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Carbon, Nitrogen and Phosphorus Mineralization Potential of Native Agroforestry Plant Residues in Soils of Senegal

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The objectives of this study were to investigate Piliostigma reticulatum *(shrub) and* Cordyla pinnata *(tree) residues for chemical composition, and C, N, and P mineralization in Senegalese soils. Soil samples* (Sols ferrugineux tropicaux) *were collected from a native agroforestry system beneath and outside a* C. pinnata *canopy. Soils were incubated for 11 weeks with* P. reticulatum *(leaves),* C. pinnata *(stem, leaves, or stem + leaves), peanut* (Arachis hypogea), *or pearl millet* (Pennisetum glaucum) *residues. Nitrogen and P mineralization for the soil-plant mixtures was determiaed by periodic leaching with a 0.01 M $CaCl_2$ solution. An additional separate incubation was conducted to investigate C mineralization. The results showed that only peanut residues caused net N mineralization, while N immobiiizution occurrer! in the remaining treatments in both the soils derived from beneath or outside* the *canopy. This indicates that, at least in the short-term, these agroforestry residues would not likely be a source of N for crops. Net P mineralization varied among plant residues and soils sites but* P. reticulatum *amended soits increused soluble PO, in both soils. This suggested that it could bc useful for improving P availability. Peanut residues had the highest CO, evolution in both soils suggestinq a probable relationship* between *C and N mineratization.*

Keywortls *Piliostigma reticulatum, Cordyla pinnata*, peanut, millet, parkland

Depletion of soil quality and desertification of sub-Saharan Africa is increasing and

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is likely related to increasing rural populations and agricultural intensity, and reduction of woody species on the landscape. The residues of native woody species could be important as soil nutrient sources and for improving soil quality. Early studies showed *Faidherbia (Acacia) albida* (Del.) A. Chev. improved physicochemical properties beneath the tree canopies (Charreau and Vidal 1965; Dancette and Poulain 1968).

This mode1 of the site enrichment by the tree was the basis for the development of alley farming. In this system continuous addition of prunings from hedgerow maintains nutrient status (Kang, Wilson, and Lawson 1984), especialiy nitrogen (N) when the tree or shrub is a leguminous species. Nitrogen release and mineralization in alley cropping systems, following addition of prunings to the soil, has been extensively studied (Constantinides and Fownes, 1993; Constantinides and Fownes 1994; Hundoyanto, Godisch, and Giller, 1994; Fox, Meyers, and Vallis 1990; Palm and Sanchez 1991). However, in many countries the most common agroforestry system is the parkland system. In this system trees are randomly allowed to grow in crop fields.

Parkland systems of *F. albida* and other species have been reported in West Africa (Samba 1997). In Burkina Faso, Depommier, Jadonet, and Olivier (1992) confirmed the previous results obtained in Senegal by Charreau and Vidal (1965) and Dancette and Poulain (1968) where millet or sorghum yield increased beneath *F. albida* (relative to yield outside of the *F. albida* canopy). Besides showing the improvement in physicochemical properties beneath *F. albida*, Dancette and Poulain (1968) and Depommier et al. (1992) suggested that the canopy crowns created microenvironments with higher relative humidity, a lower evapotranspiration potential, reduced maximum temperature, increased soil humidity, and greater rain interception.

Unlike other agroforestry systems such as alley cropping, little attention has been paid to parkland systems. In West Africa and especially in Senegal the tree species *Cordyfa. pinnata* [(A. Rich.) Milne-Redh] is an important species in peanut and millet fields (Samba 1997). Besides trees, other woody shrub species can be found in these regions as well. A widely distributed and dominant shrub in central and southern Senegal that is commonly found with *C. pinnata* is *Piliostigma reticulatum* [(DC.) Hochst.] (M. Diatta, ISRA, Dakar, Senegal, persona1 communication). The traditionai management consists of cutting the shrubs and burning the aboveground residue before soil cultivation. Although burning conserves cations, significant amounts of N and sulfur are volatihzed and it does not contribute to the improvement of soil quality. No information is available on mineralization of the residues from *P. reticulatum* and *C. pinnata* or whether soil from beneath the canopies of *C. pinnata* can affect mineralization rates. To determine whether these residues could be managed to provide nutrients, chemical characterization and nutrient rnineralization studies are needed. We included in the study, two of the most common crop residues in Senegal [Pearl millet, *Pennisetum glaucum* (L). R. Br. and peanut, *hachis hypogea* L.]. This would provide a relative point of comparison for the potential agronomic effectiveness of the agroforestry residues to provide nutrients.

The objectives of this study were to investigate two agroforestry (*P. reticulatum*, *C. pinnata*) and two crop residues (pearl millet and peanut) for: (1) chemical composition; and (2) carbon, N, and phosphorus (P) mineralization in Senegalese soil.

Materials and Methods

Soils and Plant Materials

The experimental site was located in Paoskoto, Kaolack, a semiarid agroecoiogical zone in the peanut basin, between 13" 35' and 14" 30'N and 14" 35' and 16" 45'W.

