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Carbon, nitrogen and phosphorus mineralization potential of semiarid Sahelian soils amended with native shrub residues

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ABSTRACT

Two native shrubs (*Piliostigma reticulatum* and *Guiera senegalensis)* commonly coexist with crops in fields throughout the Sahel but aboveground residue is annually coppiced and burned. An alternative, with potential to improve soil quality, would be non-thermal return of residues to soils but information is needed on the potential of residues' to provide nutrients before such systems can be adopted. The objective of this research was to characterize carbon (C), net nitrogen (N) and phosphorus (P) mineralization of shrub residues during decomposition in soil beneath or outside shrub canopies. Two lab incubation (30 °C for 118 days) studies (1 for each shrub species/soil type system) had a 2 by 4 factorial design with two soil sources (beneath or outside the shrub canopy) and four residue soil amendments (leaf, leaf+stem, beef manure, or control of soil only). Soils amended with *P. reticulatum* or *G. senegalensis* leaf residues immobilized N during the first 62 and 76 days, respectively, but later had net release of inorganic N. The addition of stems to leaf amendments for both shrub species resulted in net N immobilization throughout the incubation. Manure had positive but shrub residues negative release of inorganic P. However, if the leached P released at time zero is included in the summation, all amendments released more P than the control. Cumulative net release of C, N or P over the incubation was higher in soil originating from beneath than outside the shrub canopy except for release of P from soil associated with *G. senegalensis*. Residue chemistry was related to nutrient release, particularly high lignin content of stems, which corresponded to N immobilization. Our results suggest that none of the shrub residues when added to soil would potentially provide short-term plant available N and that additional fertilizer would be required for optimal crop yield.

1. Introduction

In the arid and semiarid Sudano Sahelian zones, soils are inherently of low fertility (Bationo and Buerkert, 2001), and intensive cropping combined with shorter fallow periods and greater livestock pressure is causing significant loss of organic matter and depletion of nutrient reserves in soils (Sanchez et al., 1997). Organic matter input to the soil has been shown to be critical for improving soil quality and optimizing nutrient and water efficiencies, and ultimately crop productivity in these degraded agroecosystems (Woomer et al., 1994; Sanchez et al., 1997; Badiane et al., 2000; Sinaj et al., 2001; Tschakert et al., 2004). Various non-indigenous vegetative systems to increase organic matter input to soils of the Sahel have been proposed, but received limited rates of adoption due to socio-economic constraints (Rhoades, 1997; Buresh and Tian, 1998; Bationo and Buerkert, 2001). Consequently, technologies that build upon farmers' indigenous practices are most likely to have greater impact at the landscape level. One such opportunity in the Sahel is shrubs that are allowed to grow, to varying degrees, in farmers' fields (Pullan, 1974).

In Senegal, there are two dominant, native shrubs, *Piliostigma reticulatum* (DC.) Hochst and *Guiera senegalensis* J.F. Gmel., which potentially can provide more organic inputs to cropped fields than any other source in the Sahel (Lufafa et al., 2008). However, their role in nutrient cycling and ecosystem function is not well understood. Traditional management of these shrubs includes coppicing and burning of residues at the beginning of each cropping season (Diack et al., 2000). Non-thermal management of these organic materials holds potential to

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add organic matter to soils and thus, be a source of nutrients such as nitrogen (N) or phosphorus (P), which is geochemically controlled in many arid environments (Cross and Schlesinger, 2001).

Litter decomposition and 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 are often found to be the major factors governing decomposition processes (Jarvis et al., 1996; Vanlauwe 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; Vanlauwe et al., 1996; Mafongoya and Nair, 1997; Bernhard-Reversat, 1998).

Shrubs in arid and semi-arid environments create a spatially heterogeneitic distribution of soil resources, which affects nutrient cycling and availability (Van Miegroet et al., 2000). In these environments, soils beneath the canopy of shrubs typically have higher C and N levels than soils outside the canopy (Kieft et al., 1998). In addition, the improved water conditions and microclimate beneath the shrub create a favorable environment for biological activity (Gallardo and Schlesinger 1995). The improved soil quality beneath the shrub canopy may further stimulate mineralization and plant availability 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, information is needed on the potential of residues (leaves and stems) to release nutrients. 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 the shrub canopy may influence this process (Diack et al., 2000; Iyamuremye et al., 2000).

The objectives of this study were to determine the influence *P. reticulatum* or *G. senegalensis* on: (1) soil chemical properties; and (2) C, N and P release patterns from soils beneath or outside the canopy amended with residues of either shrub species under laboratory conditions.

