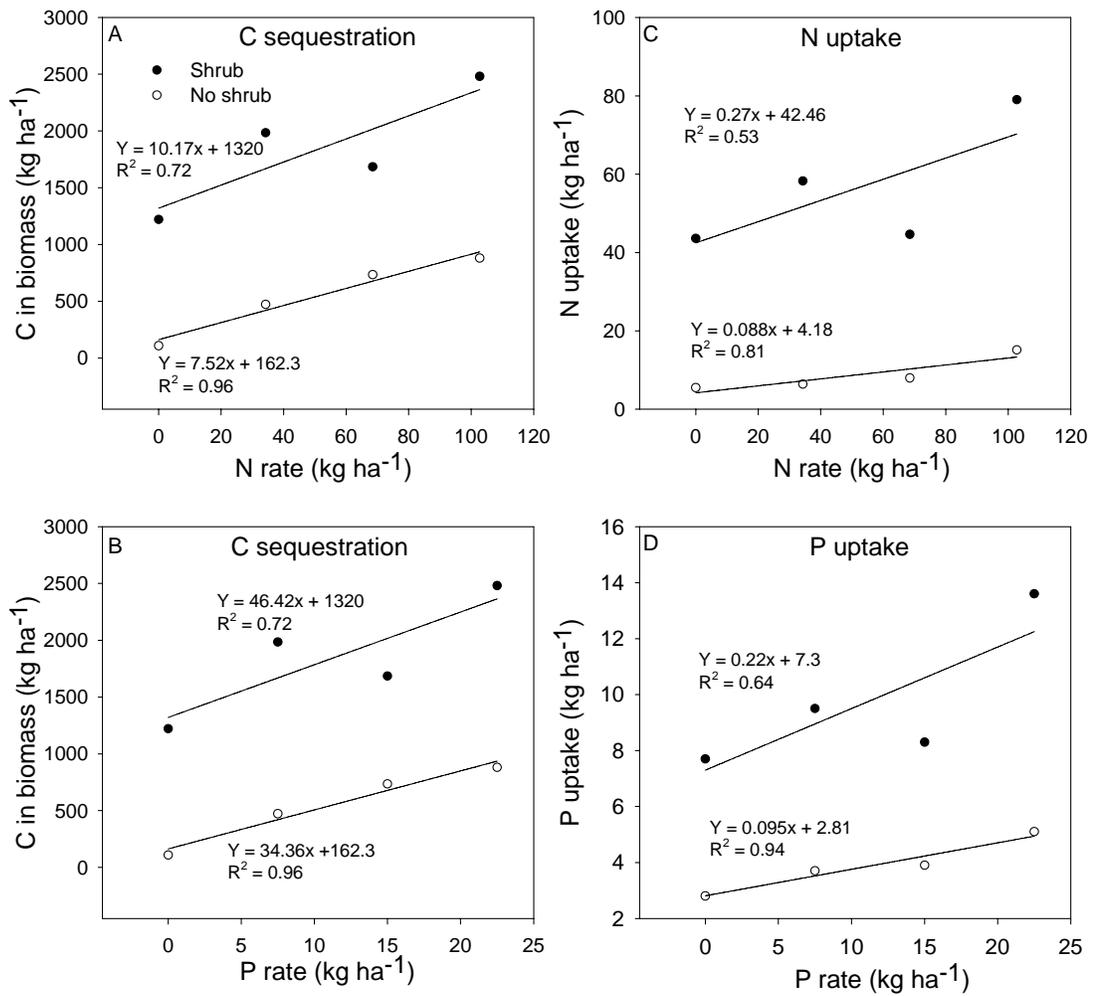


Figure 3.5. Biomass C sequestration (A, B), N (C) and P uptake (D) efficiencies as a function of fertilizer rate in presence or absence of shrub (*G. senegalensis*) at Keur Mata. Data are from 2005 season; crop is pearl millet.

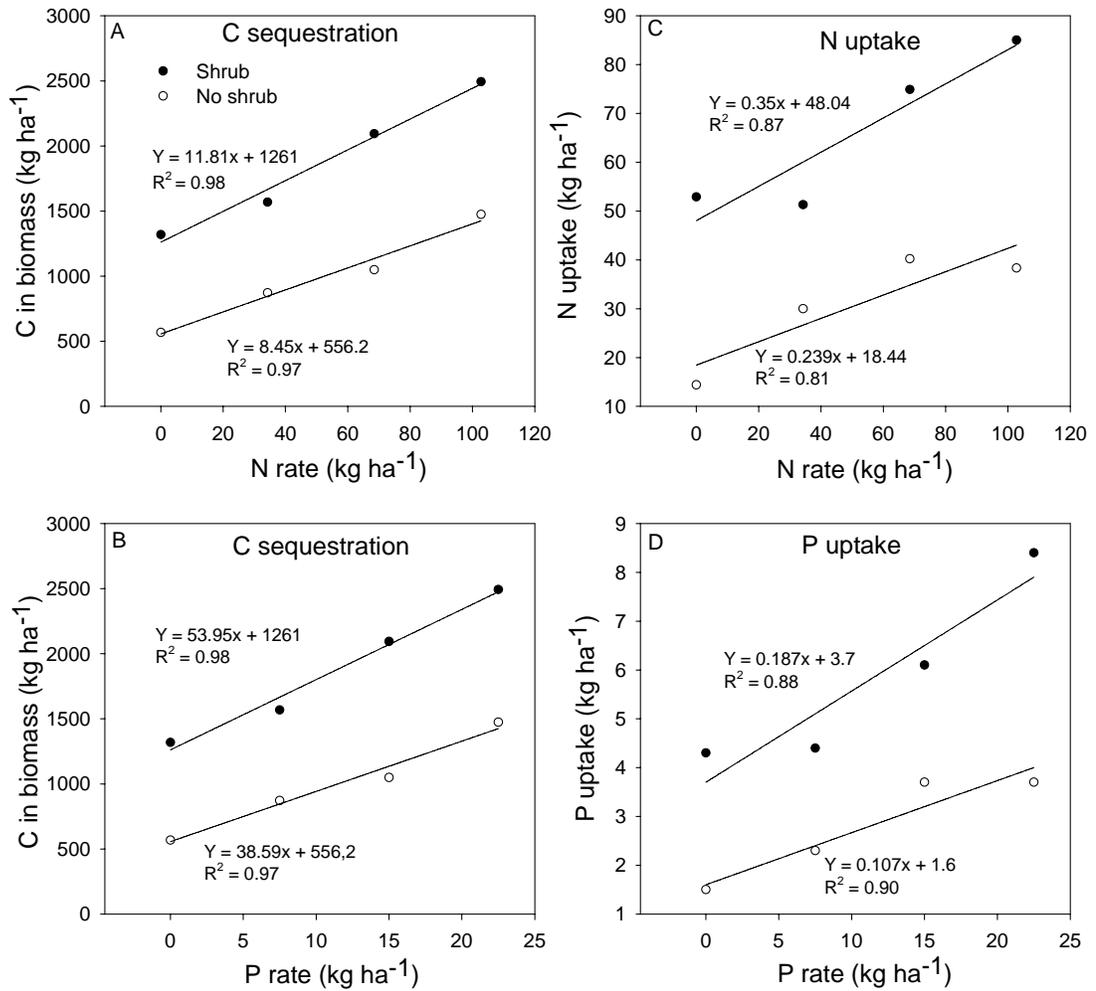


Figure 3.6. Biomass C sequestration (A, B), N (C) and P uptake (D) efficiencies as a function of fertilizer rate in presence or absence of shrub (*P. reticulatum*) at Nioro. Data are from 2005 season; crop is pearl millet.

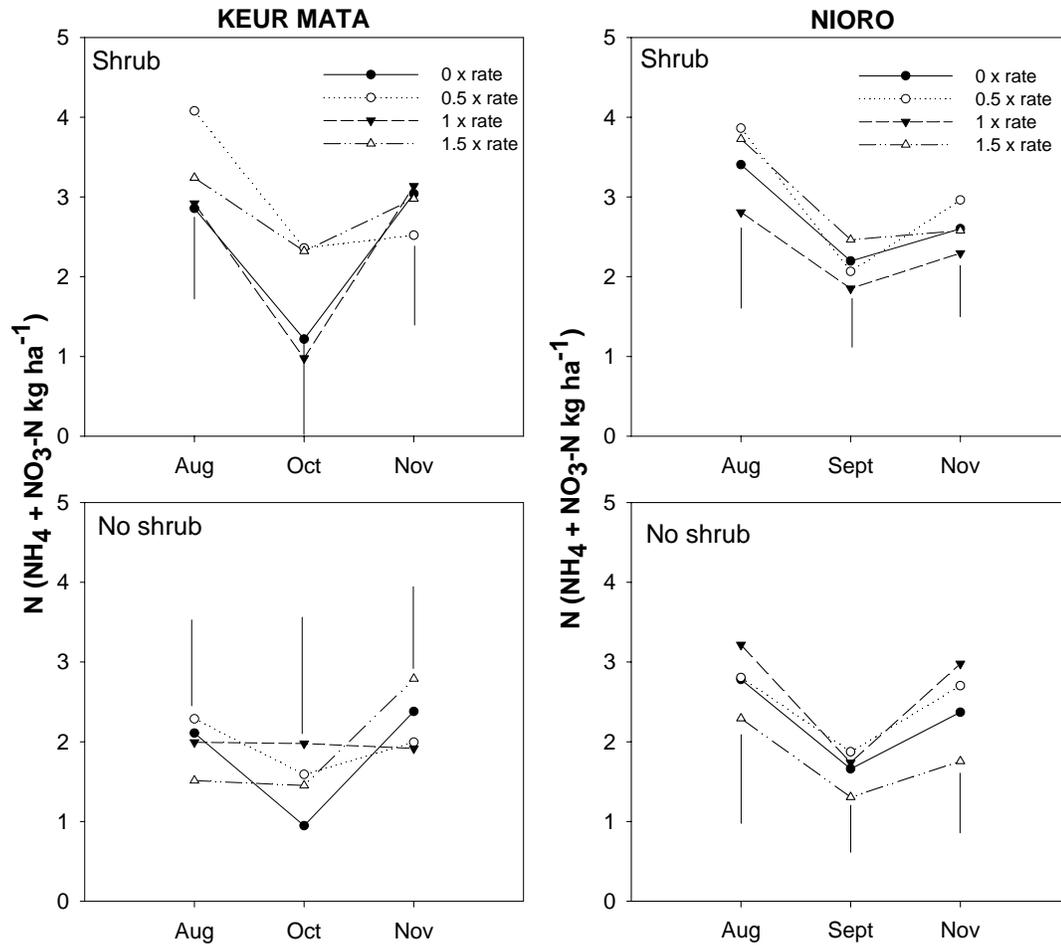


Figure 3.7. Mineral N dynamics in soils as affected by presence of shrubs and fertilizer rate at Keur Mata and Nioro in 2004. Vertical bars represent LSD values at $P < 0.05$.

