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SOIL NITROGEN MINERALIZATION UNDER TREE CROPS AND A LEGUME COVER CROP IN MULTI-STRATA AGROFORESTRY IN CENTRAL AMAZONIA: SPATIAL AND TEMPORAL PATTERNS

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SUMMARY

Under rainforest vegetation, the central Amazonian Ferralsols are characterized by relatively high availability of N in relation to other nutrients. After forest clearing, several tree crops also have not shown yield responses to N fertilizer. To elucidate the mechanisms of this apparent N sufficiency, the mineralization of soil N was measured under three tree crops and a leguminous cover crop (*Pueraria phaseoloides*) in a multi-strata agroforestry system at two fertilizer input levels on a Xanthic Ferralsol in central Amazonia. *In situ* incubations of topsoil (0–10 cm) were carried out using the buried-bag method on five occasions over ten months. The highest mineralization rates were found under the cover crop, intermediate rates under rubber trees (*Hevea brasiliensis*) where the soil was also covered by the cover crop, and lowest rates under peach palm (*Bactris gasipaes*) and cupuaçu (*Theobroma grandiflorum*) with no cover crop. The increased N mineralization under the cover crop was due to more total N in the soil, higher soil moisture and, presumably, a larger pool of readily mineralizable soil N compared with the soil under the tree crops. Other fertility parameters also differed significantly between sampling positions within the plots, but this had no major influence on net N mineralization. Also, the input of NPK fertilizer and dolomite had no significant influence on N mineralization, indicating that N mineralization was not nutrient-limited. High total N mineralization rates in the soil (approximately 350 kg ha^{-1} a^{-1} at 0–10 cm depth) explained earlier observations of nitrate leaching into the subsoil under multi-strata agroforestry at this site. Considering the spatial patterns of N mineralization with maximum values under the cover crop, the exploration of the soil volume by crop roots should be maximized to increase the uptake of mineralized soil N by the crops and reduce nitrate leaching. Appropriate measures are narrow tree spacing, use of annual and semi-perennial intercrops and encouragement of the lateral root development of the trees. In addition, the mineralization of soil N close to the tree crops can be influenced through the management of the cover crop. In view of the high total N mineralization rates in the system and unclear yield responses of tree crops to N fertilizer, the application of N fertilizer to tree crops with well-developed root systems and a well-managed cover crop may often be unnecessary on this soil type. This may facilitate the further development of tree crop agriculture in the region.

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INTRODUCTION

The Amazonian uplands (*terra firme*) are dominated by acid and infertile Ferralsols and Acrisols (von Uexküll and Mutert, 1995). Studies in central Amazonia and neighbouring regions established that biological activity in the primary forests growing on these soils is not limited by the availability of N, but rather by that of P, Ca and Mg (Vitousek and Matson, 1988). Recently, evidence was reported that under primary forest on a clay Ferralsol in the Manaus region some mineral N is leached into the subsoil (although not necessarily lost from the system), despite the efficient nutrient recycling mechanisms of this vegetation type (Schroth *et al*., 1999). This may be a further indicator of the N-sufficiency of the forests on these soils.

After slashing and burning the forest for agricultural use, the N mineralization in the soil, and thus the N availability for plant growth, may increase further (Montagnini and Buschbacher, 1989). The increased N mineralization and the disruption of the dense root systems and mycorrhizae of the forest trees also increase the potential for leaching of mineralized N and other nutrients into the subsoil where they are inaccessible for shallow-rooted crop plants (Cahn *et al*., 1993). Under these conditions, annual crops such as maize (*Zea mays*) may respond to N fertilizer after several years of continuous cultivation (Cravo and Smyth, 1997).

The situation may be different, however, in cropping systems based on tree crops. On a central Amazonian Ferralsol, application of N fertilizer to oil palm (*Elaeis guineensis*) over 15 years did not lead to significant yield increases although the leguminous cover crop had largely disappeared a few years after plantation establishment, and limitation by other nutrients was precluded by fertilizer application (Rodrigues *et al*., 1997; Schroth *et al*., 2000a). On a nearby site with similar soil, several tree crop species with a cover crop of *Pueraria phaseoloides* also showed no clear yield response to N fertilizer (Schroth *et al*., 1999), and foliar N concentrations were generally unaffected (E. M. A. Elias and G. Schroth, unpublished). Furthermore, substantial accumulations of nitrate in the subsoil at both sites confirmed the relatively high N availability in this type of soil (Schroth *et al*., 1999; Schroth *et al*., 2000a).

Where a leguminous cover crop is present, the high N availability in the soil could be partly a result of biological N_2 fixation, which can amount to about 150 kg N ha^{-1} a^{-1} as shown in other regions (Giller and Wilson, 1991). Following its release from decomposing legume biomass, this N could either be taken up by the tree crops or be leached into the subsoil.

