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Projektleitung:

Prof. Dr. Reinhard Lieberei (Universität Hamburg, Institut für Angewandte Botanik)

Dr. Luadir Gasparotto (Embrapa Amazônia Ocidental, Manaus, Amazonas)

Projektkoordination in Manaus:

Dr. Luadir Gasparotto (Embrapa Amazônia Ocidental, Manaus, Amazonas)

Dr. Götz Schroth (Universität Hamburg, Institut für Angewandte Botanik)

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Spatial and temporal patterns of N availability and N mineralization under tree crops and a cover crop in a multi-strata agroforestry system of central Amazonia

Götz Schroth, Enir Salazar, José Pereira da Silva Junior, Rosangela Seixas and Jeferson L.V. Macêdo

Abstract

Under rainforest vegetation, the Oxisols and Ultisols which dominate the Amazonian uplands are characterized by relatively high availability of N in relation to other nutrients. When the rainforest vegetation is converted into agricultural systems, the disruption of the nutrient recycling mechanisms of the forest under conditions of intensive rainfalls and permeable soils increases the potential for N leaching. In a previous study, substantial amounts of mineral N were found in the subsoil of a central Amazonian Oxisol under various tree crops and a leguminous cover crop, indicating that even under perennial cropping systems, much of the mineralized soil and fertilizer N may be lost unproductively. We hypothesized that the spatial and temporal patterns of N availability and N mineralization in the soil of a polycultural system would influence the efficiency with which N is taken up by the trees instead of being leached. The analysis of such patterns could lead to strategies for improving this efficiency and reducing the dependence of the system on external nutrient inputs. The concentration of mineral N and the net N mineralization in the topsoil were measured at five occasions during 10 months in a multi-strata agroforestry system on an Oxisol in central Amazonia, Brazil. The system was composed of three tree crop species and a leguminous cover crop, and was studied at two fertilization levels. The net N mineralization was highest under the cover crop, intermediate under a tree crop where the soil was also covered by the cover crop, and lowest under two tree crops where the soil was kept free from the cover crop. This resulted in higher mineral N concentrations in the soil under the cover crop than under the tree crops during part of the rainy season. The increased N mineralization under the cover crop was due to higher total N in the soil, higher soil moisture and presumably a larger pool of readily mineralizable N components in the soil compared to 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 fertilization level had no significant influence on N mineralization. As most of the N was mineralized under the cover crop at some distance from the trees, the uptake of the mineralized N by the tree crops could presumably be increased, and N leaching reduced, by a higher tree density and an altered management of the cover crop to increase N mineralization in the soil close to the trees. In view of the high total N mineralization rates in the system (349 kg ha^{-1} yr^{-1}) and unclear yield responses of the tree crops to N fertilization at this site, it is concluded that after an establishment phase, the fertilization with N of tree crops with well-developed root systems may not always be necessary on this soil type.

Keywords: *Bactris*, cover crop, *Hevea*, Nitrogen cycling, Nitrogen leaching, Nitrogen mineralization, *Pueraria*, *Theobroma*

Introduction

The Amazonian uplands (*terra firme*) are dominated by acid and infertile Oxisols and Ultisols (IBGE-SUDAM, 1990; Soil Survey Staff, 1992). Studies in central Amazonia (Vitousek and Matson, 1988) and adjacent regions (Cuevas and Medina, 1986; Cuevas and Medina, 1988) established that biological activity in the primary forests stocking on these soils is not limited by the availability of N, but rather by that of P, Ca and Mg. Recently, some evidence was reported that the primary forest on a very clayey Oxisol in the Manaus region looses some mineral N by leaching into the subsoil, despite the efficient nutrient recycling mechanisms of this vegetation type (Schroth et al., 1998). This may be a further indicator of the N-sufficiency of the primary 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 further increase (Montagnini and Buschbacher, 1989). However, in the undisturbed state, the central Amazonian Oxisols are typically well-structured and permeable and the rainfalls are intensive, so that the increased N mineralization and the disruption of the dense root systems of the forest trees also increase the potential for the leaching of mineralized N and other nutrients into the subsoils where they are unaccessible for shallow-rooted crop plants (Cahn et al., 1993). Under these conditions, demanding annual crops such as maize may respond to mineral N fertilization after several years of continuous cultivation (Cravo and Smyth, 1997).

However, N leaching does not only occur under annual crops, but also under perennial crops including tree crop associations. Recently, nitrate accumulations in the subsoil below 1 m depth as an indicator of N leaching losses were found under several tree crops in a multi-strata agroforestry system in a central Amazonian Oxisol (Schroth et al., 1998). Particularly high subsoil accumulations of nitrate were measured under the leguminous cover crop *Pueraria phaseoloides* which grew between the tree crops in this agroforestry system, although the cover crop had never been fertilized with N. This could indicate that N sufficiency or deficiency in perennial polycultures is not only determined by total quantities of N mineralized in soil and litter and their temporal patterns relative to the N demand by the crops, but also by the spatial patterns of N availability and N uptake within the system.

The present work was based on the hypothesis that the spatial and temporal patterns of N availability within polycultural systems with tree crops would affect the efficiency with which soil N is taken up by the trees rather than being leached unproductively into the subsoil. The understanding of such patterns could be of use for the development of nutrient-efficient land use systems with reduced dependence on external inputs for optimum growth and development of the crops. We investigated the spatial and temporal patterns of N availability and net N mineralization in the topsoil of a perennial polyculture system with three tree crops and a leguminous cover crop over one rainy season on a central Amazonian Oxisol. The study was part of a larger research program on the recuperation of abandoned land with perennial polycultures in this region.

Materials and methods

Study site

The study was conducted on the research station of Embrapa Amazônia Ocidental near Manaus in central Amazonia of Brazil (3° 8' S, 59°52' W, 40-50 m a.s.l.). The climate is of the Köppen Am type 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 Typic Acrudox (Soil Survey Staff, 1992) (Xanthic Ferralsol according to FAO/Unesco (1990); Latossolo Amarelo according to the Brazilian classification (Embrapa, 1988)) with a clay content of about 80%. It is acidic with a very low cation exchange capacity, high aluminium saturation and low available phosphorus contents. Topsoil characteristics from the study plots are given in Tab. 1, and analysis data from soil profiles under primary forest, fallow and agriculture are given in Schroth et al. (1998).

The study site was first cleared from primary forest in 1980, using heavy machinery for windrowing and the removal of tree stumps. In 1981, an experiment with rubber trees (*Hevea brasiliensis*) was established, which was abandoned in 1986 because of heavy disease attack. The developing secondary forest was manually cleared in 1992 and the vegetation was burnt on the site. The experimental plots were planted in February/March 1993. The total experimental area was about 13 ha.

The study was carried out in a polyculture system with cupuaçu (*Theobroma grandiflorum*, Sterculiaceae), peachpalm (*Bactris gasipaes*, Arecaceae) for the production of palmito (heart of palm), and rubber (*Hevea brasiliensis*, grafted with a crown of *Hevea pauciflora*, Euphorbiaceae). The trees were grown in rows with 5 m spacing between the rows (Fig. 1). A row of cupuaçu (at 6.4 m spacing within the row) alternated with a row of peachpalm (at 2 m spacing within the row), a row of rubber (at 4 m spacing within the row), a row of peachpalm and again a row of cupuaçu. During the first three years of the experiment (1993-95), one row of papaya (*Carica papaya*, Caricaceae) was grown in every interspace between the tree rows at 2 m spacing within the rows. The papaya plants died progressively during 1995. Between the trees, *Pueraria phaseoloides* (tropical kudzu, Fabaceae) was sown as a cover crop or developed from residual seed from the former rubber plantation.