The region is characterized by a tropical Sudanian climate with an annual rainfall of 700 mm and evapotranspiration of 1,800 mm yr^{-1}. Temperatures range from averages of 16°C in December–January to averages of 39°C m April-June.

A Deck Dior loamy-sand [fine-sandy, mixed Haplic Ferric Lixisol (FAO 1991)], leached ferrugeneous tropical soil (probably an Ultisol), was used in this study (Table 1). It was collected from the Ap horizon (O-10 cm depth) at a farmer's field that had been under millet (*Pennisetum glaucum).* Soil samples were taken randomly with a shovel either beneath the canopy-(3 m radius from trunk; approximately one-half canopy dia.) or outside the canopy influence (30 m radius from trunk) of a C. pinnata tree in the millet field. The soil was composited, homogenized and then crushed to pass 2-mm mesh screen and maintained at field moisture and stored at 22°C. Soils and plant residues of *P. reticulatum* and *C. pinnata* were collected in March 1998. All materials came from farmers' fields near Kaolack, Senegal during the dry season. The peanut (*Arachis hypogea*) and pearl millet *(Pennisetum glaucum)* residues were collected at crop maturity in September 1997. The C. *pinnata* litter was senescent residue that had recently fallen from the trees. The P. *reticulatum* residue (approximately 1 m in height at harvest time) was cut green at ground level. Leaves and stems *of P. reticulatum* woody species were separated and then all plant residues were dried at 35°C for five days and individually chopped to pass a 1-cm sieve and kept in sealed plastic bags.

Mineralization Incubation Experiments

Mineralization of N and P was conducted following the methods of Stanford and Smith (1972) with slight modification of the nutrient solution added to the soil samples incubated to study P mineralization. Seventy-five g of soil samples were thoroughly mixed with 1.5 g of plant material and transferred into the leaching tubes with a bottom packed with glass wool to retain the soil. A thin layer of glass wool was placed on top of the soil to minimize dispersion during leaching. At time zero 100 mL 0.01 A4 $CaCl_2$ was added in four increments under a suction of 600 MPa to remove readily soluble N (NH_4^+ and NO;) and phosphate. Then 30 mL of the nutrient solution as described by Stanford and Smith (1972) was added and put under 500 MPa tension to remove excess solution. In the case of P mineralization, phosphate was omitted from the nutrient solution and replaced with 0.022 *M* NH_4NO_3 . This was repeated at each sampling interval.

Each tube was capped with cellophane, with a small hole was made in it to allow exchange of gas, and put into an incubator at 35°C for 91 days (7, 14, 21, 28, 35. 42, 49, 63, 77, 91). Duplicate samples were used for each treatment.

The C mineralization study was done on the same soils and plant material as those used in the N and P mineralization described above by the static procedure of Zibilske (1994). Fifty g of soil were thoroughly mixed with 1 g of plant material artd this mixture was transferred into a glass tube sealed with septa at each end. Soil moisture was adjusted to 8% (wt/wt) and then the tubes were incubated at 25°C.

TABLE 1 Characteristics of soils

Soil location	pH	Total N	Total C	Total P
		g kg^{-1}		
Soil under canopy	6.07	0.449	4.01	0.090
Soil outside canopy	6.05	0.233	2.96	0.054

CO_2 samples were collected after 7, 14, 21, 28, 35, 42, 56, 70, 84 days and stored in vacutainer tubes. Samples of 500 μL were analyzed on a gas chromatograph. After each sampling the tubes were opened and allowed to equilibrate with ambient CO_2 levels. All incubations were carried out in duplicate.

Both experiments employed completely randomized designs where the treatments were: (1) *P. reticulatum* leaves; (2) *P. reticulatum* stems; (3) *P. reticulatum* stem plus leaves (in same proportion as found under field conditions); (4) *C. pinnata* leaves; (5) aboveground millet residue; (6) aboveground peanut residue; and (7) control (soil only). Because soil sampling came from only one tree, statistical analysis was done separately for each soil.

Laboratory Analysis

pH was determined with a glass electrode (soil: water ratio 2: 1). Total soil C was determined by combustion on a C analyzer (Dorhman, Santa Clara, California) and total C in residue was measured by LECO WR-12 C autoanalyzer (LECO Corp., St. Joseph, Missouri). Total N in soils and organic residues was done by Kjeldahl digestion followed by steam distillation according to Bremner and Mulvaney (1982). The leachate was analyzed for NO_3^--N and NH_4^+-N by steam distillation procedure of Bremner and Keeney (1965). Phosphorus in the leachate of mineralization was measured colorimetrically (Murphy and Riley 1962). Total P in plant residue and soils was determined by the methods of Cresser and Parsons (1979) and Dick and Tabatabai (1977), respectively. Lignin, cellulose, and hemicellulose were determined by the method of Goering and Van Soest (1970).