An additional explanation for the apparent N sufficiency of tree crops on this soil could be high soil N mineralization, in agreement with the rapid N cycling in the primary forests of the region (Vitousek and Matson, 1988). Soil N mineralization could also be influenced by the cover crop through microclimatic effects and through the input of N-rich litter which may augment the mineralizable N pool in the soil. Marrs *et al*. (1991) reported increased N mineralization after the addition of $CaSO_4$ or lime to a northern Amazonian soil. Thus, another factor influencing N mineralization could be the acidity of the soil and the availability of certain limiting nutrients. In perennial cropping systems, fertilizer is usually applied to the area immediately around the trees, and pronounced differences in nutrient availability in the soil may occur, therefore, over small distances within a plot.

The objective of the research reported here was to analyse the spatial and temporal patterns of N mineralization within a multi-strata agroforestry system comprising three tree crop species at two fertilizer input levels as influenced by the presence of a leguminous cover crop and small-scale differences in soil fertility arising from the localized distribution of mineral fertilizer. The authors hypothesized that the understanding of these patterns could be of use for the development of land use systems with increased nutrient efficiency and reduced dependence on external inputs for optimum growth and development of the crops.

MATERIALS AND METHODS

Study site

The study was conducted on the Embrapa Amazônia Ocidental research station near Manaus in central Amazonia, Brazil (3°8′S, 59°52′W, 40–50 m a.s.l.). The climate is typical of tropical humid lowlands with an annual precipitation of 2622 mm, air temperature of 26°C and atmospheric humidity around 85% (mean values 1971–93, O. M. R. Cabral and C. Doza, unpublished). The driest months are July to September, and the wettest months are February to April. The soil is a Xanthic Ferralsol according to FAO/UNESCO (1990) with a clay content of about 65% in the topsoil, increasing with depth. It is acidic with a low cation exchange capacity, high Al saturation and low available P contents. Topsoil characteristics from the study plots are given in Table 2. A more general analysis of soil characteristics under primary forest, fallow and agriculture are provided by Schroth *et al.* (2000b).

Using heavy machinery for windrowing and removing tree stumps, the study site was first cleared of primary forest in 1980. In 1981, an experiment with rubber trees (*Hevea brasiliensis*) was established. This was abandoned in 1986 because of heavy disease attack. In 1992, the developing secondary forest was manually cleared and the vegetation burned on the site. The experimental plots were planted in February–March 1993.

Cupuaçu (*Theobroma grandiflorum*), peach palm (*Bactris gasipaes*) for the production of palmito (palmheart), and rubber trees (*Hevea brasiliensis*, grafted with a crown of *Hevea pauciflora*) were grown in alternating rows spaced 5 m apart (Fig. 1). Cupuaçu was planted at 6.4 m within the rows, peach palm at 2 m and rubber at 4 m. Single rows of papaya (*Carica papaya*) with within-row spacing of 2 m were interplanted between the rows of trees for the first three years of the experiment (1993–95). The N-fixing legume *Pueraria phaseoloides* (tropical kudzu), from sown seed and volunteer plants from the former rubber plantation, was grown as a cover crop between the trees.

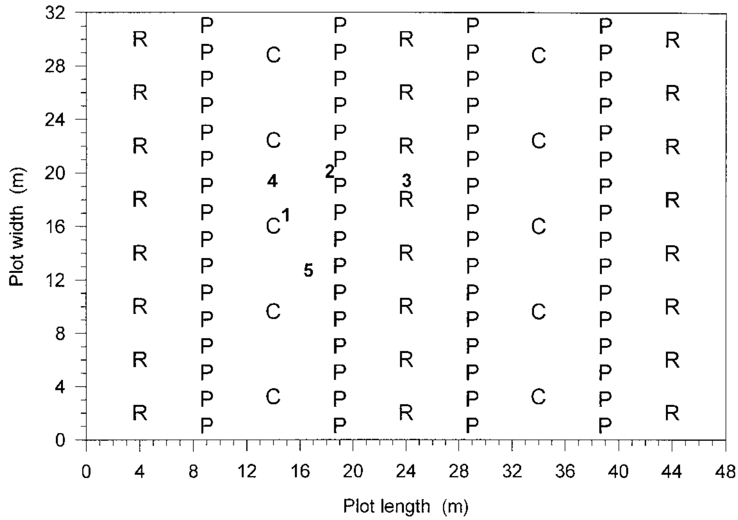

Fig. 1. Layout of an agroforestry plot with cupuaçu (C), peach palm (P) and rubber trees (R) in central Amazonia. The soil between the trees is covered by *Pueraria phaseoloides*. The numbers show the sampling positions referred to in the text.

The study carried out in this multi-strata agroforestry system consisted of experimental plots arranged in a randomized block design with four replications of two fertilizer treatments. Plot size was 48 by 32 m. Yield data are from four replications, three of which were used for the N mineralization study (the fourth block was excluded from the soil studies because of its heterogeneous relief). The fertilizer treatments were (i) full fertilizer input of N, P, K, micronutrients and dolomitic lime according to local recommendations and (ii) low fertilizer input of 30% of full rate with no further N and dolomite applied after May 1996 (Table 1). The latter treatment was introduced as a minimum input level where N was supplied only by the soil and the cover crop, and soil acidity was not corrected. The fertilizer was applied in two doses during the study year (1997–1998); in the first week of December 1997 (beginning of the rainy season) and in the first week of June 1998. In November–December 1996, dolomitic lime had been broadcast at a rate of 2.1 t ha^{-1} in the full-, but not the low-fertilizer input plots.