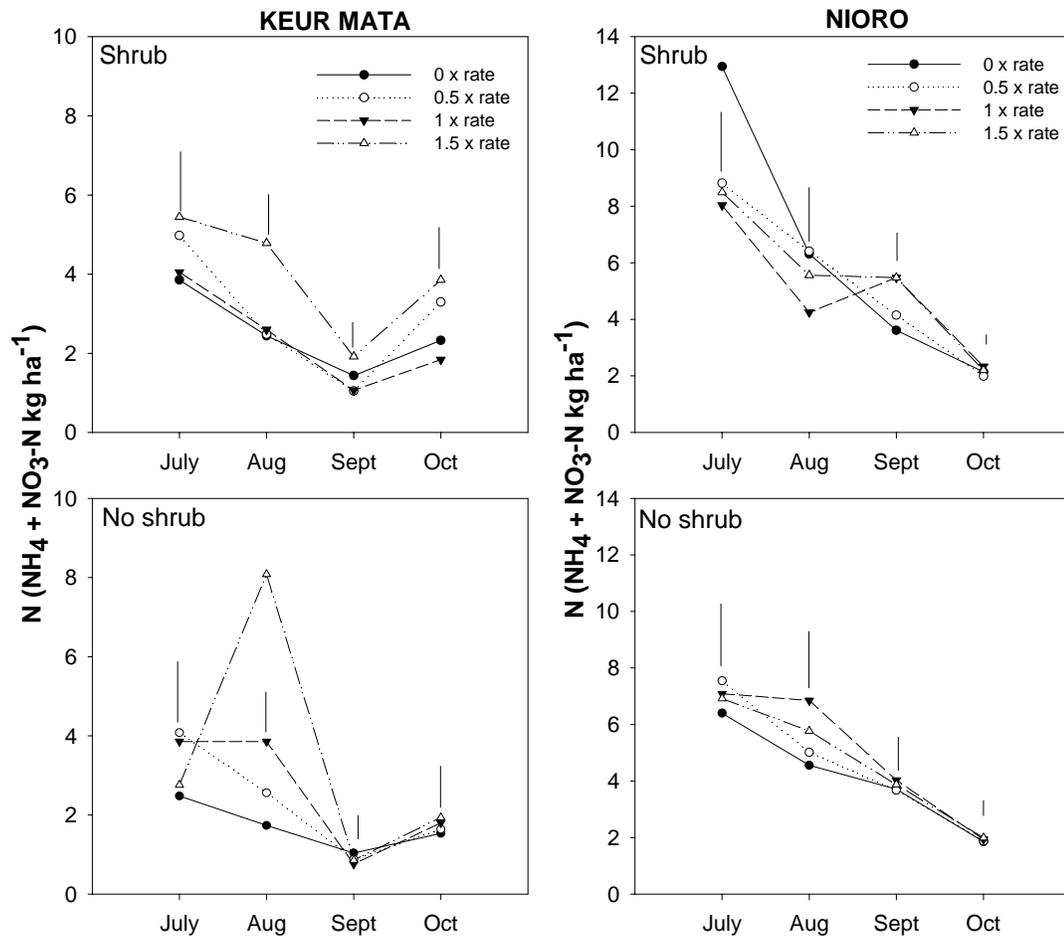


Figure 3.8. Mineral N dynamics in soils as affected by presence of shrubs and fertilizer rate at Keur Mata and Niro in 2005. Vertical bars represent LSD values at $P < 0.05$.

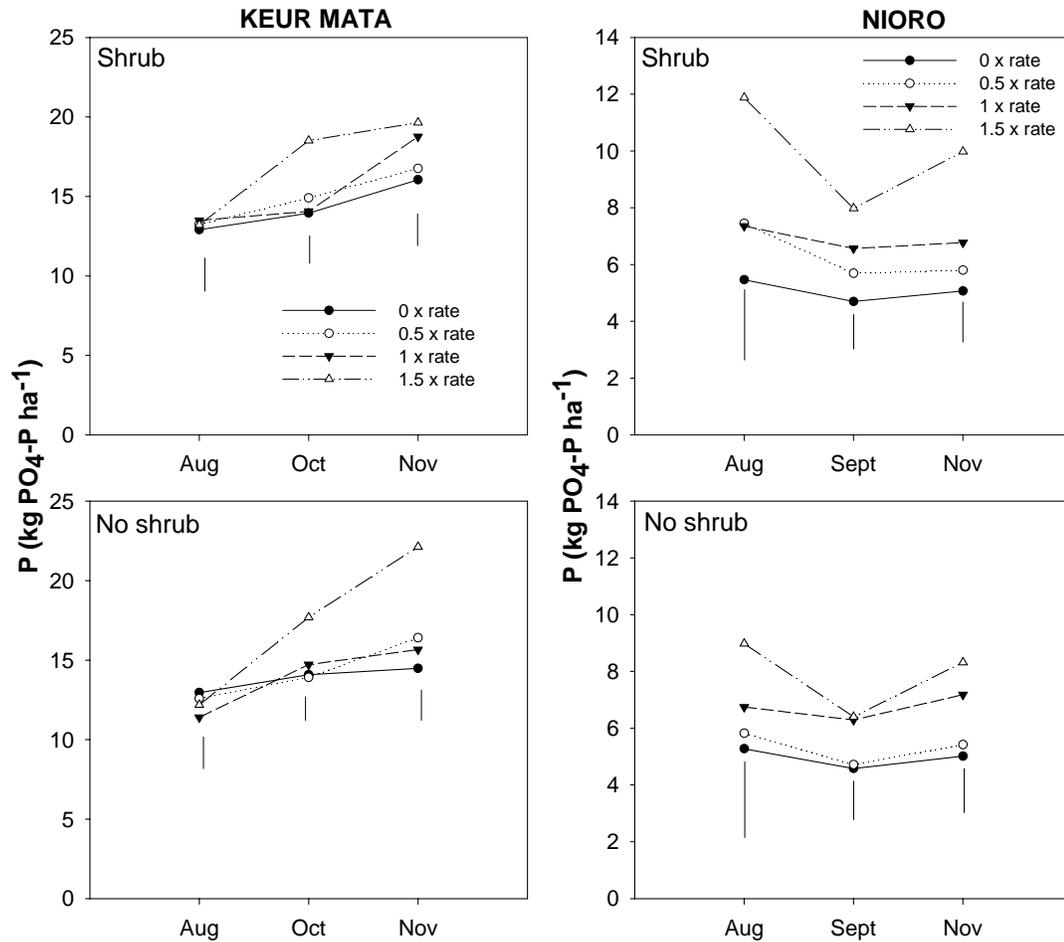


Figure 3.9. Extractable P dynamics in soils as affected by presence of shrubs and fertilizer rate at Keur Mata and Nioro in 2004. Vertical bars represent LSD values at $P < 0.05$.

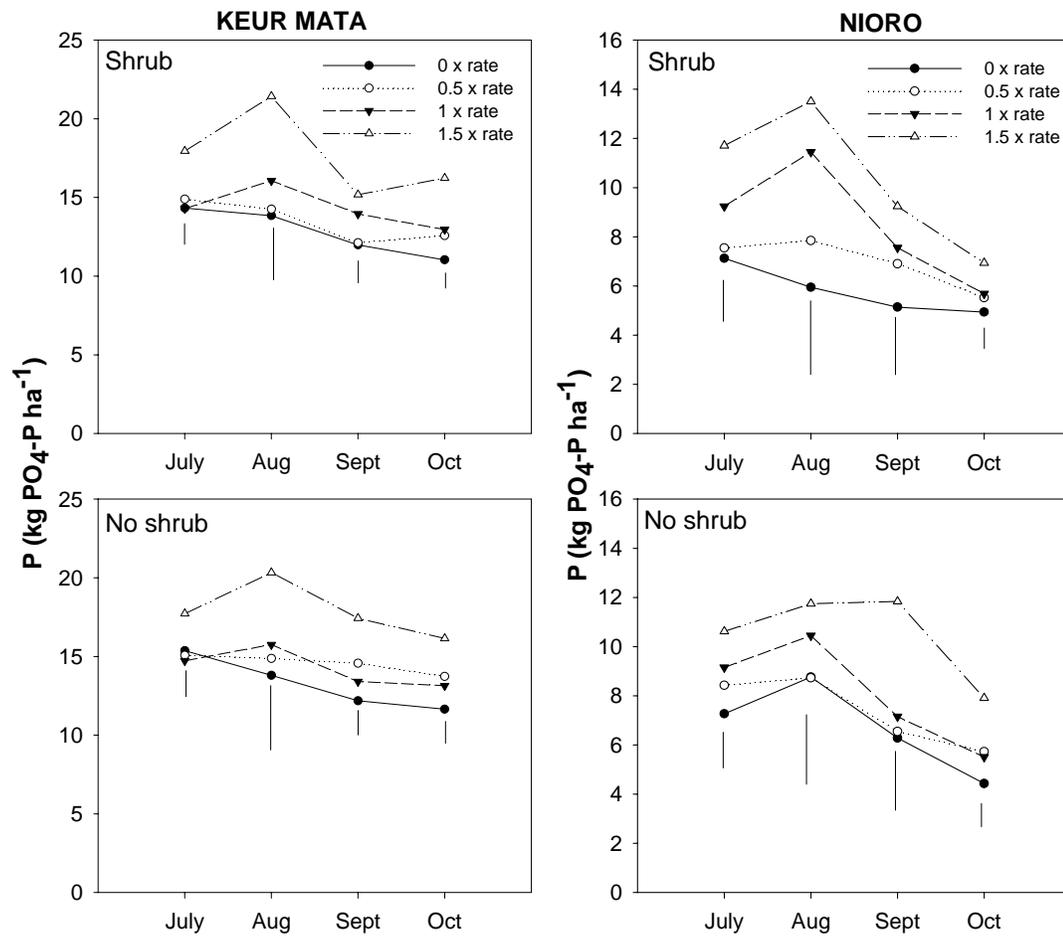


Figure 3.10. Extractable P dynamics in soils as affected by presence of shrubs and fertilizer rate at Keur Mata and Niro in 2005. Vertical bars represent LSD values at $P < 0.05$.