Calculation of Kinetic Constants

The mineralization potential and the rate constants were estimated using both nonlinear and linear regression. The exponential equation used to calculate potentially mineralizable N (No) and first rate order constant k_N is as follows:

$$N_m = N_O[1 - \exp(-k_N t)], \qquad (1)$$

where N_m = cumulative amount of N removed by leaching at a specific time (t). The statistical package SAS was used to fit the data to the equation using nonlinear regression procedure. The linear regression or zero order model was of the form

$$N_{min} = B_0 + k_1 t, \qquad (2)$$

where B_0 = the intercept and k_1 is the slope.

Results and Discussion

Chemical Composition of Soils and Plant Material

Soils characteristics are shown in Table 1. Nitrogen, C, and P contents tend to be higher in soils beneath tree canopies than in soils outside tree canopy. The pH values are the same in both soils. Table 2 shows the chemical composition of the plant material used in this experiment. The total C content ranged from 34% to 39%. The N content was the lowest in the millet (0.46%) and the highest in the peanut residue (1.54%). The P content varies in the following order: *C. pinnata* leaves > *Arachis hypogea* > *Pennisetum glaucum* L > *P. reticulatum* leaves > *P. reticulatum* stem.

The lignin contents of *P. reticulatum* stems and *C. pinnata* leaves were the highest at > 28% lignin compared to peanut residues and *P. reticulatum* leaves, which had lowest lignin values.

TABLE 2 Characteristics of residues

Species	Total N	C	P	C/N	Lignin	Cellulose	Hemicellulose
	g kg-'				g kg^{-1}		
Arachis hypogea (peanut)	15.4	374	1.01	24	20	313	71
Pennisetum glaucum (millet)	4.6	388	0.85	83	171	437	249
P. reticulatum leaves	12.4	345	0.74	27	62	392.	333
P. reticulatum stems	06.2	343	0.35	55	280	459	65
C. pinnata leaves	11.4	390	1.33	34	295	178	22

Before the incubation, all samples amended with the different plant residues were leached with 0.01 *M* $CaCl_2$ solution to extract soluble inorganic N. The results are presented in Figure 1. Interestingly, the soluble inorganic N content in the first extraction was highest for the millet-amended soils, whereas the leaf material of both the tree and shrub had the lowest levels. Compared to N, considerably less P was extracted from these residues (Figure 2). Nonetheless, these values were high, suggesting there are significant levels of soluble N and P in the materials, which should be readily available for plant uptake.

N Mineralization

At any given time of incubation, the minera1 N (NO;-N + NH_4^+-N) content was dominated by nitrate N fraction (data not shown) regardless of the type of treatment. The changes of cumulative NH_4^+-N with time were variable. In the peanut

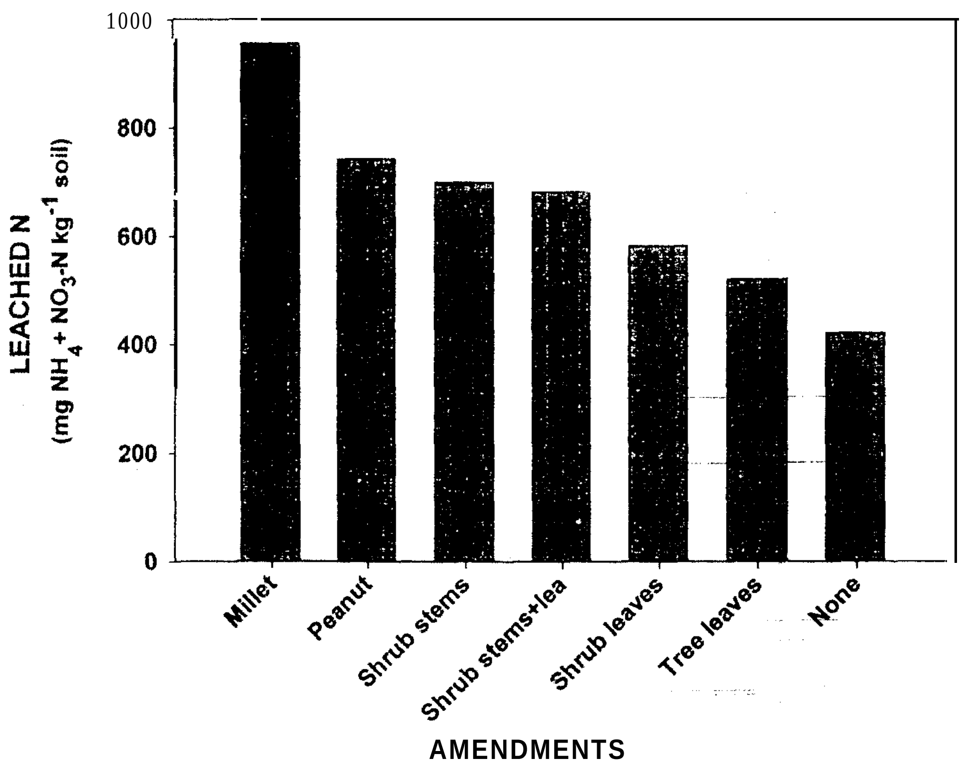

FIGURE 1 Amount of N leached at time zero after amending soil with plant residues (bars with the same letter within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range test).