Table 1. Trees per hectare and fertilizer application (g $plant^{-1}$) during the study year in a multi-strata agroforestry system in central Amazonia.

	Trees per hectare	Full fertilizer input			Low fertilizer input		
		N	P	K	N	P	K
Cupuaçu	78.1	95	77	125	0	23	38
Peach palm	500	42	22	50	0	7	15
Rubber trees	125	21	33	32	0	10	10
Whole plot (kg ha^{-1})		31	21	39	0	6	12

N was applied as ammonium sulphate (21% N), P as triple super phosphate (22% P), and K as potassium chloride (50% K). The trees also received a mixture of micronutrients.

Sample collection, incubation and analysis

To analyse the spatial patterns of N mineralization within the agroforestry plots, five sampling positions were distinguished within each plot (Fig. 1).

(1) at 50 cm distance from the stem of a cupuaçu tree,
(2) at 50 cm distance from the stem of a peach palm,
(3) at 50 cm distance from the stem of a rubber tree,
(4) under the cover crop midway between adjacent cupuaçu trees and
(5) under the cover crop midway between a cupuaçu row and the adjacent peach palm row.

Under the cupuaçu and the peach palm, the soil was free from vegetation as the *Pueraria* was periodically cut back to prevent it from climbing the trees. Under the taller rubber trees, the *Pueraria* covered the soil completely up to the trunk. Position 4 ('*Pueraria* unfertilized') differed from position 5 ('*Pueraria* fertilized') in so far as papaya had been grown only in the latter during the first three years of the plantation. Every papaya plant in the full fertilizer treatment had received relatively high doses of mineral and organic fertilizer and lime (420 g N, 93 g P, 175 g K, 1500 g lime and 36 L of chicken manure per plant) and those in the low fertilizer treatment had received 30% of these values. The purpose of comparing the different positions under the cover crop was to determine if a residual effect of the fertilizers on net N mineralization was detectable three years after the removal of the papaya intercrop.

Soil samples were collected for incubation five times during 1997–98 (Fig. 2). Using a cylindrical corer, the samples were collected at depths of 0–10 cm from each of the five positions in the six plots (two input levels, three replications). Two samples per position were collected, one each from under two different trees or places with *Pueraria* cover crop, mixed together in a bucket and larger pieces of roots or litter were removed. A subsample of approximately 300 g of the mixture was placed in a polyethylene bag and buried under a thin layer of soil and litter in one of the holes of the respective sampling position. The aim was to create microclimatic conditions as similar as possible to the undisturbed soil. The remaining soil from each sample pair was taken to the laboratory for extraction of mineral N and determination of the water content. In the following week, the same procedure was repeated, so that four separate samples were incubated for each position. The results from these four samples were averaged for the statistical analysis. After 14–15 d, the incubated samples were collected and taken immediately to the laboratory for the extraction of mineral N.

In the laboratory, all samples were processed within hours of collection from the field. From every sample, two subsamples of 20 g were used for N extraction and two of about 50 g were dried at 105°C for two days to determine the water content. For N extraction, each subsample was mixed with 150 ml of 1 M KCl solution and the mixtures were left standing overnight to ensure complete wetting of the aggregates. The next morning, the samples were extracted by mechanical shaking for 30 min. Extraction solutions were collected with a pipette without filtration after a sedimentation time of about 1 h.

The extraction solutions were analysed the same day or were kept below 0°C (but not frozen) until analysed. Ammonium and nitrate (after reduction to nitrite) ions in the extracts were analysed colorimetrically with a segmented flow analyser. Using the water content values of the soil samples, the N contents were related to the soil dry weight. N mineralization values over the whole study period per unit area were calculated by linear interpolation between the sampling dates, using a topsoil bulk density of 0.88 kg dm^{-3} (Schroth *et al.*, 1999).

Effect of soil disturbance on net N mineralization

Preliminary experiments had shown that the variability of the net N mineralization rates between replicate soil samples was high when intact soil cores were incubated. This is in agreement with information in the literature (Subler *et al.*, 1995). Disturbed soil samples that allowed mixing of soil from several sampling points within the plots and subsamples for the initial extraction of mineral N to be taken directly from the sample to be incubated were used in this study to reduce this variability. Because increased aeration and breaking of aggregates might increase N mineralization rates, the N mineralization in disturbed and undisturbed samples was compared in a separate study in one of the experimental plots. In September 1998, two undisturbed soil cores of 8 cm diameter were collected with a cylindrical root corer from the topsoil at each of the five sampling positions. The cores were placed in plastic bags and returned to their original positions. From close to the undisturbed cores, two similar cores were collected, mixed and treated as in the main experiment. The mineral N and water content data obtained thus from the disturbed samples were used also as the initial values for the corresponding undisturbed cores. After two weeks, the disturbed and undisturbed samples were collected, and mineral N and water content were determined in each sample. The N mineralization rates in disturbed and undisturbed soil samples were compared using the *t*-test for dependent samples.