CHAPTER 4**Phosphorus sorption and desorption characteristics of soils incubated with native shrub residues in semiarid Senegal**

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Abstract

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, *G. senegalensis* and *P. reticulatum* were amended to soils where each is found, the Dior (Entisol) and the Deck/Dior (Oxisol) respectively and compared to beef manure for P sorption characteristics. Amended soils (2% wt/wt) were incubated at 24°C for 30 days and 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 (EPC) compared to 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. An incubation period of 75 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 can reduce P sorption and should be included in nutrient management recommendations of deficient P-fixing Sahelian soils.

4.1. Introduction

A major 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 adsorbed by ligand exchange (Parfitt, 1978). These geochemical processes are believed to control the solubility, and thus, the plant availability of P (Cross and Schlesinger, 2001). 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).

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. Decreased P sorption following addition and mineralization of organic residue in soils (Singh and Jones, 1976; Bumaya and Naylor, 1988; Iyamuremye and Dick, 1996) has been attributed to surface complexation of organic acids from decomposing OM with Al- and Fe-oxides, which block sorption sites for P (Hue, 1991; Iyamuremye and Dick, 1996). 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 OM with the P reactive compounds of Al and Fe (Lopez-Hernandez and Burnham, 1974), inhibition of crystallization of Al and Fe oxides by organic matter (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 are coated with Fe and/or Al oxides and hydroxides that are known to sorb Pi (Iyamuremye et al., 2000). The common agricultural practice is a form of agroforestry where native shrubs (*Guiera senegalensis* and *Piliostigma reticulatum*) are allowed to grow in farmers' fields and coppiced and burnt at the beginning of each cropping season. They 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., 2006), which if incorporated into soils could modify sorption capacity of these soils (McBride, 1994). Secondly, canopy and rhizosphere of woody species in semiarid ecosystems are associated with increased OM, nutrient 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 residues amendments on P sorption characteristics of two major soils of Senegal.

4.2. Materials and Methods

4.2.1. 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 (14°45 N, 16°51 W, and 43 m above sea level). The mean annual precipitation is 450 mm. Temperatures range from 20.33°C in December-January to 33.4°C in April-June. The soil is 95% sand, mainly constituted of materials from eolian deposits, classified as leached ferric lixisol (FAO, 1991), locally referred to as a Dior soil (Badiane et al., 2000). *G. 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 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, 1991)], a leached ferruginous tropical soil. The dominant shrub species at the site is *P. reticulatum*. The top soil (0-30 cm) has organic matter content of 0.3-0.5%, average total N and P contents of 0.15 g kg⁻¹ and 65 mg kg⁻¹ respectively, with pH in the range of 5.2 to 6.3. Total N and P contents of manure were 17.9 and 3.4 g kg⁻¹ respectively. A full description of soil and organic residues characteristics is given in Chapter 2.

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 (A. Lufafa, personal communication), were randomly selected for soil and shrub biomass sampling. Each shrub was treated as a replicate. This spatial replication was maintained for subsequent laboratory incubations. In January 2003 during the dry season, soil was collected from a 0-30 cm depth beneath (approximately 1 m radius from the shrub center) and outside the influence of shrub canopy (2-3 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 to pass a 2-mm screen prior to chemical analysis 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.

The experimental design was a randomized 2 by 4 factorial design for each shrub type with two soil sources (beneath or outside the shrub canopy) and four residue treatments [leaf, leaf+stem in same proportion as found under field conditions, composted beef manure or control of soil only]. There were four replications maintained from the field replication soil sampling of the four shrubs. The residue treatments reflect possible management options of farmers. Leaf alone which represents the case where coppiced material is dried in the field and stems are stripped of leaf material and removed from fields for fencing or fuel; or when all coppiced materials are non-thermally managed and left in the fields (leaf+stem). Each shrub species was incubated with its associated soil i.e. *G. senegalensis* residues with soils from site 1 and *P. reticulatum* residues with soils from site 2.

4.2.2. 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, Missouri). 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).

4.2.3. Soil incubation

Batch adsorption isotherms were used to characterize P sorption and desorption for the two soil types in Senegal (Dior and Deck/Dior) collected beneath and outside the canopy of the associated shrub species (*P. reticulatum* for the Deck/Dior soil and *G. senegalensis* for the Dior soil) in four replicates. Organic amendments consist of leaf and leaf+stem of the above shrubs species, and beef manure locally provided by the dairy farm at Oregon State University in Corvallis. The relative mass of leaves and stems in the leaf+stem mixture was 40% and 60% respectively. Two sets of 30 g of soil mixed with 0.6 g of organic amendments were incubated at 24°C for 30 days and 75 days respectively. Soil moisture was kept at approximately 2/3s field capacity by weighing the samples every week. At the end of the incubation, the soils were air-dried and kept at 5°C until they were analyzed.

4.2.4. 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 CaCl_2 containing 0, 0.2, 0.5, 1, 2.5, 5, 7.5 and 10 mg P L⁻¹. 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 27,000 x g for 5 mn, 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 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 (mg P kg⁻¹ soil) against P in the equilibrium solution.

4.2.5. Phosphorus desorption

Phosphorus desorption values were obtained by equilibrating 2 g of soil with 20 ml of a solution containing 10 mg P L⁻¹ in a constant ionic strength background of 0.01 M CaCl₂. The pH value of the 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 0.01 M CaCl₂ 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). Difference between initially adsorbed P and P recovered in solution after desorption were considered as P retained on the soil in a relatively stable form.

4.2.6. 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 (mg P kg⁻¹)

b = adsorption maxima (mg P kg⁻¹)

k = dimensionless parameter related to binding energy

c = P concentration in the equilibrium solution (mg L⁻¹)

2) Freundlich equation:

$$q = KC^{1/n} \quad [2]$$

or modified Freundlich equation

$$q = KC^{1/n} + Q \quad [3]$$

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 separately for each shrub and associated soil as a split plot design using SAS PROC MIXED (SAS Institute, 1999), with soil location treatments (beneath or outside shrub canopy) as main plot factors and residue amendments as the subplot factors. The coefficient of determination (R^2) in the non-linear regression was estimated as:

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

4.3. Results and Discussion

4.3.1. Equilibrium solution pH

All organic amendments significantly increased equilibrium solution pH relative to the control (Table 4.1). 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 to the *P. reticulatum* soils, the magnitude of pH increase was smaller in shrub residues amended soils but greater when soil was amended with manure. The same pattern of pH decrease following 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 following addition of organic residues has been attributed to ligand exchange reactions of organic acids from decomposing organic matter with Al- and Fe-OH that produce OH⁻ in solution (Hoyt and Turner, 1975; Hue, 1992). However, such effect is transient as pH drops in the later stage of incubation due to the dynamics of organic components involved in the Al/Fe complexation reactions (Hoyt and Turner, 1975).

4.3.2. Phosphorus sorption

Sorption isotherms after 30 days of incubation are shown in Fig. 4.1 for *P. reticulatum*- and *G. senegalensis*-associated soils. The different organic amendments varied widely in their ability to sorb added Pi. The highest P sorption was observed with unamended soils while manure amended soils had the lowest. At the highest concentration of added P (10 mg P L⁻¹), sorbed P was lower in all treatments beneath canopy of *P. reticulatum* compared to their counterparts outside the canopy (Figs. 4.1A and 4.1B). In *G. senegalensis*-associated soils, P sorption patterns were similar in soils beneath and outside shrub canopy (Figs. 4.1C and 4.1D). Leaf-amended soils sorbed less P than leaf+stem-amended soils except in soils outside the canopy of *P. reticulatum* (Fig. 4.1B). An extended incubation period of 75 days generally resulted in a decrease of P sorption, particularly in the organic residue-amended soils (Fig. 4.2). The shape of the isotherms was basically the same for all treatments, depicting an L-type characteristic (Sparks, 2003).

The ability of organic amendments to decrease P sorption of soils observed in the current study is consistent with results of previous researches (Singh and Jones, 1976; Bumaya and Naylor, 1988; Iyamuremye et al., 1996). However, there are conflicting explanations for the mechanisms that control OM effects on P sorption. Some workers consider Al/Fe complex formation with- and/or competitive inhibition by organic acids from decomposing OM to be the major reactions involved (Iyamuremye and Dick, 1996; Iyamuremye et al., 1996; Ohno and Erich, 1997). Other

authors ascribed the decrease in P sorption to P released by the decomposing OM (Guppy et al., 2005), which implicitly point to a mechanism that prevents or limits sorption of P mineralized from the organic amendment onto the mineral soil. Indeed, results of Le Mare (1982) indicate that P sorbed to organic matter-associated Al and Fe is exchangeable. Our study showed evidence of P release from the organic amendments during the sorption phase, especially with manure-amended soils, which is clearly seen at 0 P mg L⁻¹ treatment. In addition, there was a negative relationship between P sorption and P levels of organic amendments and soils, which to some extent supports the contention of Guppy et al. (2005).

For the shrub residue treatments, net P release does not seem to be the major mechanism of P sorption decrease compared to unamended soils. Evidence for this is the negligible amount of P desorbed at adsorptive concentration of 0 mg P L⁻¹. Moreover, shrub residues used in this study had P content <0.2% with a C/P ratio >340, which according to different authors would not favor net P mineralization (Singh and Jones, 1976; Sharpley and Smith, 1989; Stevenson and Cole, 1999). Our results suggest that there are several interacting mechanisms for the reduction in P sorption. Other mechanisms that may have been operating include Al/Fe complexation by inorganic ligands such as F, SO₄, or physical protection of P from sorption sites on the mineral soil surface by organic matter (Iyamuremye and Dick, 1996). The former mechanism merits consideration in the case of the present study as manure-amended soils experienced the lowest P sorption.

4.3.3. 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 the Langmuir equation, whereas Freundlich model provided a better fit for this amendment (Table 4.2). 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, though being empirical, assumes that the

binding affinity decreases as adsorption increases. Such assumption is closer to reality and consistent with adsorption process than that of constant binding energy underlying 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 soils 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 exchangeable P except manure-treated soils. This may explain why the simple Freundlich equation was well fitted for most of the data.

The predicted sorption maxima were low and ranged from 29 to 44 mg P kg⁻¹ in the *P. reticulatum*-associated soils incubated for 30 days (Table 4.2). In these soils, shrub residue-amendment reduced P sorption maxima by 10% on average beneath the shrub canopy, and by 27% outside the shrub canopy. In *G. senegalensis*-associated soils, the sorption maxima ranged from 32 to 47 mg P kg⁻¹ and the decrease in P sorption caused by shrub residue amendments was 24% on average for soils outside and beneath the shrub canopy. It is worth noting that predicted P maxima were generally higher outside shrub canopy than beneath the canopy, and P sorption maxima were greater in *G. senegalensis*-associated soils than in the *P. reticulatum* ones (Table 4.2).