2. Materials and methods

2.1. Study site

Soils were collected from two sites. The first site was at Keur Mata Arame which is located in the northern region of the Senegal (14°45 N, 16°51 W, and 43 m above sea level; mean annual precipitation of 450 mm). Temperatures range from 20.3 °C in December–January to 33.4 °C in April–June. The soil has 95% sand, manily from aeolian deposits, and is classified as Rubic Arenosol (FAO, 2006), 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} (average canopy dia. ~2 m) The second site (Nioro du Rip) is located (13°45 N, 15°47 W) at 18 m above sea level with mean annual precipitation of 750 mm distributed from July to September and mean air temperatures ranging from 20 °C to 35.7 °C. The soil is a Deck–Dior (Badiane et al., 2000) loamy-sand [fine-sandy, mixed Haplic Ferric Lixisol (FAO, 2006)], a leached ferrugineous tropical soil. The dominant shrub species at the site is *P. reticulatum* with average stand density of 185 shrubs ha^{-1}.

The main crops are millet (*Pennissetum glaucum L.*) and peanut (*Arachis hypogaea L.*) grown in a peanut–millet yearly rotation. Because of low soil fertility conditions at the sites, these crops receive standard annuall N–P–K fertilization of 9–30–15 kg ha^{-1} (peanut) and 68–15–15 kg ha^{-1} (millet) in order to attain optimal yield level.

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 (Lufafa et al., 2008), were randomly selected for soil and shrub biomass sampling. Each shrub was treated as a replicate. This spatial replication was maintained 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 through 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 and subsequently used in the soil amendment treatments. Beef manure was locally provided by the dairy farm at Oregon State University in Corvallis and had some partially decomposed straw mixed in at the time of sampling.

The experimental design was a randomized 2 by 4 factorial for each shrub type with two soil sources (beneath or outside the shrub canopy) and four residue treatments (leaf, leaf+stem in same proportions as found under field conditions, 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.

2.3. 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 in the canopy zone. Soils were wetted to 2/3 s 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. Gas samples were analyzed for carbon dioxide (CO_2) after 1, 2, 3, 7, 14, 21, 28, 35, 49, 63, 77, 91, 105 or 118 days on a gas chromatograph. Cumulative CO_2 was calculated for each sampling date as mg CO_2–C per g of soil. After each sampling, jars were opened and aerated for approximately 1 h before resuming incubation, and soil moisture was adjusted gravimetrically.

The N and P mineralization study was conducted on the same soils and shrub residue treatments as 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 layer of glass wool pad was placed over the soil to minimize dispersion during leaching. Initial N and P was removed by leaching dry soils, after soils had been amended, with 30 ml of 0.01 M $CaCl_2$ solution in three increments followed by 20 mL of a nutrient solution devoid of N and P (0.004 M $CaCl_2$, 0.002 M $CaSO_4$, 0.002 M $MgSO_4$, 0.0025 M K_2SO_4). Excess water was removed under vacuum (60 kPa). 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

Table 1
Selected characteristics of the soils used in the incubation study ($n=4$)

Soil location	Total C	Total N	Total P	pH	C/N
	g kg^{-1}		mg kg^{-1}		
Nioro (P. reticulatum)					
Beneath canopy	5.77±0.40	0.21±0.01	86±4.1	6.4±0.4	26.7
Outside canopy	3.23±0.77	0.19±0.01	82±4.5	5.8±0.1	18.3
Keur Mata (G. senegalensis)					
Beneath canopy	3.35±1.44	0.20±0.02	89±5.3	5.2±0.2	17.5
Outside canopy	2.51±0.54	0.18±0.02	93±5.1	5.4±0.1	13.6

Values are mean±standard error.

10, 20, 34, 48, 62, 76, 90, 104, and 118 days. Mineral N in the leachates was analyzed for NO_3^--N and NH_4^+-N by steam distillation (Bremner and Keeney, 1965), and PO_4-P was determined by the colorimetric molybdenum-blue method (Murphy and Riley, 1962).

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 Li_2SO_4-H_2SO_4 procedure (Parkinson and Allen, 1975). Lignin, cellulose and hemicellulose were determined by the method of Goering and Van Soest (1970). Total polyphenolic content was determined in diluted hot water extracts (Valachovic et al., 2004) with the Folin–Ciocalteau 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).

2.5. 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 1st order kinetics model was of the form:

$$X_m = X_0[1-\exp(-k_1 t)] \quad (1)$$

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:

$$X_m = B_0 + k_2 t \quad (2)$$

where B_0 is the intercept and k_2 the slope.

Statistical analysis was conducted separately for each shrub species—that is the soils collected inside and outside the canopy that was amended with its own residue treatments. 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 initially 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. Because block and block x location were not significant, the model was reduced to a 2-way ANOVA which included treatment and soil location as factors. 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 day 10, 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's 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.