Chemical soil characterization

After the end of the incubation study in September 1998, further soil samples were collected from 0–10 cm soil depth in the sampling positions of the study plots. The air-dried samples were passed through a 2 mm sieve and the following analyses were conducted:

(1) total C and N by dry combustion with a CHN Analyser,
(2) extractable P, K, Ca and Mg with the Mehlich 3-method (Tran and Simard, 1993),
(3) exchangeable acidity by extraction with 1 M KCl and titration (Hendershot *et al.*, 1993),

(4) cation exchange capacity by summation of extractable cations and acidity and
(5) pH by glass electrode at a soil:solution ratio of 1:2.5 in water.

Statistical analysis

The statistical analysis was performed by analysis of variance for a randomized block, split plot design with the fertilizer level as the main-plot factor and the sampling position within the main plots as the subplot factor. Results for the five incubation dates were first calculated separately. Subsequently, all sampling dates together were compared with the same design as above and the time as repeated measurements factor.

RESULTS AND DISCUSSION

Chemical soil characteristics in the agroforestry plots

In Table 2, only mean values for fertilizer rates and sampling positions are given because the interactions between these two factors generally were not significant, with the exception of P. In the full fertilizer plots, the soil fertility was substantially higher than in the low fertilizer plots. Significantly increased pH as well as P, K, Ca and Mg contents and significantly lower exchangeable acidity were recorded in the former. Within the plots, the heavy fertilizer and lime application to the papaya crop in the '*Pueraria* fertilized' position resulted in significantly higher pH, Ca, Mg and CEC and significantly lower acidity compared with all other sampling positions. Total N was significantly higher under '*Pueraria* fertilized' than under cupuaçu and peach palm. For P, a significant fertilizer level × position interaction was observed, because higher fertilizer application increased the

Table 2. Soil characteristics at 0–10 cm depth under three tree crops and a cover crop of *Pueraria phaseoloides* in a multi-strata agroforestry system in central Amazonia at two fertilizer input levels.

	pH (H_2O)	C ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	P[a] ($mg\ kg^{-1}$)	K[a] ($cmol_c^+\ kg^{-1}$)	Ca[a]	Mg[a]	CEC[b]	Acidity[c] (%)
	Fertilizer input (means of 5 sampling positions)								
Full	4.81	25.1	2.11	72	0.17	2.05	1.02	3.94	22.5
Low	4.29	23.8	1.97	27	0.10	0.95	0.21	2.85	64.6
s.e.	0.09	0.7	0.07	3	0.03	0.01	0.06	0.22	3.5
	Positions (means of two fertilizer inputs)								
Cupuaçu	4.29	22.9	1.88	45	0.13	0.92	0.40	2.82	54.5
Peach palm	4.61	23.7	1.94	73	0.20	1.36	0.61	3.21	39.3
Rubber	4.25	25.2	2.07	50	0.12	0.76	0.41	2.70	55.4
Pueraria unfertilized	4.42	24.6	2.07	7	0.10	0.74	0.60	2.82	54.4
Pueraria fertilized	5.16	26.0	2.23	73	0.13	3.72	1.06	5.41	14.3
s.e.	0.22	1.2	0.10	15	0.03	0.57	0.20	0.54	8.2

[a] Mehlich 3 extractable fractions; [b] cation exchange capacity; [c] exchangeable acidity (1 M KCl)

available P contents under the fertilized tree crops, but not under the unfertilized cover crops. The available P content under cupuaçu, peach palm and rubber was 69, 121 and 83 mg kg^{-1} respectively at full fertilizer input levels, and 22, 26 and 17 mg kg^{-1} respectively at low fertilizer input levels. Under '*Pueraria* unfertilized', where no papaya had been grown, the soil P contents were significantly lower than in all other positions within the plots (Table 2). These data show that the variability in chemical soil fertility between the sampling positions was sufficiently large to test for a possible effect of soil fertility on soil N mineralization.

Crop yields

From the fertilizer levels in Table 3, only the levels 'full' and 'low' were included in the soil N study. The yields of an additional fertilizer level, 'low plus N' are shown to demonstrate the effect of N fertilizer (and lime) independently of the other fertilizer nutrients. Although the yields in the 'low plus N' treatment were usually slightly higher than those in the 'low' treatment without N fertilizer, the difference was never significant. This indicates that the productivity of the tree crops was not markedly limited by N at this site, confirming the previously mentioned results from this type of soil (Schroth *et al.*, 1999; Schroth *et al.*, 2000a).

Effect of soil disturbance on net N mineralization

The mean rates of net N mineralization were 1.02 (*s.d.* 0.38) mg kg^{-1} d^{-1} in the disturbed samples and 1.18 (0.44) mg kg^{-1} d^{-1} in the undisturbed samples. The difference between the two methods was not significant. The similarity between the results of the two methods was in agreement with Piccolo *et al.* (1994). They measured similar net N mineralization rates in buried bags with sieved soil and in intact soil cores within closed PVC tubes, in an Amazonian forest soil. In pasture soil, however, there was less agreement between methods.

Table 3. Crop yields in an agroforestry system on a ferralitic upland soil in central Amazonia during the study years 1997 and 1998 as influenced by fertilizer input.