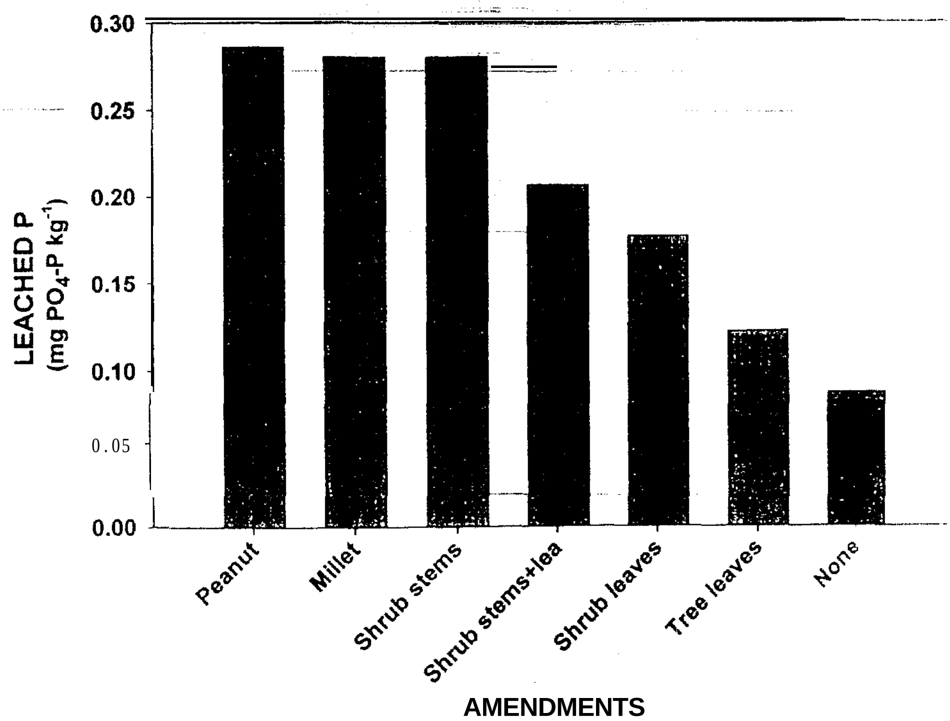

FIGURE 2 Amount of P leached at time zero after amending soil with plant residues (bars with the same letter within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range test).

treated soils (the only treatment to have net N mineralization), NH_4^+-N in the leachate increased between the third and sixth week of incubation and decreased from the ninth week. In the control samples NH_4^+-N in the leachate showed a peak at the second week of incubation and decreased for the remainder of the incubation (data not shown). Low values of NH_4^+-N in the leachate compared to NO_3^--N values are in agreement with the findings of Cassman and Muns (1980). Overall the cumulative NH_4^+-N values were greater in the soils collected beneath the tree canopy than the soil samples outside the tree canopy.

The relationships between cumulative inorganic N (NO_3^--N + NH_4^+-N) and the time of incubation are shown in Figure.3. A visual check of the curves showed that peanut amended soil and the control were curvilinear whereas the other treatments were linear or near linear.

The results show that net N mineralization occurred only in peanut amended soils, whereas net immobilization occurred in the other treatments. Comparison of the treatments where N immobilization occurred showed that soil from beneath the tree canopy, amended with millet residue or P. *reticulatum* leaves, immobilized less N than the remaining treatments. Conversely, in the soil collected outside the tree canopy, treatments showed no significant differences in N immobilizing capacity. This difference in soils was also reflected in the fact that more inorganic N was accumulated in soils beneath the tree canopy than those outside the tree canopy in all treatments.

These differences in N dynamics between soil collected beneath or outside the tree canopy may be related to the higher N content of soil beneath the tree canopy. Furthermore, C content was greater beneath the canopy (0.4 vs. 0.3% for soil outside the tree). Thus the greater amount of N and C as an energy source may have