The addition of organic amendments decreased the P affinity constant. In samples incubated for 30 days, the reduction that resulted from shrub residue amendment was about 53% beneath the canopy of *P. reticulatum*-associated soils and 28% outside the canopy. In *G. senegalensis*-associated soils, the reduction in P affinity was 72% regardless of soil location. A longer incubation time of 75 days generally reduced the predicted P affinity constants in the *G. senegalensis*-associated soils, whereas in the *P. reticulatum*-associated soils, P affinity constant values were increased. The Freundlich K varied widely for the samples and had the same ordering as the Langmuir affinity constants (Table 4.2).

The range of P concentrations used in this sorption study is low compared to 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 Langmuir P adsorption maxima estimated 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).

4.3.4. 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. 4.3. From these graphs, EPC was derived as the value of solution P concentration at zero sorption while the slope of the line gave an index of the EBC (Hartikainen, 1991; Kpombrekou and Tabatabai, 1997). These parameters are recorded in Table 4.3 for the whole set of soil amendments.

Equilibrium buffer capacity values were lowest for manure-amended soils and highest for the control, ranging from 5.22 to 62.03 L kg⁻¹ beneath the shrub canopy and from 9.93 to 156.76 L kg⁻¹ outside the canopy. *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⁻¹ beneath the canopy and 207 L kg⁻¹ outside the canopy. These values dropped to 10 L kg⁻¹ with manure amendment. Apart from manure-amended soils, which had EPC values comprised between 0.84 and 1.37 mg L⁻¹, EPC values derived for the different treatments were low (<0.1 mg L⁻¹), and were lowest for unamended soils.

In general, a prolonged incubation period (75 days) reduced the EBC in all samples except leaf+stem amendment in the *P. reticulatum* soils (data not shown). Based on the average EPC of 0.2 mg P L⁻¹ considered as required solution P for near

maximum plant growth (Fox and Kamprath, 1970), one could infer from the above results that manure would provide a fair amount of solution P that may well support optimal crop production in soil conditions of this study. Although shrub leaf added to soil may improve P availability to the crop, level of soil solution-P would most likely be sub-optimal for adequate plant growth in absence of fertilization. The standard P requirements of the soils varied similarly to the adsorption maxima and ranged from 1.73 to 10.62 mg P kg⁻¹ and were slightly higher in *P. reticulatum*-amended soils than in *G. senegalensis*-amended ones (Table 4.3).

4.3.5. Phosphorus desorption

Most of the desorbed P (>90%) was obtained by third extraction for the 30-day incubation (Fig. 4.4). 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 while 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 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. Higher amount of P was desorbed outside the shrub canopy. An extended incubation time of 75 days generally resulted in a slightly more P desorption (data not shown).

For any given solution P concentration, P sorbed onto the soil during desorption was always higher than that during sorption. This hysteresis illustrated in Fig. 4.5 has been reported in many sorption studies (Barrow, 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 not have been long enough for the reaction to come to an equilibrium.

4.4. Conclusions

The results of this study showed that organic amendments decrease 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. Generally, the decrease in P sorption was greater beneath shrub canopy than outside the canopy. A prolonged incubation time of 75 days resulted in slightly less P sorption and more EPC than when soils were incubated for 30 days. These results suggest that, shrub residues incorporated to soils may help reduce the amount of commercial P fertilizer needed for optimal plant growth. Manure of the kind used in this study, released higher amount of P in solution and at a faster rate than did the other amendments. However, given its low capacity to modulate further P addition, lower rates than those used in the current study and split applications would be sound agricultural practices that would limit leaching and runoff of P susceptible to pollute surface and groundwaters.

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Table 4.1. Effect of organic amendments on equilibrium solution pH in soils beneath and outside shrub canopy for 30 day- and 75 day-incubation. For each shrub and associated soil, values with same superscript letter within each column are not significantly different at $P < 0.05$.

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

Table 4.2. 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	[‡] b	R ²	[§] K	R ²	[†] k	[‡] b	R ²	[§] K	R ²
<u>Nioro (<i>P. reticulatum</i>)</u>											
Control	Beneath	0.64	32.8	0.99	12.2	0.99	0.94	27.9	0.99	11.9	0.99
	Outside	0.82	43.9	0.98	19.1	0.98	1.15	41.2	0.98	19.0	0.98
Leaf	Beneath	0.31	29.7	0.99	6.9	0.99	1.08	18.8	0.99	8.4	0.99
	Outside	0.64	32.2	0.99	12.0	0.99	1.02	29.3	0.99	12.9	0.99
Leaf+stem	Beneath	0.57	28.9	0.99	9.7	0.99	1.07	23.3	0.99	10.4	0.99
	Outside	0.74	32.6	0.99	12.8	0.99	1.64	28.6	0.99	15.1	0.99
manure	Beneath	[¶] NF	NF	NF	1.3	0.99	NF	NF	NF	0.9	0.99
	outside	NF	NF	NF	0.9	0.99	NF	NF	NF	1.0	0.99
<u>Keur Mata (<i>G. senegalensis</i>)</u>											
Control	Beneath	1.48	44.1	0.99	22.4	0.99	1.28	44.3	0.99	21.1	0.99
	Outside	1.45	47.2	0.98	23.9	0.99	1.69	43.2	0.99	22.6	0.99
Leaf	Beneath	0.41	32.6	0.99	9.0	0.99	0.41	30.5	0.99	8.3	0.99
	Outside	0.41	35.9	0.99	9.9	0.99	0.40	32.9	0.99	8.8	0.99
Leaf+stem	Beneath	0.80	34.4	0.99	13.6	0.99	0.69	33.8	0.99	12.2	0.99
	Outside	0.77	36.9	0.99	14.1	0.99	0.65	35.2	0.99	12.3	0.99
manure	Beneath	NF	NF	NF	3.5	0.99	NF	NF	NF	1.5	0.99
	outside	NF	NF	NF	3.6	0.99	NF	NF	NF	1.4	0.99

[†]k = binding affinity expressed in L kg⁻¹

[‡]b = adsorption maximum expressed in mg kg⁻¹

[§]K = Freundlich constant expressed in mg kg⁻¹

[¶]NF = Not fitted

Table 4.3. Equilibrium P concentration (EPC), buffering capacity (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	EBC	[†] P _{0.2}	EPC	EBC	P _{0.2}
		mg L ⁻¹	L kg ⁻¹	mg kg ⁻¹	mg L ⁻¹	L kg ⁻¹	mg kg ⁻¹
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	-

[†]P_{0.2} = P sorbed at equilibrium solution concentration of 0.2 mg P L⁻¹

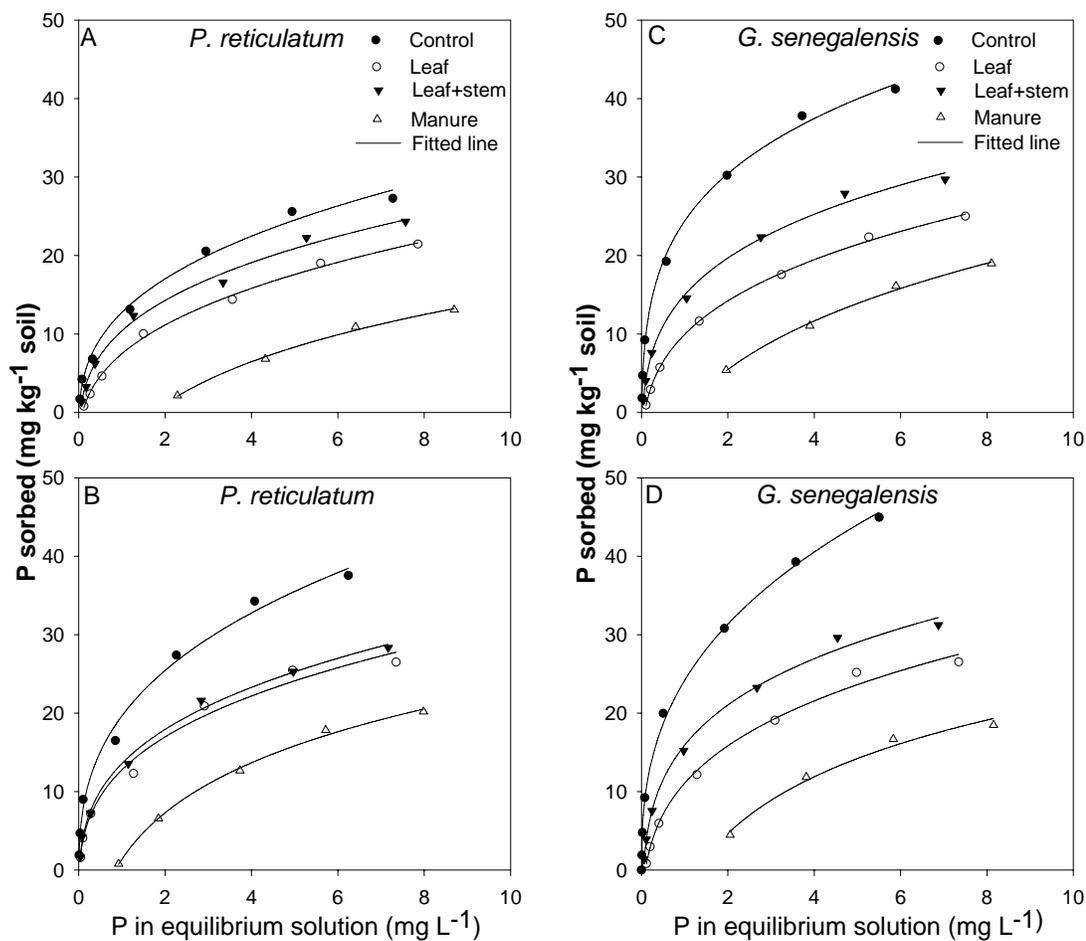


Figure 4.1. P adsorption isotherms following 30-day incubation of soils amended with *P. reticulatum* residues beneath (A) and outside shrub canopy (B); and soils amended with *G. senegalensis* residues beneath (C) and outside shrub canopy (D). Adsorption isotherms were fitted with equations $q = Q + Kc^{1/n}$ for manure and $q = Kc^{1/n}$ for all other treatments.