	Fertilizer input level			
	Low	Low + N[a]	Full	*s.e.*
	Cupuaçu (kg fresh fruit per tree)			
1997	6.1	7.8	8.0	1.2
1998	8.3	8.5	13.6	2.4
	Peach palm (kg palm heart per tree)			
1997	0.68	0.76	0.85	0.06
1998	0.55	0.55	0.62	0.07
Mean	0.62	0.65	0.73	0.04

[a] Treatment not included in the N mineralization study that received the same amount of fertilizer as 'low' plus 30% of the N and lime applied in the 'full fertilizer' treatment.

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It seems that these soils with their relatively small aggregates and low bulk density with good aeration show relatively little effect of disturbance on N mineralization. This experiment showed that net N mineralization values obtained with disturbed soil samples in the field produced reliable values under the conditions of this study.

Temporal and spatial patterns of soil N mineralization

On average, 108 (*s.e.* 22)% of the mineralized N in all incubated samples, were in the nitrate form, without significant differences between treatments. Nitrification rates similar to or higher than net N mineralization rates have also been reported from other tropical sites (Robertson, 1989).

The daily net N mineralization rates in the topsoil where in the range of 0.3–1.7 mg kg^{-1} d^{-1} (Fig. 2). They fall within the range of N mineralization rates reported by other authors from Amazonian topsoils under forest and tree plantations (Smith *et al.*, 1998). Montagnini and Buschbacher (1989) measured net N mineralization rates of 0.47 mg kg^{-1} d^{-1} under forest and 0.73 mg kg^{-1} d^{-1} under slash-and-burn agriculture in a Ferralsol in the Venezuelan Amazon. Lower values were found under an Amazonian pasture (Neill *et al.*, 1995).

The net N mineralization rates exhibited pronounced seasonal patterns (Fig. 2a–e), with significantly higher values in May–June (1.1 mg kg^{-1} d^{-1} on average in all positions, Fig. 2d) than on all other incubation dates except January–February (1.0 mg kg^{-1} d^{-1}, Fig. 2b). The lowest mineralization rate was measured in November-December, at the end of the dry season (0.8 mg kg^{-1} d^{-1}, Fig. 2a). The interactions between incubation date and the other factors (fertilizer input, plant species) as well as the three-way interaction were not significant. The seasonal patterns of net N mineralization were apparently due to differences in the soil water content, which varied significantly during the study period according to the rainfall pattern, with highest values in May–June and lowest values at the beginning and at the end of the study (Fig. 3). Higher N mineralization rates during the wet than the dry season have also been found in a tropical savanna in India (Singh *et al.*, 1991) and in coffee plantations in Costa Rica (Babbar and Zak, 1994).

Spatial patterns of N mineralization have seldom been investigated in agricultural or agroforestry systems. Babbar and Zak (1994) compared net N mineralization rates in areas beneath and between the canopies of *Erythrina* shade trees and coffee bushes in coffee plantations in Costa Rica, but could not detect significant position effects.

Within the study plots there were pronounced spatial patterns of net N mineralization (Fig. 2a–e). At the end of the dry season (November–December, Fig. 2a), N mineralization under the cover crop and under the rubber trees (soil was also covered by *Pueraria*) was significantly higher than under cupuaçu; peach palm yielded intermediate values. During the rainy season N mineralization under the cover crop was significantly higher than under cupuaçu and peach