3. Results

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 for P in the *G. senegalensis* soils, which had higher levels of P in soil outside the canopy (Table 1). Nitrogen and P contents of leaf material was higher than the corresponding contents in leaf+stem mixture for both shrub species. Whereas lignin content was similar in leaf and leaf+stem mixture of *P. reticulatum, G. senegalensis* had higher lignin content for leaf+stem than leaf materials (18.1% and 10.3% respectively) (Table 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.

3.2. Carbon mineralization

Results of CO_2 evolution with time are shown in Fig. 1. A flush of CO_2 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 CO_2 than the unamended soils ($P<0.001$). In *P. reticulatum*-amended soils, leaf material had the highest CO_2 evolution from day 1 to day 90 of incubation whereas leaf+stem and manure-amended soils evolved CO_2 at similar rates until day 52 of incubation (Fig. 1A and B). Thereafter, manure and leaf treatments mineralized C at lower rates than the leaf+stem amendment such that, by the end of the incubation, the order of cumulative CO_2

Table 2
Initial chemistry of shrub residues (*G. senegalensis* (GS), *P. reticulatum* (PR)) and manure (MAN) added to soils (n=4) (values in brackets represent standard error on mean)

		P	C	N	[a]LG	[b]CL	[c]HM	[d]PP	[e]RP	C:N	C:P	LG:N	PP:N	(PP+LG):N	RP:N
GS	Leaf	1.0 (0.08)	35.4 (1.25)	1.6 (0.06)	10.3 (1.43)	21.6 (1.4)	12.8 (0.91)	6.4 (0.09)	5.0 (0.04)	21	347	6.3	3.9	10.2	3
	Leaf+stem	0.64 (0.05)	33.3 (0.57)	1.3 (0.04)	18.1 (1.84)	45.2 (2.06)	13.3 (2.03)	3.9 (0.01)	3.6 (0.01)	26	520	14.2	3.1	17.3	2.8
PR	Leaf	1.0 (0.06)	35.2 (2.72)	1.8 (0.05)	13.1 (0.98)	19.8 (1.92)	13 (1.23)	5.3 (0.05)	4.2 (0.03)	20	348	7.4	3.0	10.4	2.4
	Leaf+stem	0.67 (0.04)	33.7 (3.06)	1.2 (0.05)	13.6 (1.12)	44.4 (3.72)	13.2 (2.54)	7.3 (0.01)	6.2 (0.04)	27	502	10.8	5.8	16.7	5
	Man	3.4 (0.23)	36.7 (1.87)	1.8 (0.1)	16.8 (3.08)	26.9 (2.30)	12.5 (1.72)	1.8 (0.01)	1.0 (0.04)	20	108	9.4	1.03	10.4	0.6

[a] LG, lignin.
[b] CL, cellulose.
[c] HM, hemicellulose.
[d] PP, total polyphenols.
[e] RP, reactive polyphenols.