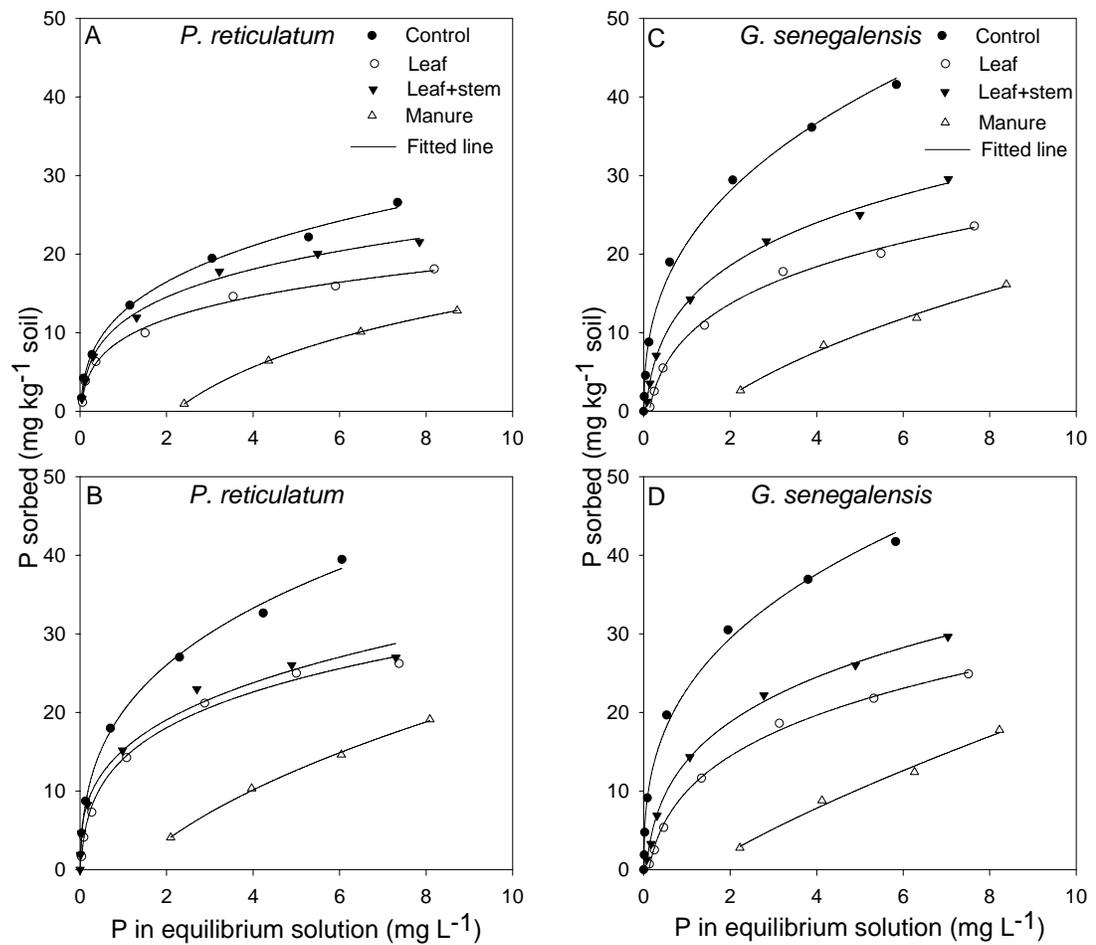


Figure 4.2. P adsorption isotherms following 75-day incubation of soils amended with *P. reticulatum* residues beneath (A) and outside shrub canopy (B); and soils amended with *G. senegalensis* residues beneath (C) and outside shrub canopy (D). Adsorption isotherms were fitted with equations $q = Q + Kc^{1/n}$ for manure and $q = Kc^{1/n}$ for all other treatments.

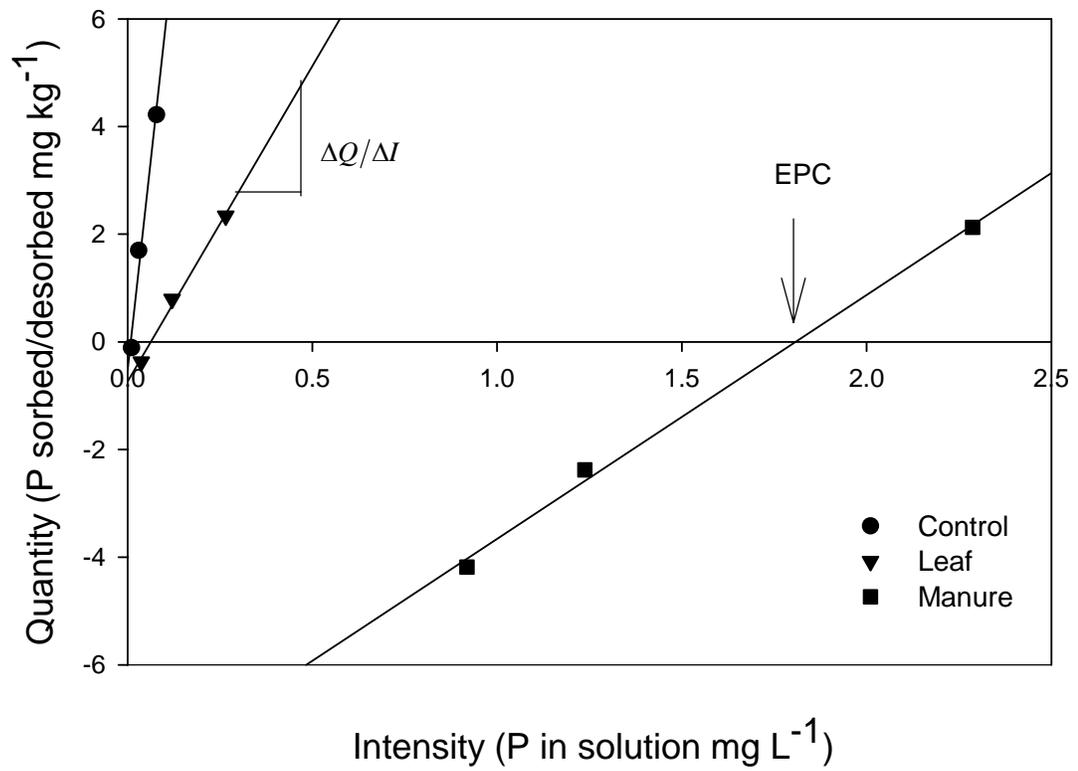


Figure 4.3. Quantity/Intensity plot for soil beneath the canopy of *P. reticulatum* incubated for 30 days.

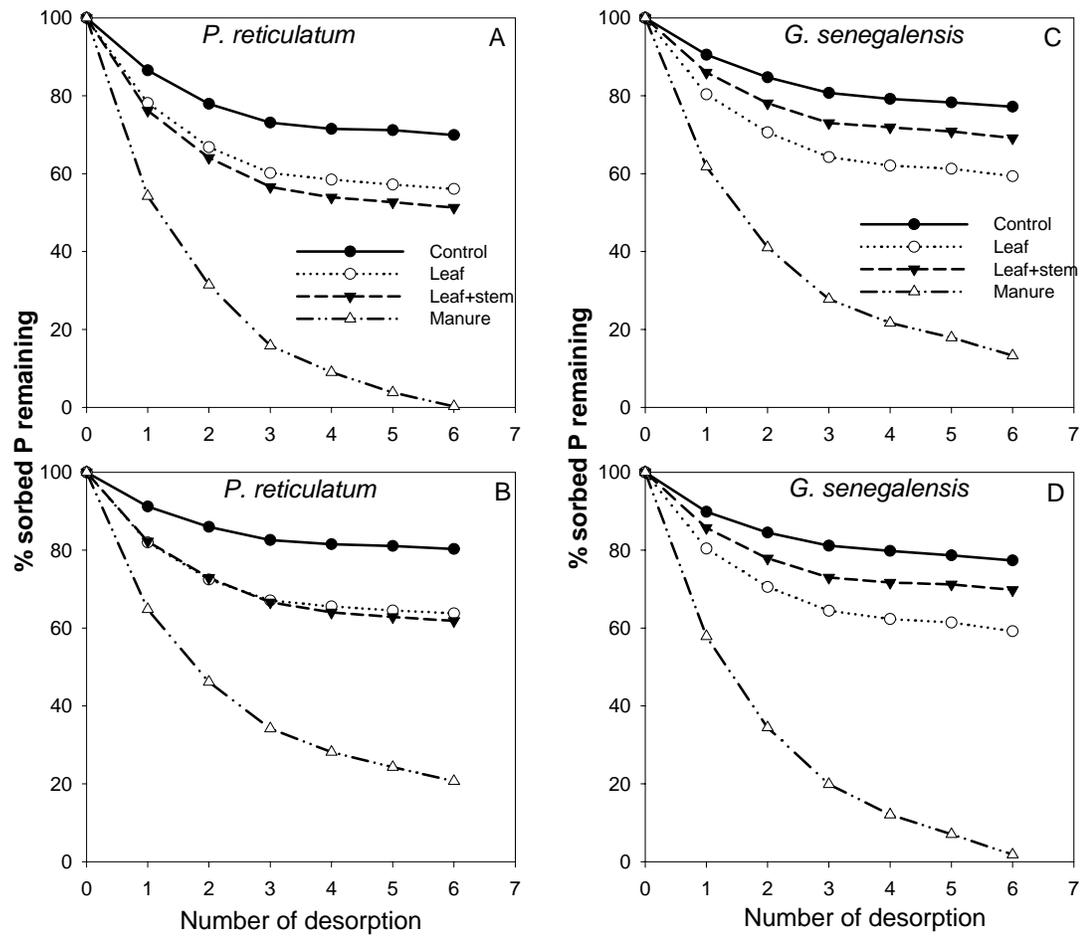


Figure 4.4. Percentage of sorbed P remaining after sequential desorptions (n = 6) in 0.01M CaCl₂ solution for *P. reticulatum* residue-amended soils beneath (A) and outside shrub canopy (B); and *G. senegalensis* residue-amended soils beneath (C) and outside shrub canopy (D). Incubation period is 30 days.