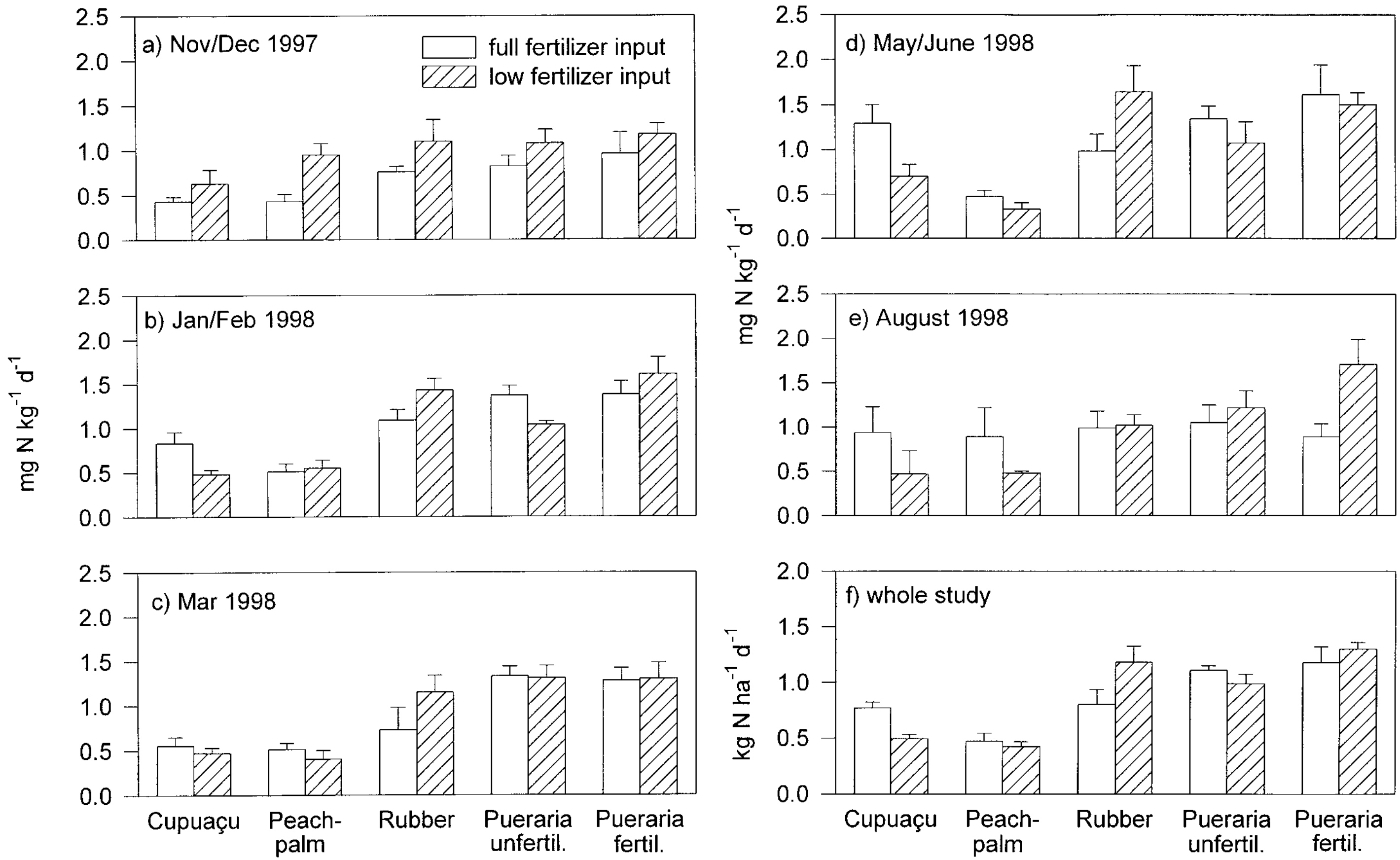

Fig. 2. Net N mineralization (means and *s.e.*) in the topsoil (0–10 cm) of a multi-strata agroforestry system in central Amazonia at two fertilizer input levels as measured in five sampling positions during one year. Figs. a-e show results from five incubation dates, and Fig. f shows weighted mean values of all incubation dates.

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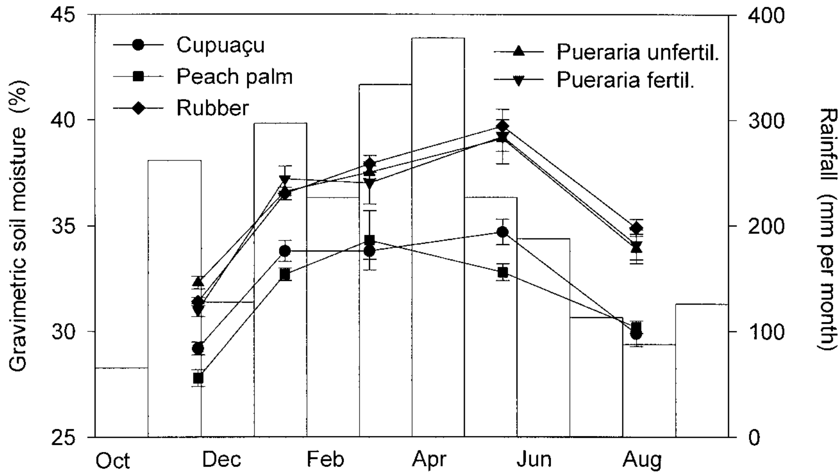

Fig. 3. Soil moisture (means of five sampling positions and *s.e.*) in the topsoil (0–10 cm) of a multi-strata agroforestry system, and monthly rainfall during the incubation study.

palm (Fig. 2b,c). The same pattern was observed during the fourth and the fifth incubations (Fig. 2d,e).

The average daily net N mineralization during the study period was significantly higher in the soil under the cover crop at both sampling positions and under the rubber trees than in the soil under cupuaçu and peach palm (Fig. 2f). Under the cover crop, approximately twice as much N was mineralized per unit area than under cupuaçu and peach palm and where papaya had been grown ('*Pueraria* fertilized'), the net N mineralization was also significantly higher than under the rubber trees. The fertilizer input × position interaction had no significant effect on N mineralization.

Differences in net N mineralization between the positions within the plots can partly be explained by higher soil water contents under the cover crop (and consequently the rubber trees) than under cupuaçu and peach palm where the soil was kept free from vegetation (Fig. 3). This difference was significant on all sampling dates and was presumably due to low soil evaporation under the dense *Pueraria* foliage and a lower transpiration rate per unit ground area of the low-growing cover crop compared with the taller trees.

The higher net N mineralization rates under the cover crop were also related to the higher total N under *Pueraria* compared with the trees (Table 2). Total N under the cover crop, however, was only 13% higher than under cupuaçu and peach palm, but net N mineralization was about twice as high as under these tree crops. This indicates that there were also qualitative differences in the composition of organic N in the soil between the sampling positions, with a larger pool of labile N under *Pueraria* (and consequently the rubber trees) than under cupuaçu and peach palm. This labile N may have consisted both of a readily mineralizable fraction of soil N and of small, N-rich root and litter fragments from the cover crop

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which were included in the incubated samples. Build-up of a pool of readily mineralizable organic N in soil amended with legume biomass has been reported by Haggar *et al.* (1993) and Barrios *et al.* (1996) among others.