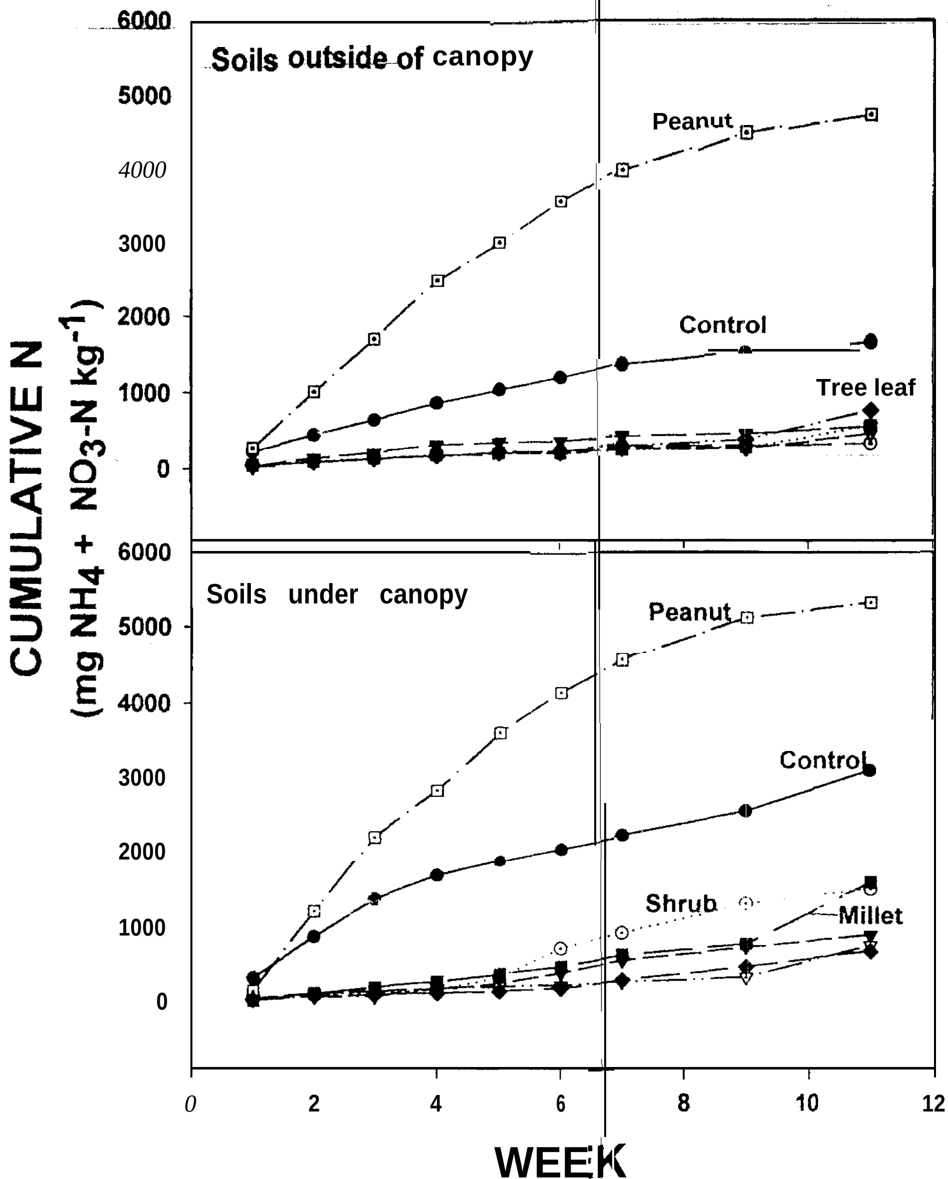

FIGURE 3 Cumulative N leached in soil amended with plant materials in soil beneath and outside the canopy of *C. pinnata* tree.

reduced the amount of N immobilization and increased total N accumulation from soil below the tree canopy. More organic C in the soil likely enabled greater microbial activity.

Our results are very consist with other studies, in that net N mineralization occurred only in soils amended with a herbaceous legume (peanut) and net immobilization dominated with nonleguminous herbaceous (millet) and nonleguminous trees and shrub material used in agroforestry (*C. pinnata* and *P. reticulaturn).* Kaboneka, Sabble, and Mauromoustakos (1997) reported net mineralization in leguminous herbaceous (soya) treated samples and net immobilization in cereal residues (maize amended soil). Also, comparing leguminous trees used in agroforestry, Constantinides and Fownes (1994) concluded that fresh legumes in general had net accumulation whereas the nonlegume fresh leaves had net depletion.

The plant materials used in our study varied in quality N, C, C/N, lignin, and other properties (Table 2). Initial N content, lignin and polyphenol concentrations have been reported to correlate with N release from plant material. But the results obtained by Melillo, Aber, and Muratore (1982), Fox et al. (1990), Palm and Sanchez (1991) and Constantinides and Fownes (1994) differed in which parameter correlated best. Along with *P. reticulatum* leaves, peanut residue material had the highest initial N content, and the lowest C/N ratio, lignin/N ratio (Table 2). But *P. reticulatum* leaves with a relatively low C/N ratio of 27 still had net N immobilization. These results overall agree with the conclusion reported by Constantinides and Fownes (1994). Other factors such as polyphenol concentration might have contributed to the low release of N from *P. reticulatum* leaves. The poor performance of *C. pinnata* leaves residues is similar to Aber and Melillo (1982) who reported the highest immobilization rates occurred in the nonleguminous tree litter (hardwood leaves) high in both lignin and N.

Another possible explanation for the net N immobilization for millet and *P. reticulatum* was the high C/N ratios of these residues, 81 and 53, respectively. This might have even been a factor for *C. Pinnata* litter N mineralization with a C/N ratio of 27. According to Stevenson (1985) net N immobilization lasts until the C/N ratio of the decomposing material has been lowered to about 20. Only peanut residue material had C/N ratio close to 20 (23). It may be that the time of incubation was too short to lower C/N ratios to 20 or that lower residue quality may be inhibiting N release.