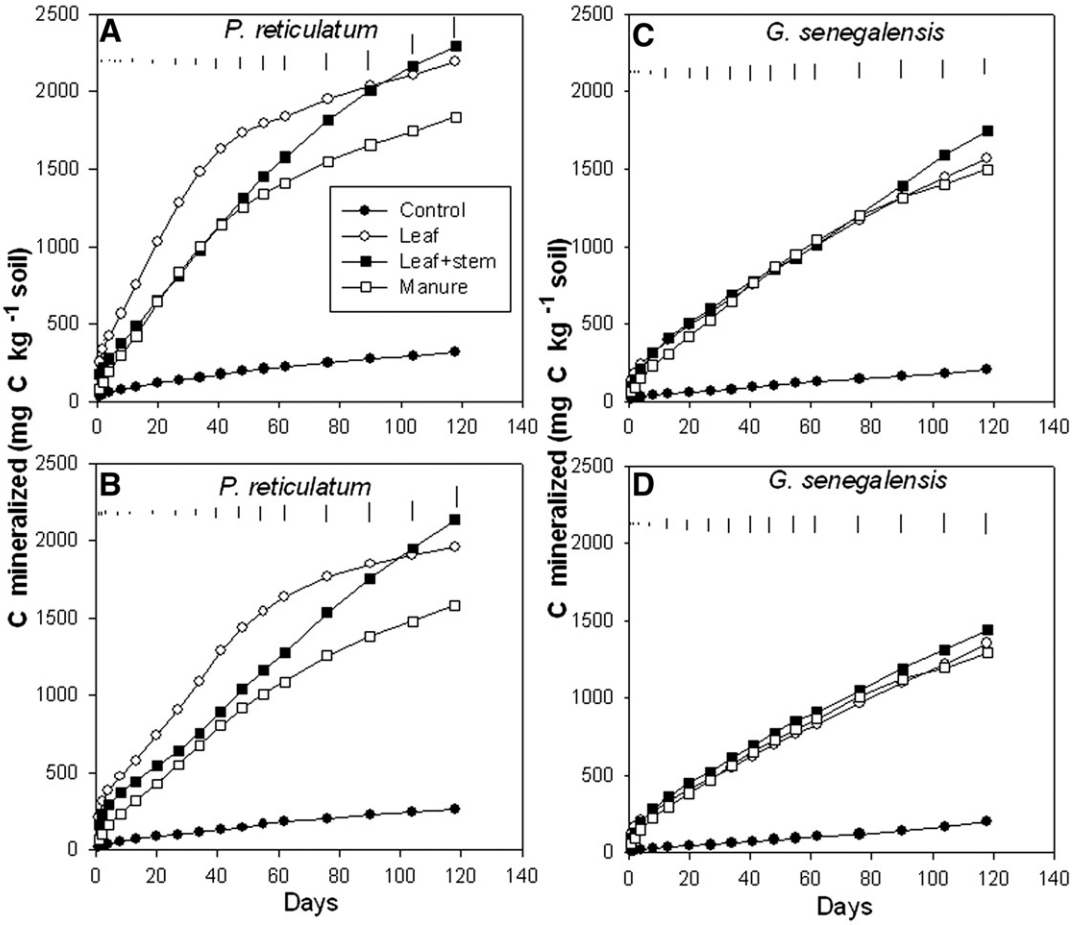

Fig. 1. Cumulative CO_2 evolution beneath (A) and outside shrub canopy (B) in *P. reticulatum* residue-amended soils; and beneath (C) and outside (D) shrub canopy in *G. senegalensis* residue-amended soils. Bars represent Tukey's Honestly Significant Difference ($P<0.05$).

released was as follows, leaf=leaf+stem>manure>control. In *G. senegalensis*-amended soils, leaf, leaf+stem and manure evolved CO_2 at similar rates and had statistically equivalent cumulative CO_2 levels at the end of the incubation (Fig. 1C and D). 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 CO_2 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.

3.3. Net N mineralization

Initial N leached from soils mixed with the different organic residues was relatively low (Table 3). In the *P. reticulatum* residue-amended soils, the initial inorganic N levels were similar 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. Nitrate was the dominant inorganic N form with ammonium only being detected 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* (Fig. 2A and B) and the *G. senegalensis* residue-amended soils (Fig. 2C and D). Irrespective of soil location, all residue amended soils immobilized N for some period of time during the experiment, and leaf+stem mixture showed the highest and longest net immobilization.

In *P. reticulatum* residue-amended soils (Fig. 2A and B), 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 or leaf-amended soils beneath the shrub canopy (Fig. 2A). In the *G. senegalensis* residue-amended soils, however, a more delayed net inorganic N release was

Table 3
Initial N and P leached from soils amended with the different organic residues

Treatments	*P. reticulatum*		*G. senegalensis*	
	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}

For each element, values in the same column having the same superscript letter are not statistically different at $P<0.05$ ($n=4$).