This system was studied at two fertilization levels, full fertilization according to local experiences and 30% of this fertilization level with no more N fertilizer applied after May 1996 (low fertilization minus N, Tab. 2). The latter treatment was introduced to test if the leguminous cover crop alone was able to supply sufficient amounts of N for the tree crops in the system. In a further fertilization treatment, "low plus N", the same fertilization was applied as in the "low minus N" plots plus 30% of the N fertilizer applied in the full fertilization plots (Tab. 2). This latter treatment was not included in the N mineralization study, but yield levels are given below. The fertilizer was applied in two doses during the study year, in the first week of Dezember 1997 (beginning of the rainy season) and in the first week of June 1998. In November/Dezember 1996, dolomitic lime had been broadcast in the plots at a rate of 2.1 t ha^{-1} in the full fertilization plots and 0.6 t ha^{-1} in the low fertilization plots plus N. No lime had been applied in the low minus N plots.

The measurement plots were arranged in a randomised complete plot design with three replications. Plot size was 48 by 32 m.

<u>Sample incubation and analysis</u>

To analyse the spatial patterns of N availability and mineralization within the polyculture plots, five sampling positions were distinguished within each plot: 1) at 50 cm distance from the stem of a cupuaçu tree; 2) at 50 cm distance from the stem of a peachpalm; 3) at 50 cm distance from the stem of a rubber tree; 4) under the cover crop in the middle between adjacent cupuaçu trees (Pueraria 1); 5) under the cover crop in the middle between a cupuaçu row and the adjacent peachpalm row (Pueraria 2). Under the cupuaçu and the peachpalm (positions 1 and 2), 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 (position 3), the *Pueraria* covered the soil completely until the trunk. Position 4 (Pueraria 1) differed from position 5 (Pueraria 2) in so far as no papaya had been grown at position 4 during the first three years of the plantation. During this time, every papaya plant in the full fertilization plots had been fertilized with 420 g N (as urea), 93 g P (as STP), 175 g K (as KCl) and 36 l of chicken manure (30% of these values in the low fertilization plots). In addition, every plant received 1500 g of lime in the full fertilization and 1150 g in the low fertilization plots. By comparing the different positions under the cover crop we wanted to test if a residual effect of this heavy mineral and organic fertilization applied to the papaya on net N mineralization was detectable three years after the removal of the crop.

Soil samples were collected for incubation five times during the year 1997/98 in each of the five positions in the six plots (two input levels, three replications). The samples were taken from 0-10 cm depth with a cylindric corer. For each position, two separate samples were taken, each of them consisting of soil collected under two different trees or places with *Pueraria* cover crop. The samples were mixed in a bucket and larger pieces of roots or litter were removed. A subsample of approximately 300 g was filled into a polyethylene bag and was placed in one of the sampling holes of the respective position. The bags were covered with a thin layer of soil and litter to create microclimatic conditions as similar as possible to the undisturbed soil. The remaining soil from each sample was taken to the laboratory for extraction of mineral N and determination of the water content. This procedure took three days for the whole experiment (one block per day). 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. The use of four independent samples for each data point allowed the exclusion of outliers (e.g. samples with unusually high initial ammonium values or samples in which the water content had changed strongly during the incubation) without loosing degrees of freedom for the statistical analysis. The incubated samples were collected after 14-15 days in the field and were taken immediately to the laboratory for the extraction of mineral N.

In the laboratory, all samples were processed within hours of their collection in the field. From every sample, two subsamples of 20 g were taken for N extraction, and two samples of about 50 g were taken for the determination of the water content by drying at 105°C for two days. To the samples for N extraction, 150 ml of 1 M KCl solution were added. The solution was mixed with the soil by short manual shaking, and the samples were left standing overnight to ensure complete wetting of aggregates and to facilitate the extraction. The next morning, the samples were extracted by mechanical shaking for 30 minutes. The extraction solution was collected with a pipette without filtration after a sedimentation time of about 1 hour.

The extraction solutions were either analysed the same day or were kept below 0°C (but not frozen) until the analysis. Ammonium and nitrate (after reduction to nitrite) in the extracts were analysed photometrically with a segmented flow analyser (Skalar, Netherlands). The N contents were related to the dry soil weight, taking into account the water content of the extracted soil samples.

<u>Comparison of N mineralization in disturbed and undisturbed soil samples</u>

Preliminary experiments had shown that the variability of the net N mineralization rates between replicate soil samples was very high when undisturbed soil cores were incubated in the plastic bags, in agreement with literature information (Subler et al., 1995). To reduce this variability, we used disturbed soil samples for the incubation which allowed to mix soil from several sampling points within the plots and to take the subsample for the initial extraction of mineral N directly from the sample to be incubated. As increased aeration and breaking of aggregates while mixing the soil before the incubation may have increased N mineralization rates, a comparative study of the N mineralization in disturbed and undisturbed samples was conducted in one of the plots of the experiment. In September 1998, two undisturbed soil cores of 8 cm diameter were collected from the topsoil from each of the five sampling positions. The cores were placed in a plastic bag and returned to their original place. On two sides of the undisturbed core, two similar cores were taken and mixed. A subsample was incubated within a plastic bag in one of the sampling positions (disturbed sample), and another subsample was taken to the laboratory for the extraction of mineral N and determination of the water content. These data were also used as the initial values for the corresponding undisturbed cores. The incubated samples were covered with soil as in the main experiment. 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 compaired by t-test for dependent samples.

Estimation of annual rates of N mineralization

The net N mineralization rates in mg kg^{-1} soil were transformed in per area values by multiplication with the topsoil bulk density of 0.88 g dm^{-3} which had been determined in a separate study within the experiment (Schroth et al., 1998). The total N mineralization during the study period was then estimated by multiplying the average daily mineralization of two subsequent incubation dates with the number of days between these incubation dates. To estimate the mineralization for a whole year, the data from November/Dezember 1997 were used both as the beginning and as the end of the series, assuming that the mineralization in November 1998 was similar to that measured one year before. The net N mineralization per hectare and year was calculated by assuming that the sampling points under the cupuaçu and the rubber trees were representative for a circular area around the tree with a radius of 1 m and that the sampling point under the peachpalm was representative for a strip of 1 m width at both sides of the palm row. This corresponded approximately to the area around the cupuaçu and the peachpalm which was kept free from the cover crop. From the remaining area of the plots, the sampling position Pueraria 1 (between the trees within the rows) was assumed to be representative for one half, and the sampling position Pueraria 2 (between the tree rows) was assumed to be representative for the other half (Fig. 1).

Chemical soil characterization

Soil samples were collected from 0-10 cm soil depth in the different positions of the study plots in September 1998, after the end of the main experiment. The air-dried samples were passed through a 2 mm sieve, and the following analyses were conducted: Total C and N by dry combustion with a CHN Analyzer; extractable P, K, Ca and Mg with the Mehlich 3-method (Tran and Simard, 1993); exchangable acidity by extraction with 1 M KCl and titration (Hendershot et al., 1993); cation exchange capacity by summation of extractable cations and acidity; and 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 complete block/split plot design with the fertilization levels as main plot factor and the sampling positions within the main plots as subplot factor (Little and Hills, 1978). The five incubation dates were calculated separately. In case of significance of the F-test at $p<0.05$, treatment means were compared by least significant difference tests at the same level of significance.