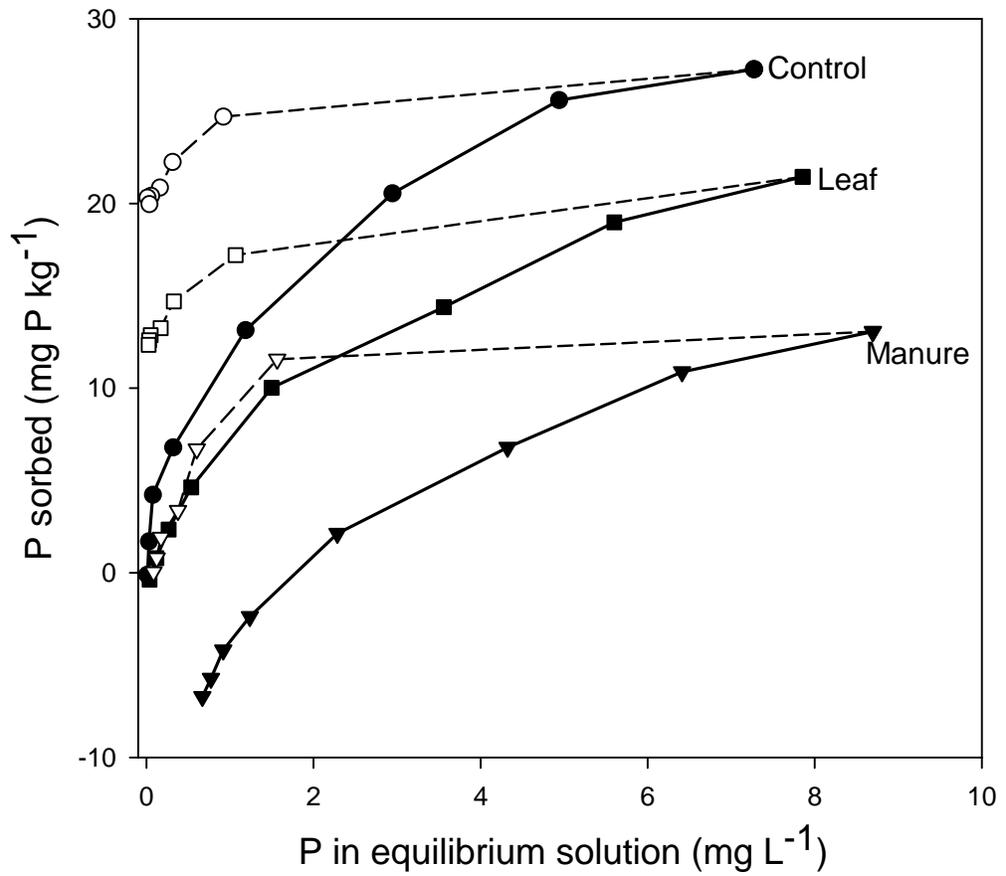


Figure 4.5. Compared P isotherms during sorption (solid line) and desorption (broken line) for soils beneath the canopy of *P. reticulatum* incubated for 30 days.

CHAPTER 5**Phosphorus fractions and nutrient patterns in two native shrublands of a semiarid ecosystem**

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Abstract

Two shrub species (*Piliostigma reticulatum* and *Guiera senegalensis*) form part of the cropping system in farmers' fields in Senegal but their effects on spatial nutrient distribution and P cycling is not well understood. This study investigated in two major soil types in Senegal nutrient distribution and inorganic and organic P pools in a gradient across shrub canopy using a modified sequential P fractionation procedure. Both soil types had low total P and low available P. Phosphorus fractions were dominated by NaOH-P. Organic P (Po) made up about half of total P, and most of the organic P was found in the NaOH-P fractions. Under shrub cover, labile P, particularly bicarb-Po was higher than outside the canopy. Similarly, C, N and P were more concentrated under shrub canopies and decreased in a gradient outwards the shrub center. *P. reticulatum* was associated with greater NaOH-Po fraction under the canopy whereas *G. senegalensis* had higher bicarb-Po at one of the site of study. Calculated index of biologically available organic P was about 60% and suggests that biological processes represent an important part of P cycling in these shrub-based ecosystems. Moreover, *G. senegalensis* had more C, N, and lower pH under its canopy than *P. reticulatum*. Our results confirm that shrub vegetation is important in preventing soil fertility degradation in fragile semiarid ecosystems of the Sahel. The differential ability of the shrubs in modifying soil characteristics and nutrients under their canopies should be taken into consideration in designing optimal management techniques of these shrub ecosystems.

5.1. 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 is kept at low levels because of Al and Fe oxides reactions with P in highly weathered soils (Parfitt, 1978).

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 makes it difficult to measure potentially mineralizable P pool. Alternatively, the sequential fractionation of soil P with chemicals of increasing strength 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 the importance of biological and geochemical controls on P cycling in various ecosystems (Hedley et al., 1982; Tiessen et al., 1984; Lajtha and Schlesinger, 1988; Cross and Schlesinger, 2001).

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 in a weathering gradient from 20 to 90% (Stevenson and Cole, 1999). Though Po is usually considered as a biologically inactive P constituent, mineralization of only small fraction of this pool can be important to meet crop P requirements (Harrison, 1982). Recent reports indicate that in P-limited ecosystems, Po mineralization may be the major source of soil solution P for the crop (Adepetu and Corey, 1976; Beck and Sanchez, 1994; Cross and Schlesinger, 2001). 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 patchiness in their woody vegetation cover that may alter nutrient cycling. 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). These zones with better soil quality have intense biological activities and presumably faster nutrient cycling (West, 1991; Gallardo and Schlesinger, 1995). Shrubs may further foster the biogeochemical cycling of nutrients by building up organic matter through litter deposition and decomposition. Species characteristics may influence soil properties around the shrub depending on site and environmental characteristics (Abrams et al., 1990).

Two native woody shrub species, *Piliostigma reticulatum* and *Guiera senegalensis*, are widely found at varying density in Senegal (Lufafa et al., 2006) 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. The objectives of this study were to determine the influence of *P. reticulatum*- and *G. senegalensis*-canopies and rhizospheres on: 1) soil inorganic and organic P fractions; and 2) spatial distribution of nutrients.

5.2. Materials and Methods

5.2.1. 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 20.33°C in December-January to 33.4°C in April-June. The soil is 95% sand, mainly constituted of materials from eolian deposits, classified as leached ferric lixisol (FAO, 1991), locally referred to as a Dior soils (Badiane et al., 2000). They have low buffer and exchange capacity (Tschakert et al., 2004). *Guiera senegalensis* is the dominant shrub vegetation, with average stand density of 240 shrubs ha⁻¹ (Kizito et al., 2006). 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, 1991)], a leached ferruginous tropical soil. The dominant shrub species at the site is *Piliostigma reticulatum* found at average density of 185 shrubs ha⁻¹ (Kizito et al., 2006).

Within each study area, eight shrubs of the dominant species were randomly selected from two plots of approximately 0.1 ha (four shrubs per plot). The shrubs selected had a canopy size of approximately 2 m, which is representative of average shrub size in farmers' fields, and were free from the influence of neighboring shrubs. This first set of soil samples further referred to as "independent site samples" was designed to evaluate soil characteristics and interaction with shrub canopy within each site. Additionally, at each site, we identified two plots that had both shrub species at approximately equal densities to examine species effect on soil P fractions and nutrient distribution. In these plots, four pairs of *P. reticulatum* and *G. senegalensis* (adjacent shrub stands separated by <2 m) were selected at each site for soil sampling. This second set of samples is further referred to as "paired shrub samples". 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 10 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 were composited 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 two years prior to soil sampling, and shrub stands were estimated from ring counts of stem cross-sections to be over 10 years of age at the time of sampling (I. Diedhiou, personal communication).

5.2.2. Laboratory Analyses

Soil pH was determined with a glass electrode in 1:2.5 soil:water ratio. Organic carbon (C) and total nitrogen were determined by combustion on a LECO WR-12 C autoanalyzer (LECO Corp., St. Joseph, Missouri). Total P was determined by a modified Kjeldahl $\text{Li}_2\text{SO}_4\text{-H}_2\text{SO}_4$ 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). Extractable P (plant-available P) was obtained by the $\text{NaHCO}_3\text{-NH}_4\text{F}$ method (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.

5.2.3. 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 shrub cover (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. 30 mL of deionized water was added with a 2.5cm² anion exchange resin strip (AR-204UZR-4R Ionics) (Abrams and Jarrell, 1992). The tubes were shaken for 16 hours on a horizontal shaker. Phosphorus was desorbed from the resin strips by adding 20 ml of 0.5M HCl solution followed by shaking for 16 hours (resin P). The water-soil suspension was centrifuged at 17, 500 rpm for 10 mn at 0°C and the supernatant discarded. The soil residue was subsequently extracted with 30 ml of the following extractants: 0.5M NaHCO_3 (pH 8) for bicarbonate-P, 0.5M NaOH (hydroxide-P), 1M 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 0.9M H_2SO_4 (Tiessen and Moir, 1993) and 5M 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, samples were digested with H₂SO₄-H₂O₂ (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.

5.2.4. Interpretation of P fractions

The terminology used in referring to the different fractions isolated in the sequential extraction of P is slightly variable depending on authors (Cross and Schlesinger, 1995). The Resin-P extracts free P 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 as 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 extract P 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 (Condon et al., 1990); hence un-extractable residual P obtained from the H₂SO₄-H₂O₂ 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), which represents the most stable P pool.

5.2.5. Statistical analyses

The independent site data were 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. *A priori* test on log-transformed data for paired shrubs data revealed statistically equal variances for the two sites [$(MSE_{site1}/MSE_{site2}) < F_{(10,10)(0.05)} = 2.98$]. Therefore, paired shrubs data were pooled for the two sites and analyzed as a 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 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 $P < 0.05$.

5.3. Results

5.3.1. Soil nutrients and pH

Soil characteristics had the same patterns in both the independent site samples and the paired shrub samples analysis. Therefore, only the latter analysis is presented. The MANOVA analysis revealed overall significant site, species and sampling location effects on soil characteristics ($P < 0.0001$). Nutrients were generally more concentrated under shrub canopy (Fig. 5.1). Soils at Keur Mata 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 extractable P, were higher under shrub canopy and decreased linearly in a gradient outside the shrub canopy (Fig. 5.1). Inorganic N (NH_4^+ -N and NO_3^- -N) were highest under shrub canopy and lowest in the outer canopy in Nioro soils, but showed no consistent pattern in Keur Mata soils (Fig. 5.1). Under *G. senegalensis*, pH values were acidic and increased in a gradient outside the canopy. In contrast, beneath *P. reticulatum*, a comparatively higher pH was observed, which tended to decrease with increasing distance from the shrub center (Fig. 5.1).