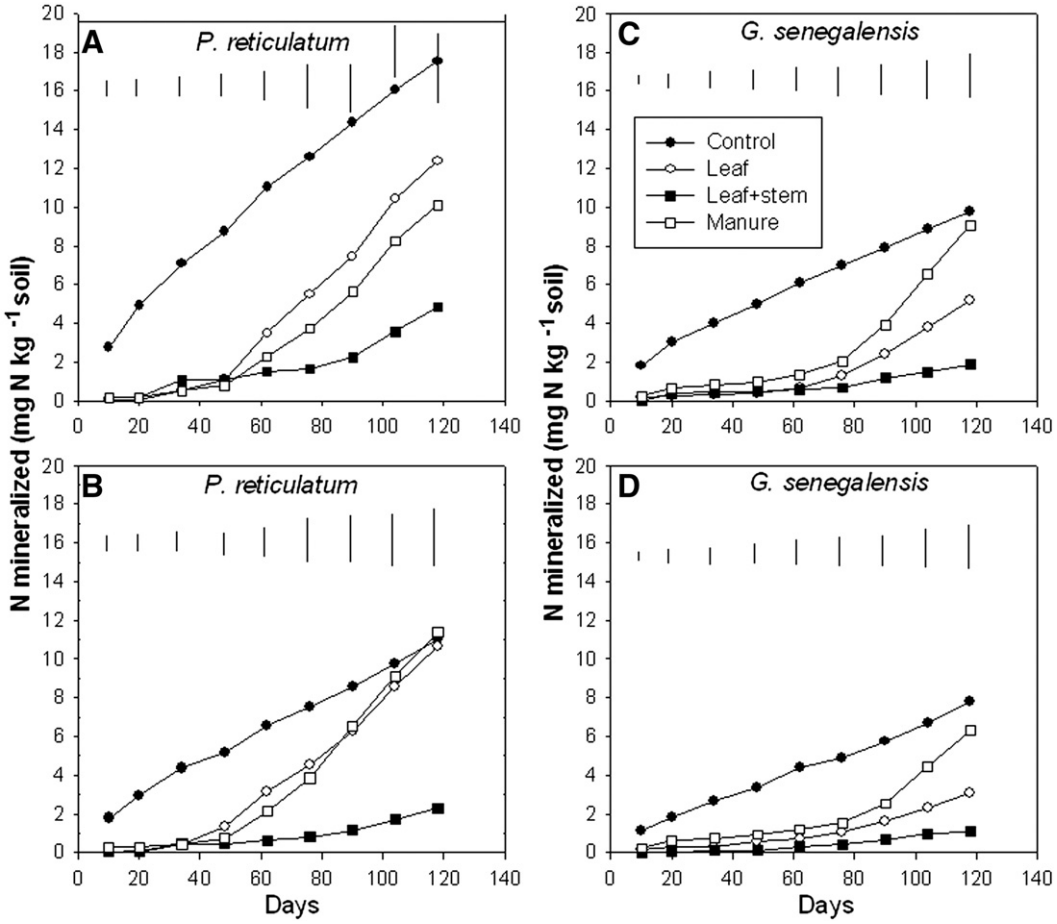

Fig. 2. Cumulative N leached from soils beneath (A) and outside shrub canopy (B) in *P. reticulatum* residue-amended soils; and beneath (C) and outside (D) shrub canopy in *G. senegalensis* residue-amended soils. Bars represent Tukey's Honestly Significant Difference ($P<0.05$).

observed from day 76 to day 90 with manure and leaf residue-treated soils while leaf+stem exhibited N immobilization for the entire duration of the experiment (Fig. 2C and D). In the *G. senegalensis* residue-amended soils, cumulative N mineralized by the end of the incubation was as follows: control = manure > leaf > leaf+stem ($P<0.001$) in both soil beneath and outside shrub canopy.

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

3.4. Net P mineralization

For both species, leaf material released high levels of P at time zero (Table 3) which was in a similar range of the 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 the canopy (Fig. 3A) and leaf+stem released slightly (but not significantly) more P than the control during the first 62 days of incubation. On soils outside the *P. reticulatum* canopy amended with residues, similar amounts of P were released to that of the control (Fig. 3B). Cumulative P at the end of the incubation period for *P. reticulatum* was higher in soils beneath the shrub canopy than in soils from outside the canopy ($P<0.01$).

In the *G. senegalensis* soils, apart from manure-amended soils, all treatments had net negative P release relative to the control (Fig. 3C and D). The leaf+stem amendment tended to release less P than leaves only for this species; however, these differences were not significant. In contrast to the trend seen with *P. reticulatum*-residue treatments, soils from outside the *G. senegalensis* canopy released more P than soils from beneath shrub canopy ($P<0.01$).

3.5. Mineralization kinetics

The first order kinetic model provided a good fit to C mineralization data with $R^2>97\%$ (Table 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 were 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 4).

For P mineralization modeling, all treatments in both *G. senegalensis* and *P. reticulatum* residues-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 with 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 to trends seen with *P. reticulatum* soils. Soils from outside shrub canopy had the highest rates in all treatments with rate constants between 0.015 and 0.05.

Model fitting for N mineralization did not yield satisfactory results (low R^2 and lack of convergence, data not shown). However, the