Results

Chemical soil characteristics in the polyculture plots

The plots with full fertilization had a significantly higher pH as well as contents of P, K, Ca and Mg and significantly lower exchangeable acidity than the low fertilization plots (Tab. 1). Total C and N also tended to be higher in the full fertilization plots, but the differences were not significant. The sampling positions within the plots differed significantly in pH, N, P, the basic cations and acidity. The heavy fertilization and liming of the papaya in the Pueraria 2 position resulted in significantly higher pH, Ca, Mg and CEC and significantly lower acidity in this position than in all other positions. Total N was also significantly higher under Pueraria 2 than under cupuaçu and peachpalm. The highest K contents were found under peachpalm. For P, a significant fertilizer-position interaction was observed, because higher fertilization increased the available P contents under the fertilized tree crops, but not under the unfertilized cover crops. Under Pueraria 1 where no papaya had been grown, the soil P contents were significantly lower than in all other positions within the plots.

Crop yields

The crop yields in the polyculture plots for the study years 1997 and 1998 are given in Tab. 3. From the fertilization levels in Tab. 3, only the levels "full fertilization" and "low fertilization minus N" were included in the N distribution study (see above). The yields of the fertilization level "low plus N" are shown to assess the effect of N fertilization independently of the other nutrient levels, although the treatments "low minus N" and "low plus N" also differed in liming in 1996 (see above). No yield data are given for the rubber trees which had not yet reached their productive age.

For both cupuaçu and peachpalm in both years, the average yields at full fertilization were higher than at low fertilization, and they were higher at low fertilization with N than without N. However, the effect of the fertilizer level on yields was in no case significant (Tab. 3). In the relatively wet year 1998, the effect of N fertilization (and liming) on the yields of both crops was very small (low-N vs. low+N, Tab. 3). In the relatively dry El Niño year 1997, in contrast, the effect of the N fertilization (and liming) on the palmito yields was almost significant. In another perennial polyculture system at the same site, no effect of N fertilization on the yields of peachpalm, cupuaçu and urucum (*Bixa orellana*) and on the growth of Brazil nut trees (*Bertholletia excelsa*) could be detected (Schroth et al., 1998). This insignificant yield effect of N fertilization may indicate that agricultural production was not strongly limited by N at this site, except possibly under drought conditions. An alternative (or additional) explanation may be that much of the fertilizer N was too rapidly leached from the topsoil to be taken up by the tree crops, as indicated by nitrate accumulations in the subsoil under several tree crops at this site (Schroth et al., 1998).

Comparison of N mineralization in disturbed and undisturbed soil samples

The net N mineralization (mean ± S.D.) was 1.02±0.38 mg kg^{-1} day^{-1} in the disturbed samples and 1.18±0.44 mg kg^{-1} day^{-1} in the undisturbed samples. The difference between the two methods was not significant ($p=0.389$). Therefore, no correction factor for the use of disturbed soil samples in the N mineralization measurements was applied in the calculation of field N mineralization, as had initially been intended. The similarity of the results of the two methods was in agreement with Piccolo et al. (1994) who 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, although the agreement between methods was less in pasture soil. It seems that these soils with their relatively small aggregats and low bulk density with consequently good aeration show relatively little effect of disturbance on N mineralization. In contrast, in an agricultural soil from Germany, net N mineralization in sieved soil was approximately twice as high as in undisturbed soil (Stenger et al., 1995).

Mineral N concentration in the topsoil

The concentration of mineral N in the topsoil (0-10 cm) showed pronounced seasonal fluctuations and spatial patterns within the study plots (Fig. 2). The highest concentrations were found at the first sampling date at the end of the dry season (November/December 1997). Most of the mineral N was in the nitrate form. This indicated that N mineralization in soil and litter as well as nitrification continued during the dry season. The highest mean concentrations of mineral N were found under the cover crop between the cupuaçu trees (Pueraria 1), and the lowest values were found directly under the cupuaçu trees.

Between the first and the second sampling, the plots were fertilized with P and K, the full fertilization plots also with N. This may have contributed to the significantly higher mineral N concentration under the fully fertilized cupuaçu than under the cupuaçu with low fertilization in January/February 1998. In the soil under the other two tree species which had received lower fertilizer doses than cupuaçu (Tab. 2) the fertilizer N could not be detected any more when the soil samples were collected. Although the fertilizer had been applied only around the trees, the highest concentrations of mineral N were again measured under the cover crop between the cupuaçu trees, and the lowest values were measured under the cupuaçu (low fertilization level). The mineral N concentrations in general were much lower during the second and the two following sampling intervals, corresponding to the rainy season, than during the first sampling at the end of the dry season (Fig. 2), despite higher N mineralization rates in the rainy season than in the dry season under the cover crop (see below). This was presumably because both the leaching of mineralized N out of the topsoil and the N uptake by the vegetation were higher during the rainy season than during the dry season.

Between the second and the third sampling interval, the mineral N availability under the tree crops cupuaçu and peachpalm decreased further, and by March 1998 the topsoil under the cover crop in both sampling positions (Pueraria 1 and 2) had significantly more mineral N than the topsoil under the cupuaçu and the peachpalm, the soil under the rubber trees being intermediate. In May/June, the situation was very similar to that in March, with still significantly lower mineral N concentrations under cupuaçu and peachpalm than under the cover crop and the rubber trees.

After the fourth sampling in June, the trees were again fertilized. However, the increased concentrations of mineral N in the soil in August were more likely an effect of the relatively dry weather and consequently reduced N leaching in June and July (Tab. 4) than of residual fertilizer because there was no difference in N concentration in the soil between the two fertilization levels. The dry weather may have also reduced the growth and N uptake by the vegetation. Because of the small differences between positions and the high variability of the N concentrations especially under peachpalm, there was no significant effect of the sampling position at this date ($p=0.251$).

N mineralization

As the mineral N concentrations, the net N mineralization rates in the topsoil also exhibited pronounced seasonal and spatial patterns within the plots (Fig. 3). At the end of the dry season (November/December), the N mineralization under the cover crop and under the rubber trees (where the soil was also covered by *Pueraria*) was significantly higher than under the cupuaçu, the peachpalm being intermediate. On the average, the N mineralization in the low fertilization treatment was higher than in the full fertilization treatment in all positions, but this effect was not significant (p=0.233).

During the rainy season (second to fourth incubation), the N mineralization rates in the *Pueraria* positions were higher than at the end of the dry season (first incubation), probably as an effect of the higher soil water content (Tab. 5). Under cupuaçu and peachpalm, in contrast, the N mineralization rates remained as low as at the end of the dry season or decreased even further (Fig. 3). In these positions, the soil water content was also higher during the rainy season than during the dry season, as would be expected, but the soil always remained drier under cupuaçu and peachpalm than under the surrounding cover crop. The soil under the rubber trees, which was covered by *Pueraria*, had a similar water content as under the cover crop at all except the first sampling events (Tab. 5). This may partly explain the significantly lower N mineralization rates under cupuaçu and peachpalm than under the cover crop at the second and third incubation, with the rubber trees being intermediate (Fig. 3). The higher N mineralization rates under the cover crop in both positions than under the tree crops cupuaçu and peachpalm at the second and third incubation explain the higher concentrations of mineral N in the topsoil in these sampling positions (Fig. 2).