Chemical fertility had only a small influence on N mineralization rates in the plots. Two years after the removal of the heavily fertilized papaya from between the tree rows, the soil in these positions was the most fertile, whereas the soil between the cupuaçu trees where no papaya had been grown was the least fertile (Table 2). The net N mineralization rates did not differ significantly between these positions, although they tended to be higher in the more fertile soil (Fig. 2f). Soil fertility also differed significantly between the two input levels (Table 2), but this did not result in significant differences in N mineralization (Fig. 2). This indicates that even in the least fertile positions of the study N mineralization by the soil microflora was not limited by nutrient availability.

From the daily net N mineralization rates for the whole study (Fig. 2f), annual net N mineralization values of between 197 kg ha^{-1} (mean of cupuaçu and peach palm) and 418 kg ha^{-1} (mean of the two *Pueraria* positions) were calculated. Since about 75% of the plot area was covered by *Pueraria*, the annual net N mineralization for the whole system would have been close to 350 kg ha^{-1}, in accord with values from Amazonian forest and plantation soils (196–328 kg ha^{-1} a^{-1}) (Smith *et al.*, 1998). Even this coarse estimate shows that the N mineralization in this soil was very high and supplied far more mineral N to the system than was applied as mineral fertilizer in the full fertilizer treatment (Table 1). Additional N was mineralized in the soil below 10 cm depth. Also, the leguminous cover crop released mineral N derived from biological N fixation from its decomposing biomass. The high N availability in the system, in combination with the rapid nitrification of the mineralized N, explains the observed accumulations of leached nitrate in the subsoil (Schroth *et al.*, 1999). This also helps to explain the absence of a clear yield response of tree crops to N fertilizer at this site.

Management consequences

In view of the high N availability in this system, a management objective would be to reduce or omit external N inputs and to make maximum use of the available N in the soil, thereby reducing N leaching with its negative side-effects, soil acidification, cation leaching and, eventually, groundwater contamination. For this, it would be important to take the observed spatial and temporal patterns of N supply into consideration. The highest N mineralization rates were measured during the rainy season, when the leaching risk was also greatest. Furthermore, most of the N was mineralized under the cover crop, at 1 m or more from the tree crops. When the trees in this experiment were three years old, root excavations showed that near the soil surface the coarse roots of peach palm extended laterally about 3.5 m from the plants, but those of cupuaçu extended only about 1.5 m (Haag, 1997). This showed that for young trees with their small root systems, the mineral N pool under the cover crop may be inaccessible. It also explains the higher subsoil accumulations of nitrate under the unfertilized *Pueraria* than under several fertilized tree crops in another multi-strata system at this site (Schroth *et al.*, 1999).

To increase crop use of the available N in the system and reduce N leaching, it is essential that during all development stages the exploration of the soil volume by crop roots is as complete as possible. This can be achieved by close tree spacing and the inclusion of annual or semi-perennial intercrops in the system for as long as possible to occupy the spaces between the longer-living tree crops. Nutrients such as P that are applied to such intercrops as mineral or organic fertilizers can have a pronounced, long-lasting effect on the fertility of the plot (Table 2), and should improve the lateral root development of the tree crops (Schroth *et al.*, 2000a). Reducing or suspending the application of N fertilizer to the tree crops would also increase their demand for the N mineralized under the cover crop. Where the supply to the tree crops of native N is insufficient, it could be increased by allowing the cover crop to grow close to the tree stems, as demonstrated by the increased N mineralization under the rubber trees compared with the uncovered soil under cupuaçu and peach palm (Fig. 2). This would require more frequent control of the *Pueraria* vines to prevent them overgrowing smaller trees.

CONCLUSIONS

Under the pedoclimatic conditions of the study region, the inclusion of leguminous cover crops into perennial cropping systems contributes to high N mineralization rates in the soil, which may exceed the requirements of tree crops. As a consequence, important N losses into the subsoil may occur, as previously observed at the study site (Schroth *et al.*, 1999). Within the investigated multi-strata system, this problem was aggravated by the spatial pattern of N mineralization; rates increase with distance from the trees. When designing the planting and management of agroforestry systems, such spatial patterns of N supply and demand should be taken into consideration. Once the root systems of the tree crops are sufficiently developed to take advantage of the high rates of mineralized N in the soil, application of N fertilizer to tree crops with a well-managed leguminous cover crop, may be unnecessary. This perspective should facilitate the further development of tree crop agriculture in Amazonia, where agrochemicals are expensive due to transport costs over great distances from the industrial centres.

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REFERENCES

Babbar, L. I. & Zak, D. R. (1994). Nitrogen cycling in coffee agroecosystems: net N mineralization and nitrification in the presence and absence of shade trees. *Agriculture, Ecosystems and Environment* 48:107–113.