N Mineralization Models

Data from the peanut amended samples and the control fit the first order model regardless of the soil sites (data not shown). Data from soils outside tree canopy sites treated with *P. reticulatum* leaves also fit the first order model with the remaining treatments fitting the linear zero order model. Peanut amended samples had the greatest mineralization N potential (N_0).

We did not find the model fitting to be very useful for interpreting the data. which indicates these models are poorly suited for developing N mineralization parameters for soils amended with organic residues. In some cases, N_0 was greater than the total cumulative mineralized N (e.g., peanut amended samples) and others were smaller than the total cumulative N. Dou and colleagues (1996) attributed the values of N_0 smaller than the cumulative mineralizable N to the weakness of the single model, which should be greater than the observed cumulative mineral N. On the basis of the studies by Juma, Paul, and Mary (1984), Cabrera and Kissel (1988). and Sierra (1990), it was suggested that because of the dependence of goodness of fit and the magnitude of the parameters on specific models and incubation time, the parameters derived from models do not predict N mineralization for a given soil; if such potential exists under a given set of conditions (Dou et al. 1996). These values are, however, merely mathematically defined quantities obtained by nonlinear regression analysis (Faustian and Bonde 1987).

Phosphorus Mineralization

The changes of cumulative inorganic P mineralization with time are presented in Figure 4. Contrary to N mineralization, P mineralization investigations have limitations because of the susceptibility of PO_4^{3-} (mineralization product) to chemical

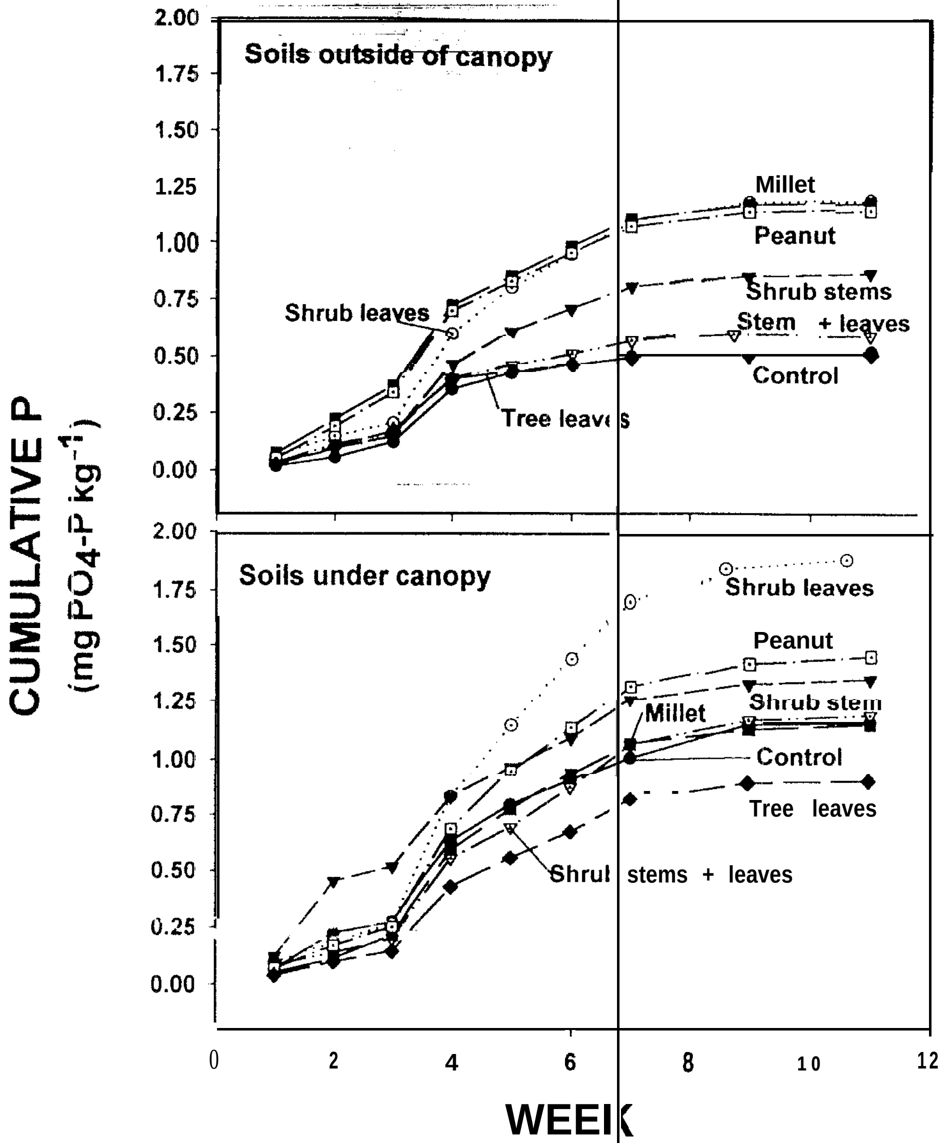

FIGURE 4 Cumulative P leached in soil amended with plant materials in soil beneath and outside the canopy of *C. pinnata* tree.

sorption and precipitation reactions (Sharpley and Smith 1989). Thus the P determined in the leachate is not quantitative for P mineralization, but rather is the net effect of P mineralization and degree of P fixation reactions. Consequently, the results are most useful from a comparative basis among the treatments.