From the third to the fourth incubation date, the N mineralization under cupuaçu increased for unknown reasons, leading to a less clear spatial pattern. However, the highest N mineralization rates were still measured under the cover crop and the lowest rates under the peachpalm. In August, the interaction between fertilizer level and position was non-significant only by a low margin (p=0.053), because higher N mineralization rates were measured under the cover crop than under cupuaçu and peachpalm at the low but not at the high fertilization level. The rubber trees were again intermediate.

Total N mineralization per year

Fig. 4 shows the total amount of mineralized N per year in the five sampling positions. Summed over one year, the net N mineralization 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 peachpalm, which did not differ between each other. On the average, approximately twice as much N was mineralized per kg of soil under the cover crop than under the cupuaçu and the peachpalm. Under the cover crop were papaya had been grown (Pueraria 2), the N mineralization was also significantly higher than under the rubber trees. The fertilization level had no significant effect on N mineralization in any of the investigated positions.

As for none of the investigated species a significant effect of the fertilization level on the annual N mineralization had been found (Fig. 4), the total N mineralization per hectare and year in the polyculture system was calculated from the average N mineralization values of the two fertilization levels for each species. The estimated net N mineralization was 349 kg ha^{-1} yr^{-1} in the top 10 cm of soil (Tab. 6). Most of this N was mineralized in the soil under the cover crop (84%) which covered most of the plot area (74%), in addition to having the highest N mineralization rates in the polyculture plots (Fig. 4).

Discussion

Temporal and spatial patterns of N-availability and N mineralization

The daily net N mineralization rates of 0.3-1.7 mg kg^{-1} day^{-1} measured in this study 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} day^{-1} under forest and 0.73 mg kg^{-1} day^{-1} under slash-and-burn agriculture in an Oxisol in the Venezuelan Amazon. Lower values were found under an Amazonian pasture (Neill et al., 1995). The total annual net N mineralization found in this study (349 kg ha^{-1} yr^{-1}) lay above the values in the forest and plantation soils in Amazonia (196-328 kg ha^{-1} yr^{-1}) reported by Smith et al. (1998) and those from shaded and unshaded coffee plantations in Costa Rica (148 and 111 kg ha^{-1} yr^{-1}, respectively) (Babbar and Zak, 1994). The higher values in this study were at least partly due to the presence of the leguminous cover crop (Tab. 6).

The seasonal trends in mineral N concentrations and N mineralization in the topsoil observed in this study are in agreement with Singh et al. (1991) who also found highest mineral N concentrations in the dry season and highest N mineralization rates in the wet season in a tropical savanna in India. Babbar and Zak (1994) measured higher N mineralization rates during the wet season than during the dry season in coffee plantations in Costa Rica.

Figs. 2 and 3 give evidence for a considerable within-plot variability of both the concentration of mineral N in the topsoil and the daily rate of net N mineralization. The effect of the fertilization with mineral N around the trees in the full fertilization plots was of short duration, indicating that the N which was not taken up by the tree crops within weeks after the fertilization was leached out of the topsoil, contributing to the accumulation of mineral N in the deeper subsoil which has been reported earlier from the same site (Schroth et al., 1998). Also, the N mineralization rates were consistently highest under the cover crop and the rubber trees (under which the soil was also covered by *Pueraria*), and were consistently lowest under the tree crops cupuaçu and peachpalm under which the soil was not covered by *Pueraria.* As a consequence of the short duration of the fertilizer pulse, the higher N mineralization under the cover crop than under the tree crops and presumably the higher net N uptake by the tree crops compared to the cover crop, the availability of mineral N for plant growth was higher under the unfertilized cover crop than under the fertilized tree crops during an important part of the year, especially the months with high rainfall (and presumably high tree growth), March to June (Fig. 3 and Tab. 4).

The spatial patterns of N mineralization have seldom been investigated in agricultural or agroforestry systems, although there are studies from fallow and forest ecosystems (Robertson et al., 1988; Boerner and Koslowsky, 1989). Babbar and Zak (1994) compared areas beneath and between the canopies of *Erythrina* shade trees as well as beneath and between the coffee canopy in coffee plantations in Costa Rica, but they could not detect significant position effects on net N mineralization.

The higher net N mineralization rates under the leguminous cover crop than under the trees was related to the higher total N under the *Pueraria* than under the cupuaçu and the peachpalm (Tab. 1). However, total N under the cover crop was only 13% higher than under the cupuaçu and the peachpalm, but net N mineralization was twice as high under the cover crop than under these tree crops (Tab. 6). This indicates that there were also qualitative differences in the composition of the organic N between the sampling positions, with a larger pool of labile N under the *Pueraria* (and the rubber trees) than under the cupuaçu and the peachpalm. This labile N may have consisted both of small, N-rich root and litter fragments as well as leachates from the *Pueraria* and of a readily mineralizable fraction of soil N. This built-up of a pool of readily mineralizable organic N in the soil has also been observed by Haggar et al. (1993) who measured increased mineralization of soil N after 7 years of mulching with leguminous biomass in an agroforestry system in Costa Rica. Schroth et al. (1995) found that litter and root mass of different leguminous tree species were positively correlated with net N mineralization in the soil and explained this with N inputs into the soil with litter and dying roots as well as increased C availability for microbial activity in soils with high litter and root inputs.

A further reason for the differences in net N mineralization between sampling positions may have been the higher soil water content under the cover crop compared to the tree crops cupuaçu and peachpalm (Tab. 4). The likely reasons for this were low soil evaporation under the dense *Pueraria* foliage (F.W. Correia, unpublished) and probably a lower transpiration per unit ground area of the low-growing cover crop compared to the taller trees.

Apart from the mentioned differences in soil N, the chemical soil fertility had a relatively small influence on N mineralization rates in the plots. Two years after the removal of the heavily fertilized papaya from the interrows between the tree rows (Pueraria 2), the soil in these positions was the most fertile in the plots, whereas the soil between the cupuaçu trees where no papaya had been grown (Pueraria 1) was the least fertile of the sampling points within the plots (Tab. 1). The net N mineralization rates did not differ significantly between these positions, although they tended to be higher in the more fertile soil of the Pueraria 2 position (Fig. 3). Also, soil fertility differed significantly between the two input levels (Tab. 1), but this did not result in significant differences in N mineralization (Fig. 3). In contrast, Marrs et al. (1991) observed an increase of net N mineralization in an upland soil in northern Amazonia (Roraima) following the addition of Ca, indicating that N mineralization was limited by nutrient availability.

Although there was thus little direct effect of the soil fertility on net N mineralization rates, the fertilizer applied to the papaya may have had an important indirect effect by improving the development of the cover crop during the first years after the establishment of the experiment. In neighboring plots where annual crops had been associated with the tree crops during the first year instead of the papaya, the development of the cover crop had been much slower.