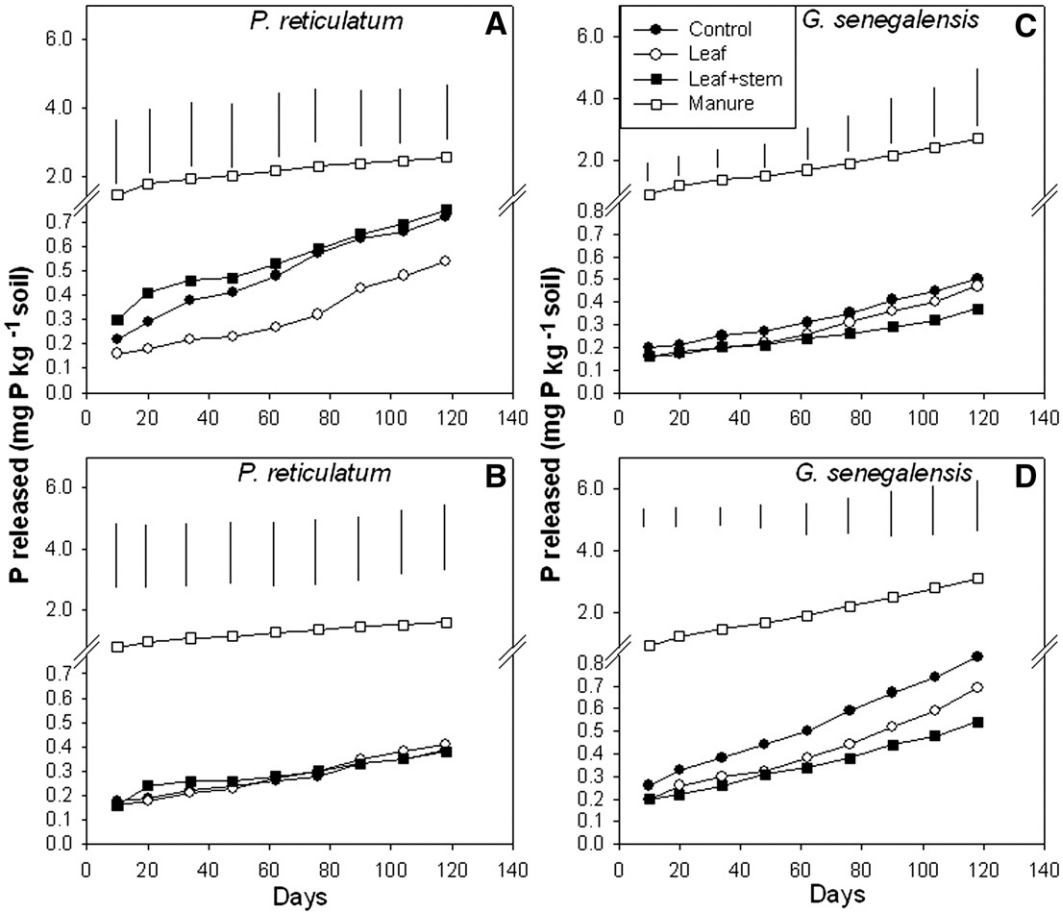

Fig. 3. Cumulative P leached from soils beneath (A) and outside shrub canopy (B) in *P. reticulatum* residue-amended soils; and beneath (C) and outside (D) shrub canopy in *G. senegalensis* residue–amended soils. Bars represent Tukey's Honestly Significant Difference ($P<0.05$). Length of HSD bars reflects scale before break of axis.

unamended soils fitted a 1st 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. These rates are considerably lower N mineralization rates than what has been found in unamended surface soils of other studies in China 0.123 day $^{-1}$ (Roelcke et al., 2002) and the USA 0.136 to 0.139 (Dou et al., 1996). This would be expected as our soils are from semi-arid and sandy with low organic matter contents.

Table 4
Parameter values for the first order exponential model to describe C mineralization in *P. reticulatum* and *G. senegalensis* residues amended soils beneath and outside shrub canopy

Treatment	Beneath shrub canopy			Outside shrub canopy		
	C potential	*k*	R^2	C potential	*k*	R^2
	g kg^{-1}	day^{-1}		g kg^{-1}	day^{-1}	
Nioro (P. reticulatum)						
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
Keur Mata (G. senegalensis)						
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

Values in brackets represent the standard error on estimate.
K = 1st order rate constant and C potential = potentially mineralizable C.

4. Discussion

4.1. Residue source, type and C mineralization

We used CO_2 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,

Table 5
Correlation coefficients (r) 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	[a]LG	[b]PP	[c]RP	[d]CL	[e]HM	C:N	LG:N	PP:N	(PP+LG):N	RP:N
C mineralization											
1	0.54	−0.37	ns	ns	−0.48	ns	−0.45	−0.50	ns	−0.45	ns
118	[f]ns	ns	0.35	0.41	ns	ns	ns	ns	0.41	ns	0.41
N mineralization											
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

[a] LG, Percent lignin.
[b] PP, Percent total polyphenols.
[c] RP, Percent reactive polyphenols.
[d] CL, Percent cellulose.
[e] HM, Percent hemicellulose.
[f] ns, not significant at $P<0.01$.

cumulative CO_2 evolution in leaf+stem amended soil 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), under field conditions, reported a higher decomposition rate of *P. reticulatum* stems compared with leaf residues of the species, which they attributed to the high concentration of fructose in the stem. In *G. senegalensis* residues-amended soils in our study, however, decomposition rates were similar for all organic residues added to soils.