Although the soils used in this experiment are characterized as very sandy soils, these soils are coated with Fe and Al oxides or hydroxides (personal communication, A. Badiane) that are well known to strongly sorb added P to soil.

The curve of cumulative P in the leachate vs. time of incubation is curvilinear. However, these curves present two distinctive segments corresponding to two periods of incubation (from day 7 to day 21, and from day 21 to day 77). Generally, a visual check of the curves showed that during the first three weeks of incubation cumulative P was linear with time. During the second stage of incubation (day 21 to day 77), this relationship was curvilinear. These results agreed with those of Sharpley and Smith (1989) who observed an initial phase during residue decomposition of P immobilization the first 14 days with maximum mineralization occurring at 28 days. After 77 days cumulative P in the leachate followed treatments in the order of: *P. reticulatum* leaves = *Arachis hypogea* ≃ *Pennisetum glaucum* > *P. reticularum* stem/leaf mixture > *P. reticulatum* stem = control = *C. pinnata* leaves for soil outside the tree canopy. The treatment order for net P release in soil beneath the tree canopy was: *P. reticulatum* leaves > *Arachis hypogea* ≃ mixture *P. reticulatum* leaves + stem > *Pennisetum glaucum* ≃ *P. reticulatum* stem ≃ control > *C. pinnata* leaves.

Cordyla pinnata leaves caused net P immobilization in soil beneath the tree canopy. The *Cordyla pinnata* and *P. reticulatum* stem + leaf residue caused zeto change in the soils outside tree canopy. The remaining plant materials caused cumulative P levels that were greater than the control. The highest cumulative P was in soil amended with millet, *P. reticulatum* leaves, or peanut (soil outside tree canopy) or with *P. reticulatum* leaves amended samples (soil beneath tree canopy). *P. reticulatum* leaves consistently caused the highest amount of P in the leachates of both soil beneath and outside the canopy followed by peanut residues. A careful observation of Figure 4 suggests that soil source might have influenced the amount of P released from the residue. The consistently higher P content in the leachate of soil amended with *P. reticulatum* leaves is probably the result of its high P content (0.10%) and relatively low C/P ratio. Except millet which had variable trends, overall, peanut and *P. reticulatum* leaves that had a relatively low C: P ratio, had also a greater amount of P accumulation. Dalal (1977), Fuller, Nelson, and Miller (1956), and Sharpley and Smith (1989) suggested that for residues with C: P ratio equal or less than 200, P mineralization occurs and if the ratio was higher than 300, immobilization occurs. Soil characteristics of the two sites could have affected P release from the residues. Relatively greater amounts of P accumulation were found in the soils beneath the tree canopy, which is consistent with other studies (Kamara and Haque 1992; Samba 1997; Jung 1970; Dancette and Poulain 1968; and Charreau and Vidal 1965) that have report-d higher P content in the soil beneath the tree canopy than outside tree canopy.

Sharpley and Smith (1989) reported that mineralization of residue P appeared to be a positive linear function to available soil P content. The high C: P ratio (Table 2) of *C. pinnata* leaves (which is the only tree material) may explain why it had net P immobilization or near zero P mineralization.

Another factor for greater levels of soluble P by peanut and *P. reticulatum* may be that these residues were more effective in decreasing P fixation. Organic amendments have been shown to increase 0.01 *M* $CaCl_2$ extractable P and Bray I P content (Iyamuremye and Dick 1996; Sharpley and Smith 1989). During decomposition organic compounds may be released that reduce potential for P fixation reactions (Iyamuremye and Dick 1996) and thus less P may have been adsorbed allowing for more mineralized P to remain in solution and be leached.

Our results suggest that *P. reticulatum* residue could be useful for increasing P availability in this Senegalese soil. This could be important because P is a major limitation for crop production in the important agroecological zone of Senegal. Furthermore, farmers there have limited resources to purchase fertilizers. However, this needs to be tested under field conditions.

Carbon Mineralization

The relationship between the cumulative CO, and time of incubation is shown in Figure 5. These data indicate that, at any given time, CO, evolved was greater for all the residue treated soils over the control samples.