<u>Management consequences</u>

The estimated annual N mineralization in the agroforestry system was 349 kg ha^{-1} in the top 10 cm of soil, which was about 10 times the quantity applied as mineral N in the full fertilization plots (Tabs. 2 and 6). It is not known how much N was mineralized below 10 cm depth in this soil, but the amount was probably not negligeable as total soil N at 10-50 cm soil depth was still about half that at 0-10 cm depth (Schroth et al., 1998). So, even when potential errors arising from the temporal and spatial interpolation in the calculation of the annual N mineralization values per hectare are taken into consideration, it is clear that on the plot level, the soil in the polyculture system released more mineral N than what could have actually been used by the tree crops. This conclusion is supported by the afore-mentioned accumulation of nitrate-N in the subsoil under other perennial cropping systems (Schroth et al., 1998) and the unclear response of the tree crops to N fertilization at this site (Tab. 3).

The bulk of the N was mineralized under the cover crop, at 1 m distance or more from the tree crops (Tab. 6). The high N mineralization rates here and the insufficient demand for, or access to, the mineralized N by the tree crops are the obvious reasons for the significantly higher subsoil accumulation of nitrate under the unfertilized *Pueraria* than under three fertilized tree crops (Schroth et al., 1998). The *Pueraria* covered approximately ¾ of the area of the polyculture plots, and it is obvious from the data in Tab. 6 that the total N mineralization in the plots would be reduced by increasing the tree density in the system, for example through the inclusion of semi-perennial species. At the same time, the mineralized N would be taken up more efficiently instead of being lost by leaching into the subsoils. On the other hand, the N mineralization in the soil close to the trees would be increased by allowing the cover crop to grow until close to the tree stems instead of maintaining an area around the stem free from vegetation, as the high N mineralization under the rubber trees clearly demonstrates. This could be a particular advantage in dry years (or periods) as indicated by the fact that the N fertilization close to the trees had a larger (although non-significant) effect on crop yields in the dry year 1997 than in the normally wet year 1998 (Tab. 3). The price for the application of this cover crop management also to the cupuaçu and the peachpalm would be the need for more frequent control of the *Pueraria* vines to prevent them from climbing these smaller trees. So, changes in the planting design and the management of the cover crop could influence both the total quantity of N mineralized in the plots and the access to it by the tree crops and could thus contribute to a better adjustment of the N mineralization to actual plant needs. As a result, N leaching would probably decrease, and fertilization with mineral N could possibly be reduced.

In view of the high N mineralization rates and the unclear response of the tree crops to N fertilization at this site, the question under which conditions fertilization with mineral N is necessary for satisfactory growth and yield of tree crops on this soil type deserves consideration. As the highest net N mineralization occured under the cover crop at some distance from the trees, the lateral root development of the trees is probably a critical factor in this respect. When the trees in this experiment were 3 years old, root excavations showed that near the soil surface, the coarse roots of peachpalm extended laterally about 3.5 m from the plants, but those of cupuaçu extended only about 1.5 m (Haag, 1997). This indicates that for young trees with their small root systems, the mineral N pool under the cover crop may be insufficiently accessible. The competition between a recently established cover crop with accumulating biomass and young tree crops for soil nutrients may also be most intensive during this phase (Pérez et al., 1993), and supplementary N fertilization near the trees may thus be necessary. When the trees become older and their root systems more extensive, the increasing access to the mineral N under the cover crop should progressively reduce their dependence from fertilizer N. Unfortunately, this model cannot be tested with the yield data from this experiment, as the treatment without N fertilization was only introduced at the end of 1996 when the trees had been almost four years in the field. However, a fertilization experiment with oil palm (*Elaeis guineensis*) and a cover crop of *Pueraria phaseoloides* at a near-by site indicated that the palms responded to N-fertilization with slightly increased diameter growth during the first 3 years after planting, after which no growth or yield response to N fertilization was observed any more (Rodrigues et al., 1997). The possibility that after an establishment phase of variable length, at least certain perennial crops may not depend on external N inputs on this soil type when associated with a vigorous leguminous cover crop may be of considerable importance for the development perspectives of tree crop based land use systems in Amazonia, where agrochemicals are very expensive due to the long transport distances from the industrial centers.

The temporal variations of the mineral N concentration in the soil give an indication concerning the optimum timing of N fertilizations. In the study region, N and other nutrients are usually applied at the onset of the rainy season in November/Dezember. Fig. 2 shows that after the dry season shortly before the fertilization the mineral N concentrations in the soil were already relatively high for reasons discussed above. The lowest N concentrations under the tree crops were reached several months later during the rainy season. So, small doses of N applied in the proximity of the trees may be a more useful supplement to the N mineralized in the soil when they are given later in the rainy season rather than at its beginning.

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 perennial crops. As a consequence, important N-losses into the subsoil may occur as observed at the study site. Within the investigated polyculture system, this problem was aggravated by the spatial pattern of N mineralization, as the highest mineralization rates occured further from the trees and the lowest rates occured in the proximity of the trees. As a consequence of the high rates of soil N mineralization, the fertilization with N of perennial crops with a well-developed leguminous cover crop may not always be necessary under these conditions, once the root systems of the tree crops are sufficiently developed to take advantage of the mineralized soil N.

On the other hand, it is questionable if such high N mineralization rates as those observed in the present study can be sustained indefinitely. If the N-losses from the soil organic matter through net mineralization are higher than the inputs from above-ground litter and root turnover, the mineralizable N pool in the soil will necessarily be depleted and the rates of N mineralization will decrease after some time of continuous land use. The need for N fertilization will then increase again.

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Tab. 1: 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 fertilization levels

	pH	C	N	C/N	P	K	Ca	Mg	CEC	Acidity
	H_2O	g kg^{-1}			mg kg^{-1}	-------- $cmol_c$ kg^{-1}---------				%
Full fertilization										
Cupuaçu	4.44	23.9	1.97	12.1	69b	0.16	1.45	0.67	3.33	35.5
Peachpalm	4.97	23.9	1.96	12.2	121a	0.29	2.20	1.10	3.98	10.2
Rubber	4.30	25.4	2.08	12.2	83ab	0.13	1.22	0.65	3.10	35.4
Pueraria 1	4.81	25.0	2.14	11.7	9d	0.11	1.25	1.07	3.24	27.6
Pueraria 2	5.51	27.4	2.37	11.5	79ab	0.14	4.12	1.59	6.03	4.0
Low fertilization										
Cupuaçu	4.15	21.8	1.78	12.3	22d	0.10	0.40	0.12	2.32	73.4
Peachpalm	4.24	23.6	1.91	12.4	26cd	0.12	0.52	0.12	2.43	68.5
Rubber	4.21	24.9	2.07	12.1	17d	0.10	0.30	0.17	2.31	75.4
Pueraria 1	4.04	24.1	1.99	12.1	6d	0.09	0.23	0.13	2.40	81.1
Pueraria 2	4.80	24.6	2.09	11.8	68bc	0.11	3.32	0.52	4.79	24.6
Position means										
Cupuaçu	4.29b	22.9	1.88b	12.2	45a	0.13b	0.92b	0.40b	2.82b	54.5a
Peachpalm	4.61b	23.7	1.94b	12.3	73a	0.20a	1.36b	0.61b	3.21b	39.3a
Rubber	4.25b	25.2	2.07ab	12.2	50a	0.12b	0.76b	0.41b	2.70b	55.4a
Pueraria 1	4.42b	24.6	2.07ab	11.9	7b	0.10b	0.74b	0.60b	2.82b	54.4a
Pueraria 2	5.16a	26.0	2.23a	11.7	73a	0.13b	3.72a	1.06a	5.41a	14.3b
Fertilizer means										
full	4.81a	25.1	2.11	12.0	72a	0.17a	2.05a	1.02a	3.94a	22.5b
low	4.29b	23.8	1.97	12.1	27b	0.10b	0.95b	0.21b	2.85b	64.6a
F (Fertilizer)	33.9*	3.6	3.3	1.0	183**	4.2	127**	154**	24.2*	144**
F (Position)	5.4**	2.0	3.8*	2.5	6.5**	4.2*	9.7***	3.6*	8.9***	9.3***
F (Fert. x Pos.)	1.0	0.4	0.6	0.5	3.1*	2.4	0.2	0.9	0.2	1.6

*=p<0.05; **=p<0.01; ***=p<0.001; values followed by similar letters are not significantly different at p<0.05 (LSD test).