Rates of CO_2 release at different stages of mineralization were correlated with different litter quality indices. The initial CO_2 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 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 contradicts 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 types of polyphenols present. Other litter characteristics might have contributed to the contrasted C mineralization patterns shown by the two shrub species. Indeed, leaf of *G. senegalensis* is reported to be waxy, which is the reason for not using material of the species in composting in Senegal (M. Khouma, personal communication). Additionally, antifungal properties were reported with guieranone A, a ketone derivative isolated from leaves of *G. senegalensis* (Silva and Gomes, 2003), which could have contributed to the lower decomposition rate constant.

Rates of C mineralization of shrub materials in this laboratory study are comparable to constant rates reported in soils from with various tropical woodland and savanna plant species (Table 6; Budelman, 1988; Palm and Sanchez, 1990; Kachaka et al., 1993; Mtambanengwe and Kirchmann, 1995; Mugendi and Nair, 1997; Mtambanengwe et al., 1998; Kwabiah et al., 2001).

Cumulative evolution of CO_2 in soil amended with the different residues was well described by a single exponential model ($R^2>96\%$) (Table 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 CO_2 data.

4.2. Nitrogen and P mineralization

Nitrate was the dominant form of inorganic N leached from soils during this incubation study which would indicate there were rapid rates of nitrification. This would be expected as our soils were in a pH range when nitrifiers would still be active (Diallo, 2005). These findings are in agreement with those of Iyamuremye et al. (2000) who found that NO_3^--N was the dominant form of N in soils incubated with various organic residues in Senegal.

All amended soils immobilized N but the time of immobilization varied as a function of 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 to day 90. Mineralization and immobilization occur simultaneously when organic amendments are added to soils and which process dominates is dependent on residue chemistry (Palm and Sanchez, 1991; Constantinides and Fownes, 1993; Lehmann et al., 1995; Schwendener et al., 2005). The N immobilization pattern shown in our study has been commonly found in other studies on residues from agroforestry tree species that have been added to soils. (Mtambanengwe and Kirchmann, 1995; Vanlauwe et al., 1996; Mafongoya et al., 1998).

Residue chemistry did show relationships to N mineralization rates and temporal patterns. At day 10, the rate of N mineralization was 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 that when stems were added to leaf amendments there was inhibition of N mineralization. This was likely due to the high C/N and high lignin/N ratios of stems in both shrub species. Similar results were obtained by Constantinides and Fownes

Table 6
Range of carbon mineralization rates (k) estimated from first order exponential equation for multipurpose agroforestry species in tropical ecosystems

Method	Soil class	Location	Rate constant k (day^{-1})	Reference
Lab incubation	Alfisol	Zimbabwe	0.023–0.032	Mtambanengwe and Kirchmann (1995)
Lab incubation	Alfisol	Nigeria	0.003–0.025	Kachaka et al. (1993)
Lab incubation	Alfisol	Zimbabwe	0.014–0.041	Mtambanengwe et al. (1998)
Litter bag	Ultisol	Indonesia	0.0042–0.0059	Handayanto et al. (1994)
Pot incubation	Ultisol	Indonesia	0.0031–0.0045	Handayanto et al. (1994)
Field study	Regosol	Burkina Faso	0.006–0.008	Bayala et al. (2005)
Litter bag	Alfisol, Utisol	Kenya	0.0057–0.0224	Mugendi and Nair (1997)
Litter bag	Ultisol	Peru	0.0025–0.0102	Palm and Sanchez (1990)
Field study	Alfisol	Nigeria	0.0059–0.0232	Yamoah et al. (1986)
Field study	[a]–	Ivory Coast	0.013–0.031	Budelman (1988)
Litter bag	Alfisol	Kenya	0.0019–0.022	Jama and Nair (1996)
Litter bag	Oxisol	Kenya	0.012–0.067	Kwabiah et al. (2001)
Litter bag	Lixisol, Arenosol	Senegal	0.0004–0.0014	Diedhiou (2007)
Lab incubation	Lixisol Arenosol	Senegal	0.009–0.034	This study

[a] Data not provided in the original data set in the literature.

(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 when residues were added to soil and shows the difficulty in fitting N mineralization pattern of residues undergoing immobilization (Dendooven et al., 1997).

Phosphorus mineralization followed a different pattern than what was observed for N. For both *P. reticulatum* and *G. senegalensis* soils, manure-amended soils had the highest net P release ($P<0.001$). All the other treatments had net negative or near zero P release. In their mineralization study on multipurpose tropical tree leaves and manure, Mafongoya et al. (2000) reported the exact same trend. However, summing P released at day 0 with cumulative P released showed a total ranging from 0.67 to 1.44 mg P kg^{-1} which was always higher than total P released from unamended soils (0.41 to 0.83 mg P kg^{-1}). This has been reported for some tropical plant species litters that had high levels of P release immediately after being incorporated into soil, which was attributed to high water-soluble P content in the plant materials (Kwabiah et al., 2003).