5.3.2. Soil P fractions

Data for the independent site samples (non-specific canopy effect) are presented in Table 5.1 for Keur Mata and Nioro sites. Mean total P (calculated from the sum of individual P fractions) was $130.7 \text{ mg P kg}^{-1}$ at Keur Mata, and $65.5 \text{ mg P kg}^{-1}$ at Nioro (Table 5.1). Under shrub canopy, the contribution of P_0 to total P was 36.9% at Keur Mata and 49.6% at Nioro. In soils outside the canopy, these proportions were 36.1 and 44.9% at Keur Mata and Nioro respectively. Hydroxide extractable P

was the major soil P pool and accounted for approximately 38% of total P at both sites (Table 5.1). The second largest pool was the cHCl-P (22.5% of total P), and the smallest fraction was the resin-P, which comprised 3.5% of total P at Keur Mata and 2.5% at Nioro. The dHCl-Pi represented 9% and 7.5% of total P at Keur Mata and Nioro respectively whereas residual-P accounted for 16-18% of total P at both sites. The bicarbonate Po pool was significantly higher under shrub cover than outside the shrub canopy at both sites ($P < 0.01$). Additionally, the resin-Pi and bicarb-Pi were significantly higher under shrub canopy than outside the canopy at Keur Mata ($P < 0.05$) but identical at Nioro. All other P fractions were distributed similarly under and outside shrub vegetation cover.

Organic P represented an important portion of most P fractions. Apart from the cHCl-P and dHCl-P pools, which were mainly constituted of inorganic P, all the other P fractions were dominated by organic P. At Keur Mata, 63% of NaOH-P was in organic form whereas at Nioro, Po represented about 80% of NaOH-P. Moreover, NaOH-Po was the dominant fraction of the total soil Po and represented 62.6 to 66.8% of total Po at Keur Mata and 60.9 to 64.6% of total Po at Nioro (Table 5.1).

Examination of paired shrub samples data revealed site and species differences in P fractions. Most of the inorganic P fractions (NaOH-Pi, dHCl-P, cHCl-Pi) were higher in soils at Keur Mata than at Nioro ($P < 0.001$), and so was total P (Table 5.2). At both sites, the NaOH-Po fraction was significantly greater ($P < 0.01$) under the canopy of *P. reticulatum* than under *G. senegalensis*. The magnitude of the difference was larger at Nioro than at Keur Mata (respectively 56% and 24% more NaOH-Po with *P. reticulatum*-canopy soils than *G. senegalensis* ones (Fig. 5.2)). On the other hand, bicarbonate-Po content was higher under *G. senegalensis* at the Nioro site (Fig. 5.2). All other P fractions were equally represented beneath the canopy of the two shrub species.

5.4. Discussion

5.4.1. Soil nutrients and pH

Soil properties differed between sites, and shrub significantly influenced spatial distribution of nutrients. At Nioro, soil C, N and inorganic N contents were higher but total P and available P levels were lower than at Keur Mata. A difference in mineralogy of the two soils, the higher clay content and higher rainfall regime at Nioro may have contributed to these differences between sites. Beneath the shrub canopy, concentrations of C, N, and P were higher than in bare soils outside the canopy. Such a pattern of nutrient distribution commonly referred to as “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. Schlesinger et al. (1990) suggested that physical processes such as accumulation of wind-blown materials initiate the fertile islands, and that with time, biological processes become important as plants take up greater amounts of nutrients and recycle them through litter deposition and decomposition.

Several soil parameters showed shrub species dependency. *G. senegalensis* was associated with more acidic soil pH under the shrub cover. Conversely, *P. reticulatum* had a relatively higher pH under its canopy. The acidifying characteristic of *G. senegalensis* may be attributed to the chemistry of the shrub litter. Organic and inorganic acids produced during litter decomposition may significantly reduce soil pH when the litter is low in base-forming cations (Brady and Weil, 1999). Our results are similar to findings of Wezel et al. (2000) in a study of soil-shrubs characteristics in semiarid Niger. The authors attributed this acidifying effect to Ca^{2+} depletion under *G. senegalensis*. In that study, the lower pH was associated with higher Al^{3+} and H^+ levels under canopy of *G. senegalensis*.

Soil C was always higher under *G. senegalensis* than under *P. reticulatum*. In a previous study, we showed that *G. senegalensis* materials had a slower decomposition rate compared to materials from *P. reticulatum*. These results suggest a plausible

chemical protection of *G. senegalensis* litter in the sandy soils of this study. As expected, soil N content in these shrub ecosystems followed the exact same pattern as soil C. Keur Mata soils have C and N contents comparable to those reported for soils in semiarid Niger (Wezel et al., 2000), but Nioro soils have higher C and N contents. Shrub species effect on C and N distribution observed in the current study is contrary to results of Wezel et al. (2000) who showed higher C and N enrichment in soils beneath *P. reticulatum* than beneath *G. senegalensis*.

5.4.2. Soil P fractions

Soils in this study have low total P compared to other tropical soils (Cross and Schlesinger, 1995) but are in this respect similar to some West African soils (Nwoke et al., 2003). Total P was significantly ($P < 0.0001$) higher in soils at Keur Mata than in soils at Nioro. Organic P represented approximately 40% and 50% of total P in Keur Mata and Nioro soils respectively. These proportions are similar to those reported for Brazilian Ferralsols (Lehmann et al., 2001) and are consistent with the model that proportion of P_o in soil increases in a weathering gradient (Cross and Schlesinger, 1995; Stevenson and Cole, 1999). Differences in total P at the two sites may reflect parent material mineralogy and/or different pedogenic processes.

Under the shrub canopy, the bicarb- P_o fraction was significantly higher than in soils outside the canopy (Table 5.1). 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 cover in arid and semiarid ecosystems (West, 1991; Gallardo and Schlesinger, 1995). The bicarb- P_o is recognized as a P_o 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 P_o mineralization in soils (Halm et al., 1972).

The largest P pool represented by NaOH-P is consistent with reported values of P fractions for other tropical soils (Lehman et al., 2001; Solomon et al., 2002; Nwoke et al., 2003; Araújo et al., 2004). This P pool, which represents the amorphous

and crystalline Fe- Al- phosphates, was more important in soils at Nioro than Keur Mata. This difference is most likely due to the greater abundance of Fe that characterizes soils at Nioro (M. Sene, personal communication). The majority of Po was in the NaOH-Po fraction, which made up >60 % of the total Po (Fig. 5.2). Hydroxide-Po is generally considered as a slow 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 (Steward and Tiessen, 1987; Beck and Sanchez, 1994; Cross and Schlesinger, 2001), and an indicator of P availability in highly weathered tropical soils (Beck and Sanchez, 1994; Maroko et al., 1999). Biological turnover of Po would depend on microbial activity, which tends to be limited by low and erratic moisture regimes of arid and semiarid environments (Whitford, 2002).

Shrub species effect on P fraction distribution resulted in a higher NaOH-Po under *P. reticulatum* while *G. senegalensis* had significantly greater bicarb-Po pool at the Nioro site. 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* (E. L. Dossa, personal communication) but similar litter P content. Thus, the presumably intensified P cycling through *G. senegalensis* biomass may be a driving force for conversion of P from intermediate or slow pools, most likely NaOH-Po pool, into 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 through their biomass turnover (Chauhan et al., 1981). The species effect was more striking in Nioro soils, which had lower total P and lower extractable P than Keur Mata. Phosphorus transformation in P-limited soils may also be related to quantitative and qualitative exudates secretion by roots (Marschner, 2002), which may 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 in these soils. 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 cover and

59% outside shrub cover are higher than values of this index reported for various soil orders with the exception of highly weathered Oxisols (Cross and Schlesinger, 1995).

5.5. Conclusions and Perspectives

The soils of our study had low P reserves, which were dominated by the NaOH-P fraction. Organic P represents about half of total P. On the other hand, biologically available P (Cross and Schlesinger, 1995) was >60%, suggesting an important biotic component in the overall P cycling. Our results provide further evidence that shrubs in semiarid environments create islands of fertility by concentrating nutrients under their canopies. In these ecosystems subject to wind erosion, the presence of shrubs seems vital to limit wind erosion and to preserve soil fertility. Shrub species comparison revealed an effect on nutrient concentration and soil pH beneath the canopy.

The greater accumulation of nutrients under *G. senegalensis* may be desirable provided that the lower pH under the species does not negatively affect nutrient availability. Further research on microbial activity in relation to nutrient turnover rate may provide more insight on the ways in which these shrub species recycle nutrients and affect soil properties beneath their canopies.

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Table 5.1. Mean P fractions (mg kg⁻¹ soil) in soils at Keur Mata and Nioro sites under (1R) and outside (3R) shrub canopy (n = 8).

P fraction	Keur Mata			Nioro		
	<i>G. senegalensis</i>		Prob.	<i>P. reticulatum</i>		Prob.
	1R	3R		1R	3R	
Resin-P	5.5	4.1	P<0.003	1.5	2.2	NS
Bicarb-Pi	6.6	4.6	P<0.007	1.9	1.9	NS
Bicarb-Po	10.7	6.4	P<0.004	6.6	4.9	P<0.008
NaOH-Pi	17.5	18.1	NS	4.9	5.6	NS
NaOH-Po	31.3	30.4	NS	20	18.8	NS
dHCl-Pi	11.6	11.3	NS	3.9	5.6	NS
cHCl-Pi	22.3	19.9	NS	9.1	8.9	NS
cHCl-Po	8.0	8.7	NS	6.2	5.5	NS
Residual-P	21.9	22.4	NS	11.9	11.3	NS
Total Po	50.0	45.5	P<0.05	32.8	29.1	NS
Total Pi	85.5	80.4	NS	33.3	35.6	NS
Total P	135.5	125.9	P<0.001	66.2	64.8	NS

Table 5.2. Soil P fractions (mg kg⁻¹ soil) by shrub species under (1R) and outside shrub canopy (3R) at Keur Mata and Nioro sites. Values in column followed by the same letter are not significantly different at $P < 0.05$ (n = 8).

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
	†	<u>Keur Mata</u>											
<i>G. senegalensis</i>	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
	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
<i>P. reticulatum</i>	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
	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
		<u>Nioro</u>											
<i>G. senegalensis</i>	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
	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
<i>P. reticulatum</i>	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
	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

†1R = 1 canopy radius, 3R = 3 canopy radiuses away from shrub stem.