Tab. 2: Trees per hectare and fertilization with main nutrients in a multi-strata agroforestry system in central Amazonia during the study year

	Trees per hectare	Dezember 1997 N	P	K	June 1998 N	P	K	Yearly total N	P	K
		g plant^{-1}			g plant^{-1}			kg ha^{-1}		
Full fertilization										
Cupuaçu	78.1	47.3	38.5	62.5	47.3	38.5	62.5	7.4	6.0	9.8
Peachpalm	500	21.0	5.5	12.5	21.0	11.0	25.0	21.0	8.3	18.8
Rubber	125	10.5	22.0	15.0	10.5	11.0	16.5	2.6	4.1	3.9
Whole plot								*31*	*18*	*33*
Low fertilization minus N										
Cupuaçu	78.1	0	11.6	18.8	0	11.6	18.8	0	1.8	2.9
Peachpalm	500	0	1.7	3.8	0	3.3	7.5	0	2.5	5.7
Rubber	125	0	6.6	4.5	0	3.3	5.0	0	1.2	1.2
Whole plot								*0*	*6*	*10*
Low fertilization plus N										
Cupuaçu	78.1	14.2	11.6	18.8	14.2	11.6	18.8	2.2	1.8	2.9
Peachpalm	500	6.3	1.7	3.8	6.3	3.3	7.5	6.3	2.5	5.7
Rubber	125	3.2	6.6	4.5	3.2	3.3	5.0	0.8	1.2	1.2
Whole plot								*9*	*6*	*10*

N was applied as ammonium sulfate, P as super triple phosphate, and K as potassium chloride. The trees in both fertilization treatments received micronutrients.

Tab. 3: Crop yields in the polyculture system at three fertilization levels on a ferralitic upland soil in central Amazonia during the study years 1997 and 1998

Fertilization	low -N	low +N[a]	full	F	p
Cupuaçu (kg fresh fruit per tree)					
1997	6.08	7.76	8.03	3.18	0.078
1998	8.02	8.48	12.99	2.73	0.106
Sum	14.10	16.24	21.02	3.50	0.063
Peachpalm (kg palmito cream per tree)					
1997	0.68	0.77	0.87	3.72	0.055
1998	0.55	0.56	0.62	0.97	0.447
Sum	1.23	1.33	1.49	3.77	0.053

[a]treatment not included in the N mineralization study

Tab. 4: Rainfall at the experimental site in central Amazonia during the study years 1997 and 1998

Month	Rainfall		Month	Rainfall		Month	Rainfall	
	Events	mm		events	mm		events	mm
Jul 97	7	44.9	Jan 98	19	296.5	Jul 98	20	113.1
Aug 97	10	137.1	Feb 98	22	226.1	Aug 98	15	87.9
Sep 97	7	48.4	Mar 98	26	333.1	Sep 98	20	125.9
Oct 97	7	65.6	Apr 98	27	377.3	Oct 98	14	174.7
Nov 97	16	261.3	May 98	25	226.2	Nov 98	17	234.4
Dec 97	11	127.7	Jun 98	22	187.6			

Tab. 5: Moisture content in percent (w/w) of the incubated soil samples from five different positions in a multi-strata agroforestry system in central Amazonia

Sampling date	Cupuaçu	Peachpalm	Rubber	Pueraria 1	Pueraria 2	F
Nov/Dec '97	29.2 c	27.8 d	31.4 b	32.3 a	31.0 b	39.28***
Jan/Feb '98	33.8 b	32.7 b	36.5 a	36.6 a	37.2 a	17.96***
Mar '98	33.8 b	34.3 b	37.9 a	37.5 a	37.0 a	4.88**
May/Jun '98	34.7 b	32.8 b	39.7 a	39.1 a	39.2 a	24.76***
Aug '98	29.9 b	30.2 b	34.9 a	33.9 a	34.1 a	19.26***

*=$p<0.05$; **=$p<0.01$; ***=$p<0.001$; values followed by similar letters for the same sampling date are not significantly different at $p<0.05$ (LSD test).

Tab. 6: Estimated annual net N mineralization in 0-10 cm soil depth under three tree crop species and the cover crop *Pueraria phaseoloides* in a multi-strata agroforestry system in central Amazonia

Species	Area per species	Net N mineralization[a]	
	% of plot	(per position)	(per plot)
		$g\ m^{-2}\ yr^{-1}$	$kg\ ha^{-1}\ yr^{-1}$
Cupuaçu	2.5	22.1	6
Peachpalm	20.0	18.0	36
Rubber	3.9	34.5	13
Pueraria 1	36.8	36.6	135
Pueraria 2	36.8	43.2	159
Whole plot	*100*		*349*