The C:P ratio of residues can be a predictor of whether net P mineralization (≤200) or immobilization (≥300) will prevail during decomposition (Sharpley and Smith, 1989; Stevenson and Cole, 1999). In general leaf material or in combination with stems resulted in C:P ratios of >300 and in most cases we had an outcome of net negative release whereas the manure treatment with a C:P of 100 had a net P release, which is consistent with the C:P ratio rule of thumb. However, the near zero P mineralization of the *P. reticulatum* leaf+stem amendment (C:P of 502) did not follow this rule as it did not have net negative release but rather had a near zero P release. This 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.

The greater P release from soils collected outside the canopy of *G. senegalensis* than that from soils beneath the canopy was not expected. As seen in the *P. reticulatum* soils, we anticipated that there would be greater P release beneath the shrub canopy because of the higher C and N levels and the more intense microbial activity usually associated with these soils in arid and semiarid environments (Gallardo and Schlesinger 1995; Kieft et al., 1998). However, this trend is similar to that reported by Krämer and Green (1999) in a juniper microsite study, but is 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). The study of Iyamuremye et al. (2000) is note worthy because they also studied P mineralization in Senegal with leaf and stem litter of *P. reticulatum* but with soils collected from beneath and outside canopy of *Cordyla pinnata*, a tree species in Senegal. Here they found greater release of P with *P. reticulatum* litter amended to soil beneath the tree canopy than outside. This difference in findings may be due to difference between the soils that develops beneath *G. Senegalensis vs. C. pinnata*.

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 with 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. Further research on P chemistry and mineralization of soil beneath shrub canopies in wider range of locations is needed to determine the mechanisms and generality of these previous studies.

It must be recognized that P measured in solution during this incubation experiment does not reflect the true net P mineralization during litter microbial decomposition. Rather, it represents the P released that is in excess of what is sorbed on surfaces of soil minerals or biologically immobilized (Sharpley and Smith, 1989; Iyamuremye et al., 2000). None-the-less, the P measured in soil leachates would be reflective of plant available P from these residues for crops in the field.

5. Conclusions and perspectives

In this incubation study, shrub residues showed different patterns of mineralization. Leaf residue of *P. reticulatum* evolved more cumulative CO_2 than leaf+stem mixture until day 76 of incubation but had similar cumulative CO_2 at the end of the incubation. On the other hand, *G. senegalensis* residues evolved relatively less CO_2 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, suggesting 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 to day 90) with *G. senegalensis* residues. The addition of stem material to leaf resulted in N immobilization during the 118-day incubation. The various shrub materials did not increase release of P over the unamended control suggesting these materials would have limited potential to supply the immediate nutrient needs of the crops. It should be kept in mind that the shrubs were from fields under farmer management where there is little use of fertilizers. It is possible that shrubs grown in fields under higher fertilizer regimes for summer crops could have high N and P contents which could increase N and P release from these residues during decomposition.

Our findings suggest that residue return for the two shrub species we tested would provide limited amounts of N and P for plant uptake and that supplemental addition of mineral or other nutrient rich organic fertilizers would be needed to sustain optimal productivity in cropped Sahelian ecosystems. Addition of these residues or organic matter may be important for reasons other than immediate nutrient supply—as other work in the Sahel has shown that use of inorganic fertilizers is only optimal for nutrient efficiency and crop yields with regular additions of organic inputs (Sanchez et al., 1997; Badiane et al., 2000). 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 with wetting/drying cycles 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.

The results indicate that field studies are merited on these shrubs. We showed that these shrubs are islands of fertility (soil chemical data) which have elevated C mineralization rates (thus greater decomposition potential) and nutrient release. Thus from these outcomes, field studies can be recommended for determining the optimal shrub densities that can take advantage of these canopy soil benefits while maximizing crop productivity. Furthermore, studies are justifiable at the field scale to determine the impacts of the shrub residues on nutrient uptake and crop productivity. The greater rates of C mineralization from soil beneath shrubs indicates field studies are needed to determine if placing residues beneath the canopy is preferable for decomposing residues to prepare a seed beds for cropping. One very important outcome is the apparent N immobilization that occurred with shrub residue incorporation. Thus, to take advantage of the benefits that would be expected with non-thermal management, complementary field studies are needed on N nutrition of cropped plants to develop fertility recommendations for either inorganic or organic sources of N.

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