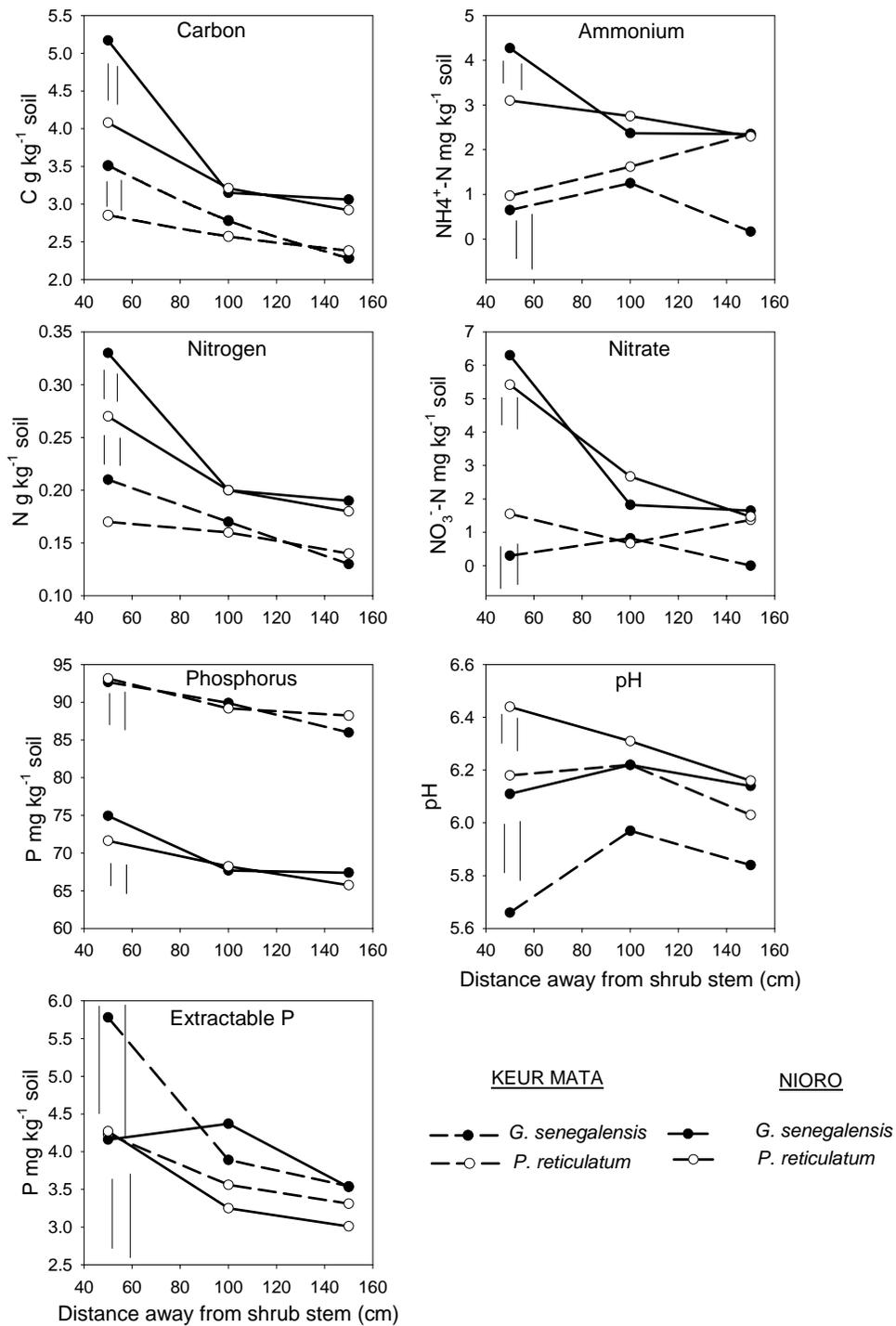


Figure 5.1. Mean soil characteristics at increasing distance from shrub center in soils under *G. senegalensis* and *P. reticulatum* at Keur Mata and Nioro sites. For each site, vertical bars indicate least significant difference LSD at $P < 0.05$ for species (left bar) and sampling positions (right bar).

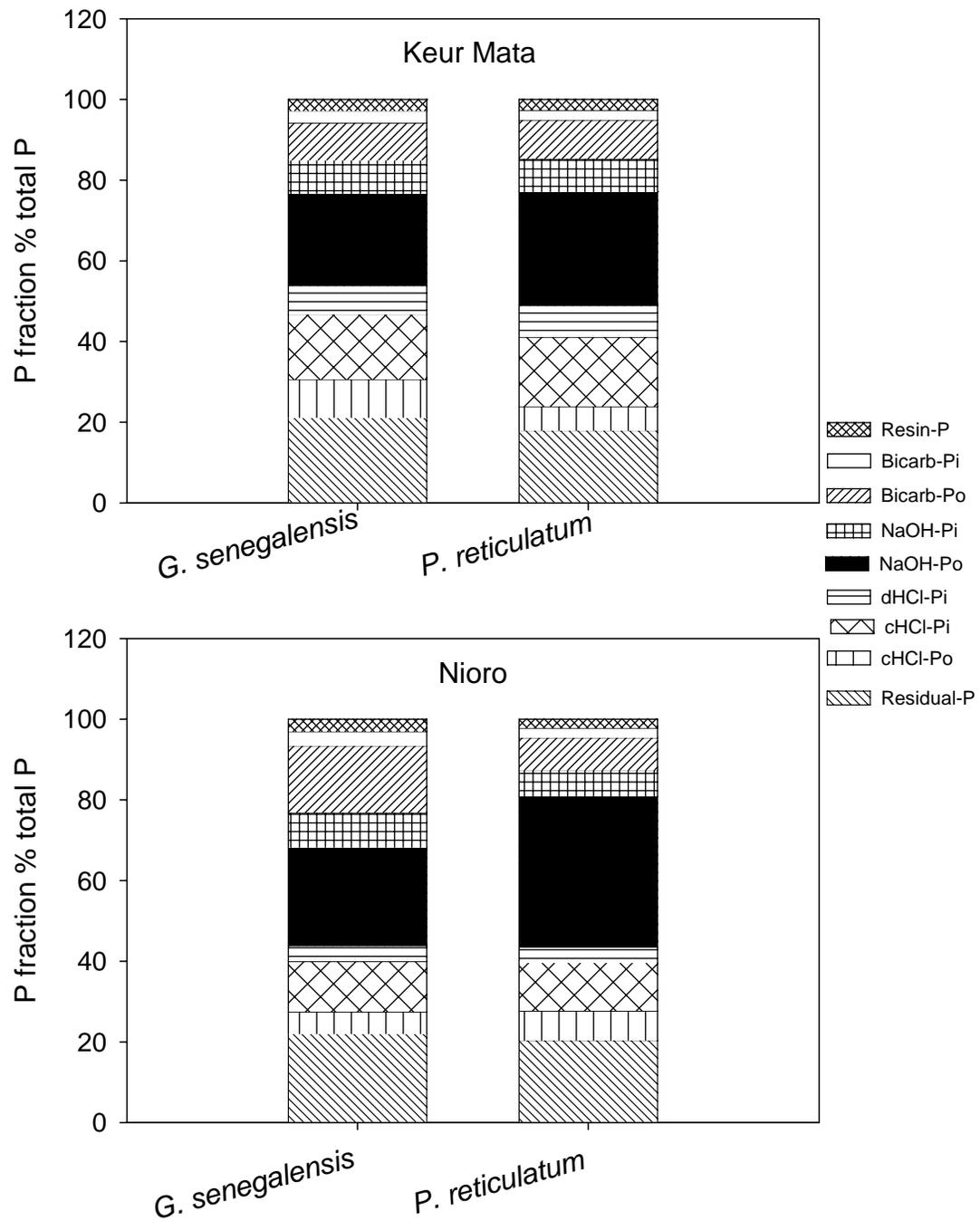


Figure 5.2. Mean proportion of P fractions relative to total P in soils beneath the canopy of *G. senegalensis* and *P. reticulatum* at Keur Mata and Nioro sites.

CHAPTER 6

General Conclusion

Unlike trees, shrub component of parklands agroforestry in SSA have been largely overlooked with respect to their contribution to ecosystem function and dynamics. The present study elucidates the role of native shrub species (*Piliostigma reticulatum* and *Guiera senegalensis*) in N, P recycling and crop productivity in Senegal. The results showed that shrub presence in fields are important with regard to crop yield and soil nutrient management. Both peanut and pearl millet yields were much higher in plots with shrubs than in sole-crop plots. This positive effect of shrub-crop association noticed in dry year and in absence of fertilization, suggest that shrub facilitate growth of associated crops.

Sandy soils in this study have a very low nutrient storage capacity. Applied nutrient, especially N exhibited a very fast dynamics throughout the growing period. At the end of season, N level dropped to insignificant level even with the highest rate of fertilizer. Nutrient efficiency was low and partly explained by the fast nutrient dynamics in soils. Residual P levels were higher than those of N, however, P use efficiency was not improved relative to N, owing to possible P sorption by soils and P immobilization in microbial biomass. In general, nutrient availability in soil was negatively related to soil water content and reflected microbial biomass return and/or changes in soil physical properties caused by drying and susceptible to modify adsorption and desorption of nutrients such as P.

The association of shrub with crops improved nutrient use efficiency and recycled more N and P in biomass. When compared on a unit of N and P fertilizer basis, plots with shrubs recycled 2 to 3-fold more N and P than sole-millet plots. One additional benefit in the shrub-crop association was a greater C sequestration in vegetation biomass. Thus, integration of shrubs in Sahelian cropping systems would contribute to greenhouse gas mitigation. This has a significant ecosystem management

implication because sandy soils of the Sahel have limited and insignificant C storage capacity.

Laboratory investigation with respect to potential of shrub residues to be used as amendment revealed that shrubs have delayed nutrient release patterns that may not satisfy immediate crop needs. When shrub materials include stem, net nutrient release was more delayed. The same shrub materials used as soil amendments significantly affected the geochemistry of P. Soils amended with shrub residues exhibited lower sorption maxima and had improved equilibrium solution P concentration and higher desorbable P. Study on shrub-associated spatial distribution and form of nutrients confirmed that the shrub constituted distinct ecosystem units characterized by higher concentration of C, N and P beneath their canopy, and a decreasing soil fertility outwards. This shrub fertile island effect was shrub-specific. Soils under *G. senegalensis* had a higher C and N content than soils under *P. reticulatum*. The two shrub species differed in their ability to modify soil pH. *G. senegalensis* decreased pH beneath its canopy while *P. reticulatum* increased it.

The results suggest that, in order to alleviate ecosystem degradation, shrub should be encouraged in farmers' fields in semiarid ecosystems. The results further showed that productivity in the shrub-crop association could be improved. In order to improve nutrient use efficiency, crop productivity and nutrient recycling, a major agricultural practice would be split application of fertilizer, especially N fertilizers. Maintaining or increasing vegetation cover represents an effective mean to increase biological activities. Increased biological activity not only contribute to a better nutrient recycling, but it also absorb and recycle part of the nutrient which is potentially leachable or sorbable by the soil. One such desirable microbial symbiosis is the mycorrhizal association, which may improve P uptake in P deficient sandy soils. The complete removal of crop residues for reasons such as household uses and fodder for livestock is not compatible with sustainable management of fragile ecosystems of semiarid.

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