[a]mean of two fertilization levels

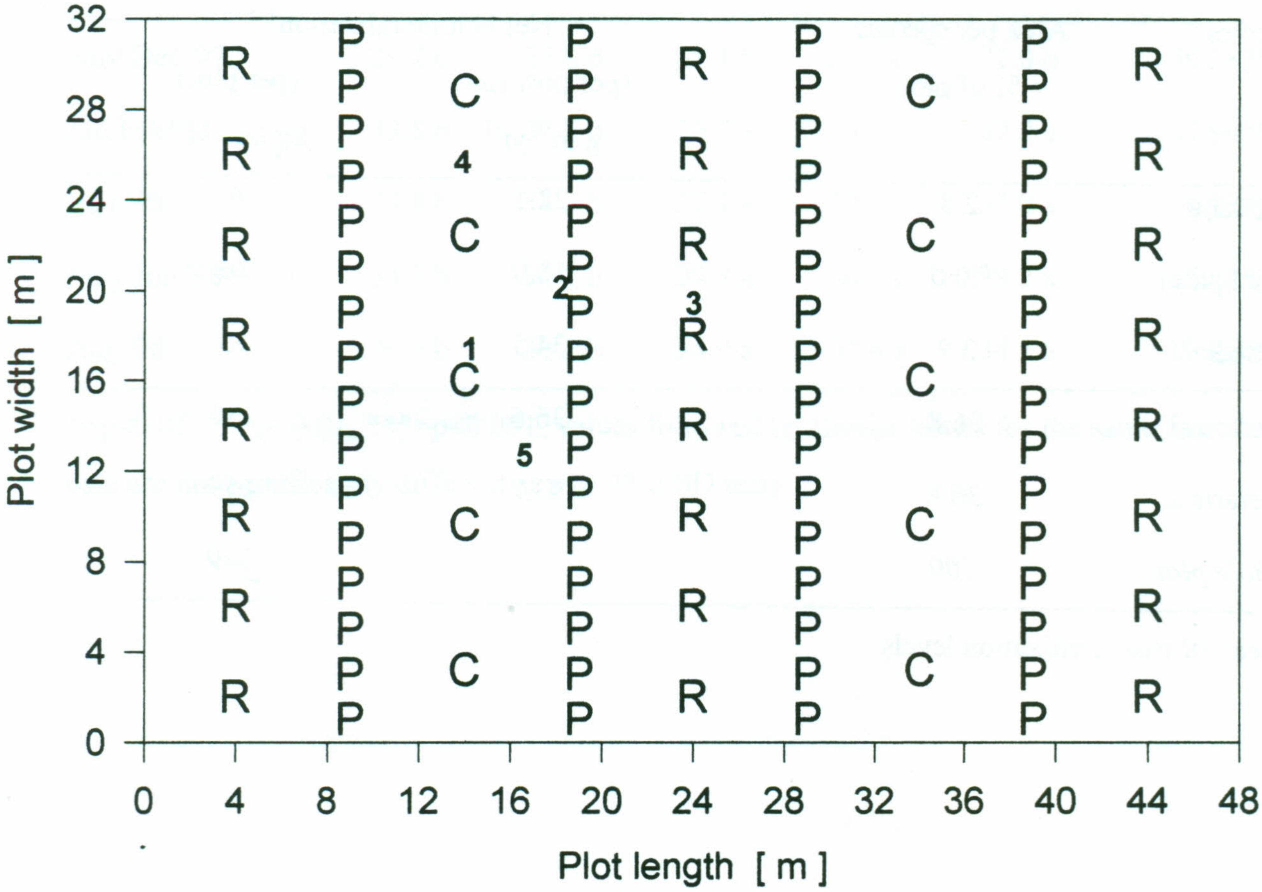
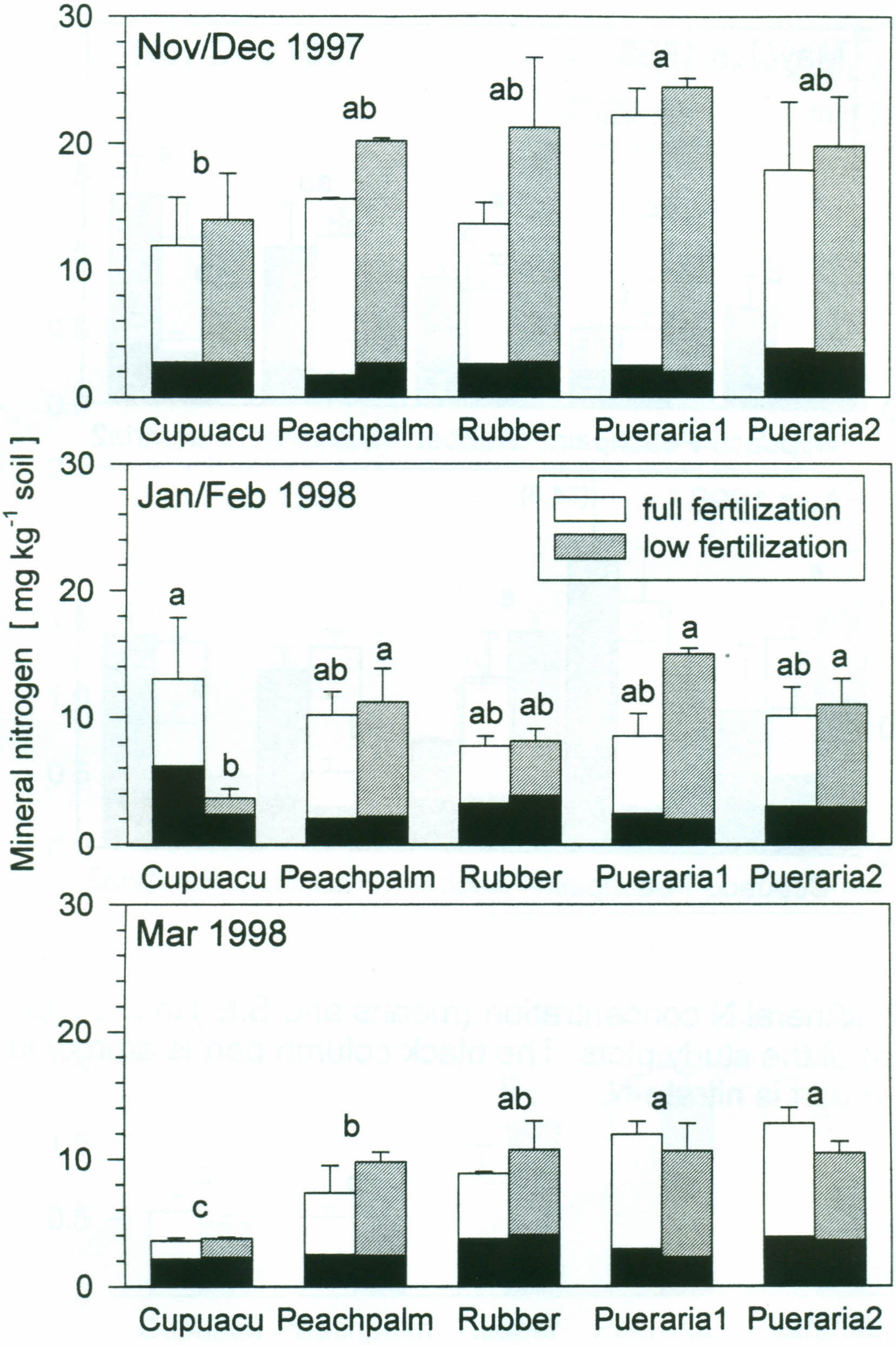


Figure 1: Layout of a polyculture plot with cupuacu (C), peach palm (P) and rubber trees (R). The numbers show the sampling positions.


Nov/Dec 1997
Jan/Feb 1998
Mar 1998
full fertilization
low fertilization
Mineral nitrogen [mg kg^{-1} soil]
Cupuacu
Peachpalm
Rubber
Pueraria1
Pueraria2
0
10
20
30
a
b
ab
c