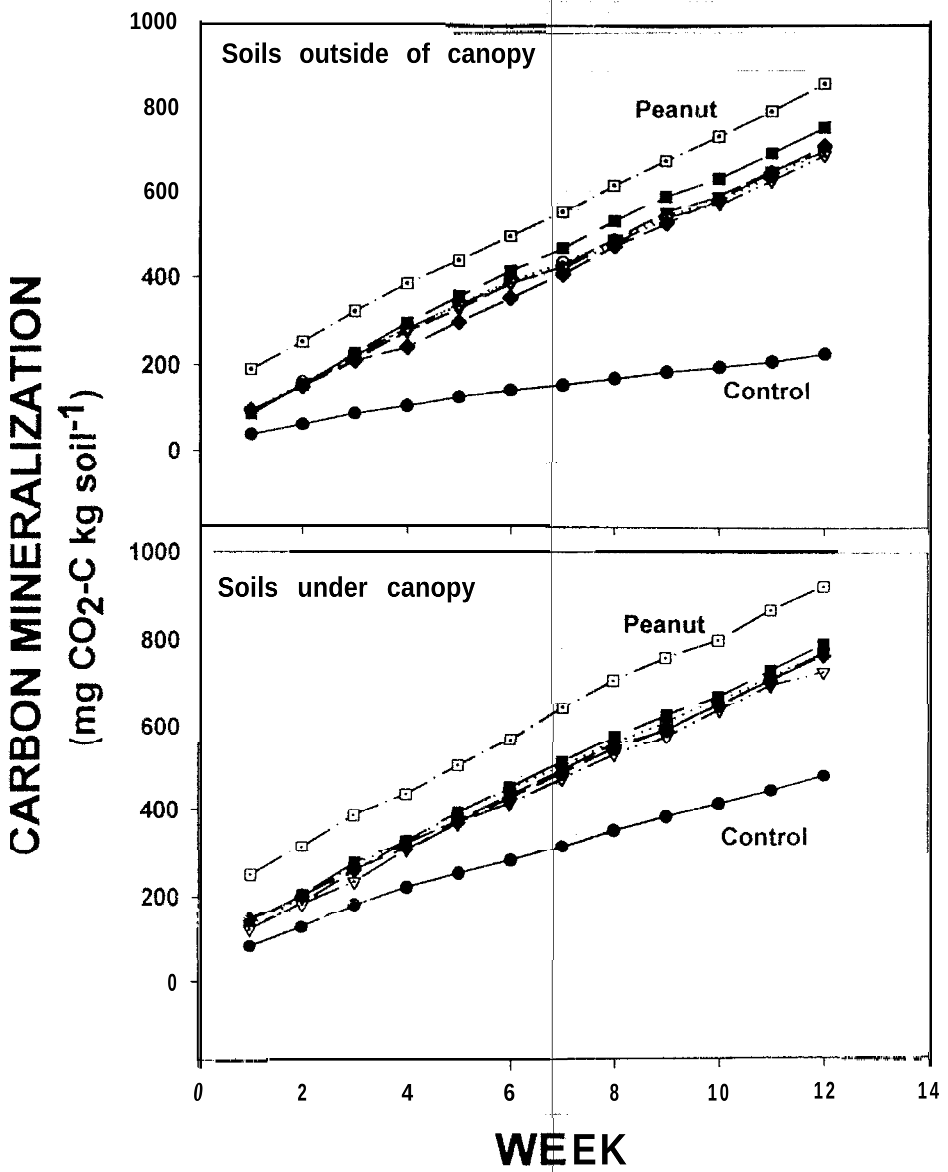

FIGURE 5 Cumulative CO_2 evolved in soil amended with plant materials in soil beneath and outside the canopy of C. *pinnata* tree.

Peanut amended samples were associated with greater CO_2 evolution. In other samples, the amount of CO_2 evolved about the same, regardless of soil origin. It is interesting to notice that peanut residues that caused net N mineralization had the most CO_2 evolution. This may suggest a relationship between C mineralization and N mineralization. Overall the relationship between CO_2 evolved and time of incubation is linear.

Conclusions

This study has shown that the millet and woody parkland species residues immobilized N during a standardized incubation up to 77 days. Only peanut residue caused net N mineralization on soils from both beneath or outside the tree canopy. *Piliostigma reticulatum* leaves had low lignin content and a relatively narrow C: N ratio (27) and yet still had net N immobilization. This may suggest that other parameters such as polyphenol concentration played a greater role in deterrnining the net release of N.

The curves of cumulative P in the leachate versus time of incubation arc curvilinear and present two segments corresponding to two periods of incubation. The highest cumulative P was in the soil amended with millet and *P. reticulatum* leaves or peanut residues (soil outside the tree canopy) or with *P. reticulatum* leaves (soil beneath tree canopy). The consistently highest P content in the leachate of soils amended with *P. reticulatum* leaves is probably the result of its relatively low C/P ratio or the high P content of these residues and their capacity of reducing P sorption capacity of the soil.

The relationship between the cumulative CO_2 and incubation time was linear, and CO_2 evolution was greater for all residues than the control. Peanut residues that caused N mineralization had the most CO_2 evolution suggesting a probable relationship between C mineralization and N mineralization. Plant residues that caused N immobilization also caused less CO, evolution or C mineralization.

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