Barrios, E., Buresh, R. J. & Sprent, J. I. (1996). Nitrogen mineralization in density fractions of soil organic matter from maize and legume cropping systems. *Soil Biology and Biochemistry* 28:1459–1465.

Cahn, M. D., Bouldin, D. R., Cravo, M. S. & Bowen, W. T. (1993). Cation and nitrate leaching in an oxisol of the Brazilian Amazon. *Agronomy Journal* 85:334–340.

Cravo, M. S. & Smyth, T. J. (1997). Manejo sustentado da fertilidade de um latossolo da Amazônia central sob cultivos sucessivos. *Revista Brasileira de Ciência do Solo* 21:607–616.

FAO-UNESCO (1990). Soil map of the world, revised legend. Rome: Food and Agriculture Organization of the United Nations.

Giller, K. E. & Wilson (1991). Nitrogen fixation in tropical cropping systems. Wallingford: CABI Publishing.

Haag, D. (1997). *Root distribution patterns in a polycultural system with local tree crops on an acid upland soil in central Amazonia*. M.Sc thesis, University of Bayreuth.

Haggar, J. P., Tanner, E. V. J., Beer, J. W. & Kass, D. C. L. (1993). Nitrogen dynamics of tropical agroforestry and annual cropping systems. *Soil Biology and Biochemistry* 25:1363–1378.

Hendershot, W. H., Lalande, H. & Duquette, M. (1993). Soil reaction and exchangeable acidity. In *Soil Sampling and Methods of Analysis*, 141–145 (Ed. M. R. Carter). Boca Raton: Lewis Publishers.

Marrs, R. H., Thompson, J., Scott, D. & Proctor, J. (1991). Nitrogen mineralization and nitrification in *terra firme* forest and savanna soils on Ilha de Maracá. Brazil. *Journal of Tropical Ecology* 7:123–137.

Montagnini, F. & Buschbacher, R. (1989). Nitrification rates in two undisturbed tropical rain forests and three slash-and-burn sites of the Venezuelan Amazon. *Biotropica* 21:9–14.

Neill, C., Piccolo, M. C., Steudler, P. A., Melillo, J. M., Feigl, B. J. & Cerri, C. C. (1995). Nitrogen dynamics in soils of forest and active pastures in the western Brazilian Amazon basin. *Soil Biology and Biochemistry* 277:1167–1175.

Piccolo, M. C., Neill, C. & Cerri, C. C. (1994). Net nitrogen mineralization and net nitrification along a tropical forest-to-pasture chronosequence. *Plant and Soil* 162:61–70.

Robertson, G. P. (1989). Nitrification and denitrification in humid tropical ecosystems: potential controls on nitrogen retention. In *Mineral nutrients in tropical forest and savanna ecosystems*, 55–69 (Ed. J. Proctor). Oxford: Blackwell Scientific Publishers.

Rodrigues, M. R. L., Malavolta, E. & Chaillard, H. (1997). La fumure du palmier à huile en Amazonie centrale brésilienne. *Plantations, recherche, développement* 4:392–400.

Schroth, G., da Silva, L. F., Seixas, R., Teixeira, W. G., Macêdo, J. L. V. & Zech, W. (1999). Subsoil accumulation of mineral nitrogen under polyculture and monoculture plantations, fallow and primary forest in a ferralitic Amazonian upland soil. *Agriculture, Ecosystems and Environment* 75:109–120.

Schroth, G., Rodrigues, M. R. L. & D'Angelo, S. A. (2000a). Spatial patterns of nitrogen mineralization, fertilizer distribution and roots explain nitrate leaching from mature Amazonian oil palm plantation. *Soil Use and Management* 16:222–229.

Schroth, G., Seixas, R., da Silva, L. F., Teixeira, W. G. & Zech, W. (2000b). Nutrient concentrations and acidity in ferralitic soil under perennial cropping, fallow and primary forest in central Amazonia. *European Journal of Soil Science* 51:219–231.

Singh, R. S., Raghubanshi, A. S. & Singh, J. S. (1991). Nitrogen-mineralization in dry tropical savanna: effects of burning and grazing. *Soil Biology and Biochemistry* 23:269–273.

Smith, C. K., Gholz, H. L. & Oliveira, F. A. (1998). Soil nitrogen dynamics and plant-induced soil changes under plantations and primary forest in lowland Amazonia, Brazil. *Plant and Soil* 200:193–204.

Subler, S., Parmelee, R. W. & Allen, M. F. (1995). Comparison of buried bag and PVC core methods for *in situ* measurement of nitrogen mineralization rates in an agricultural soil. *Communications in Soil Science and Plant Analysis* 26:2369–2381.

Tran, T. S. & Simard, R. R. (1993). Mehlich III-extractable elements. In *Soil Sampling and Methods of Analysis*, 43–49 (Ed. M. R. Carter) Boca Raton: Lewis Publishers.

Vitousek, P. M. & Matson, P. A. (1988). Nitrogen transformations in a range of tropical forest soils. *Soil Biology and Biochemistry* 20:361–367.

von Uexküll, H. R. & Mutert, E. W. (1995). Global extent, development and economic impact of acid soils. *Plant and Soil* 171:1–15.