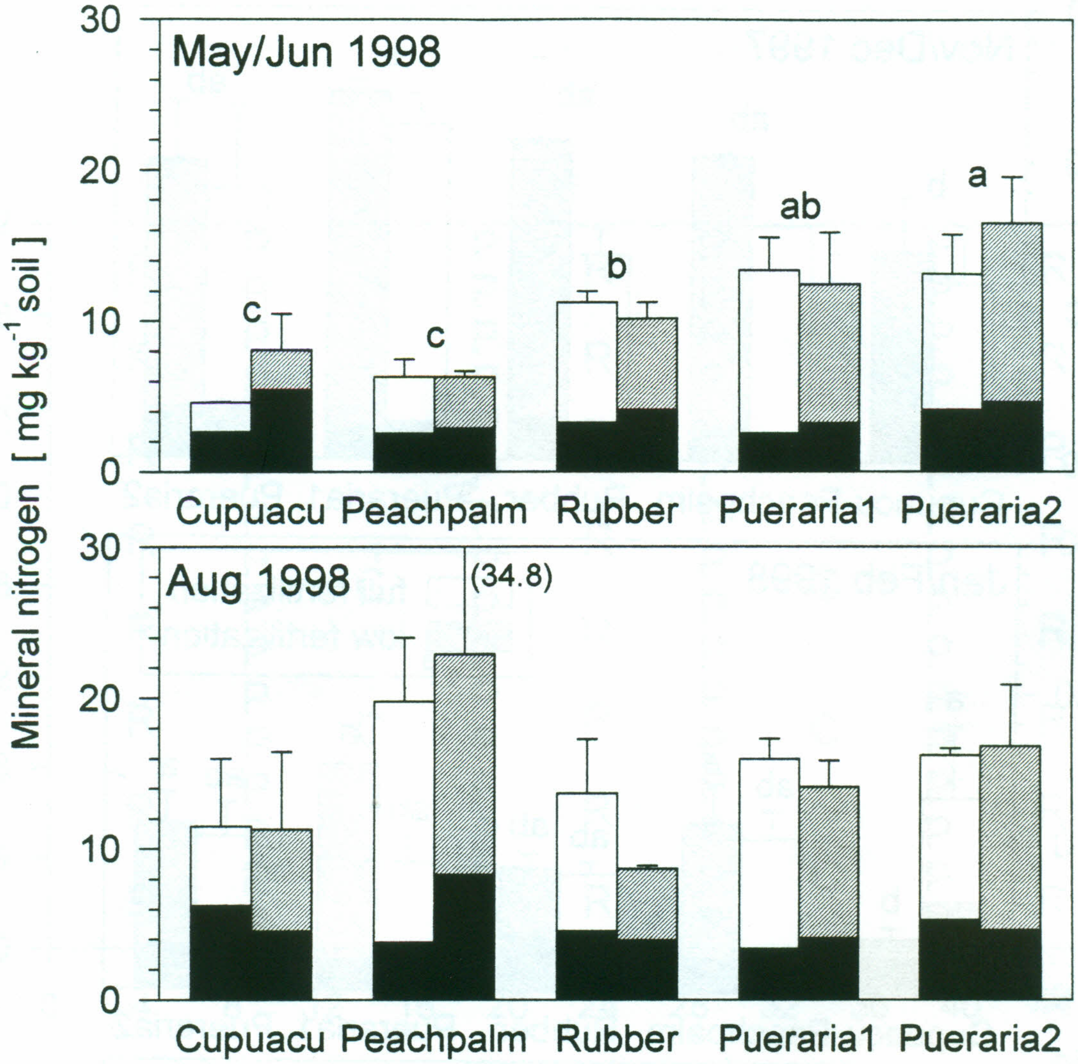
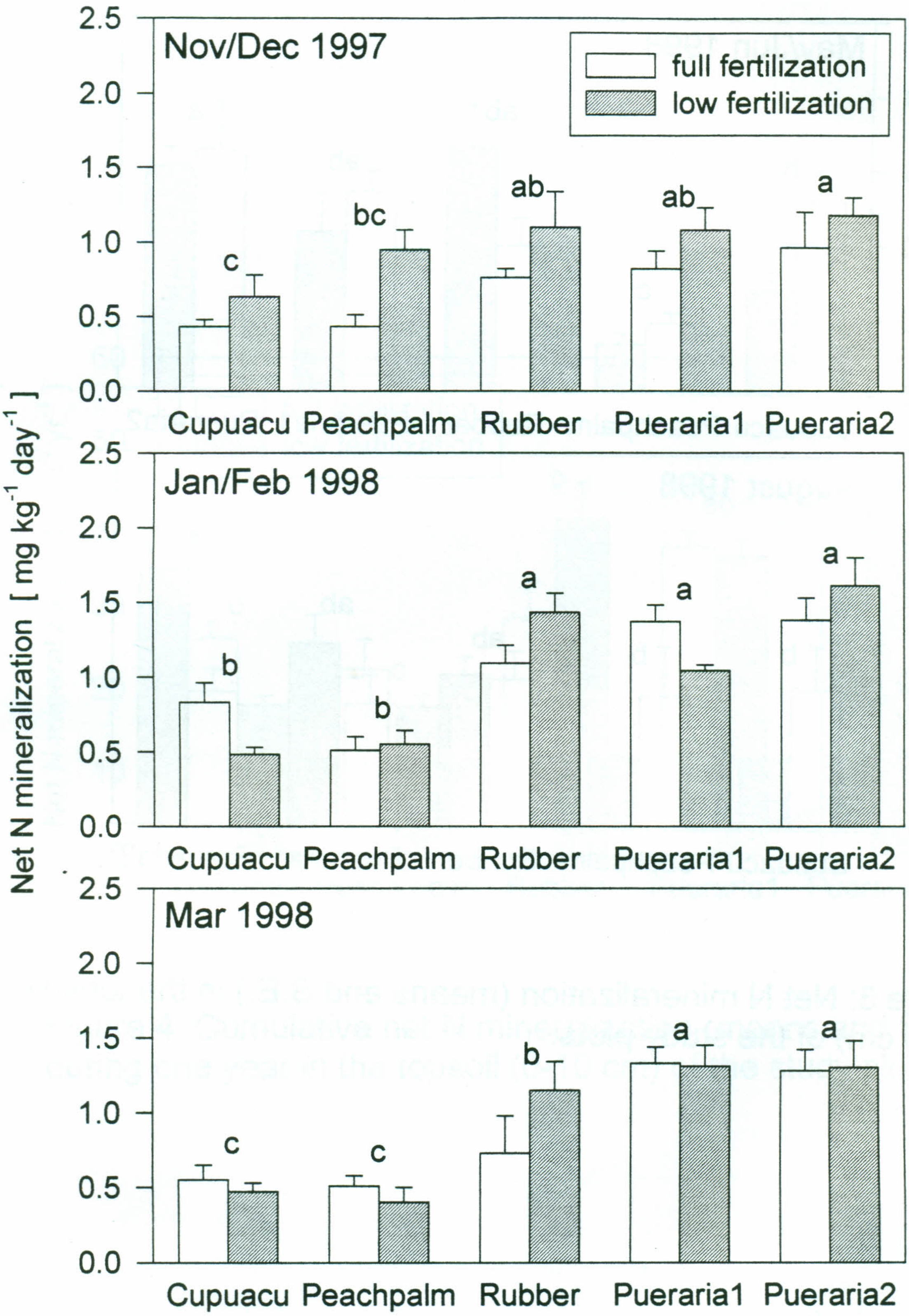


Figure 2: Mineral N concentration (means and S.E.) in the topsoil (0-10 cm) of the study plots. The black column part is ammonium-N, the upper part is nitrate-N.



Nov/Dec 1997
full fertilization
low fertilization
c
bc
ab
ab
a
Cupuacu Peachpalm Rubber Pueraria1 Pueraria2
Jan/Feb 1998
b
b
a
a
a
Cupuacu Peachpalm Rubber Pueraria1 Pueraria2
Mar 1998
c
c
b
a
a
Cupuacu Peachpalm Rubber Pueraria1 Pueraria2
Net N mineralization [mg kg^{-1} day^{-1}]
0.0
0.5
1.0
1.5
2.0
2.5

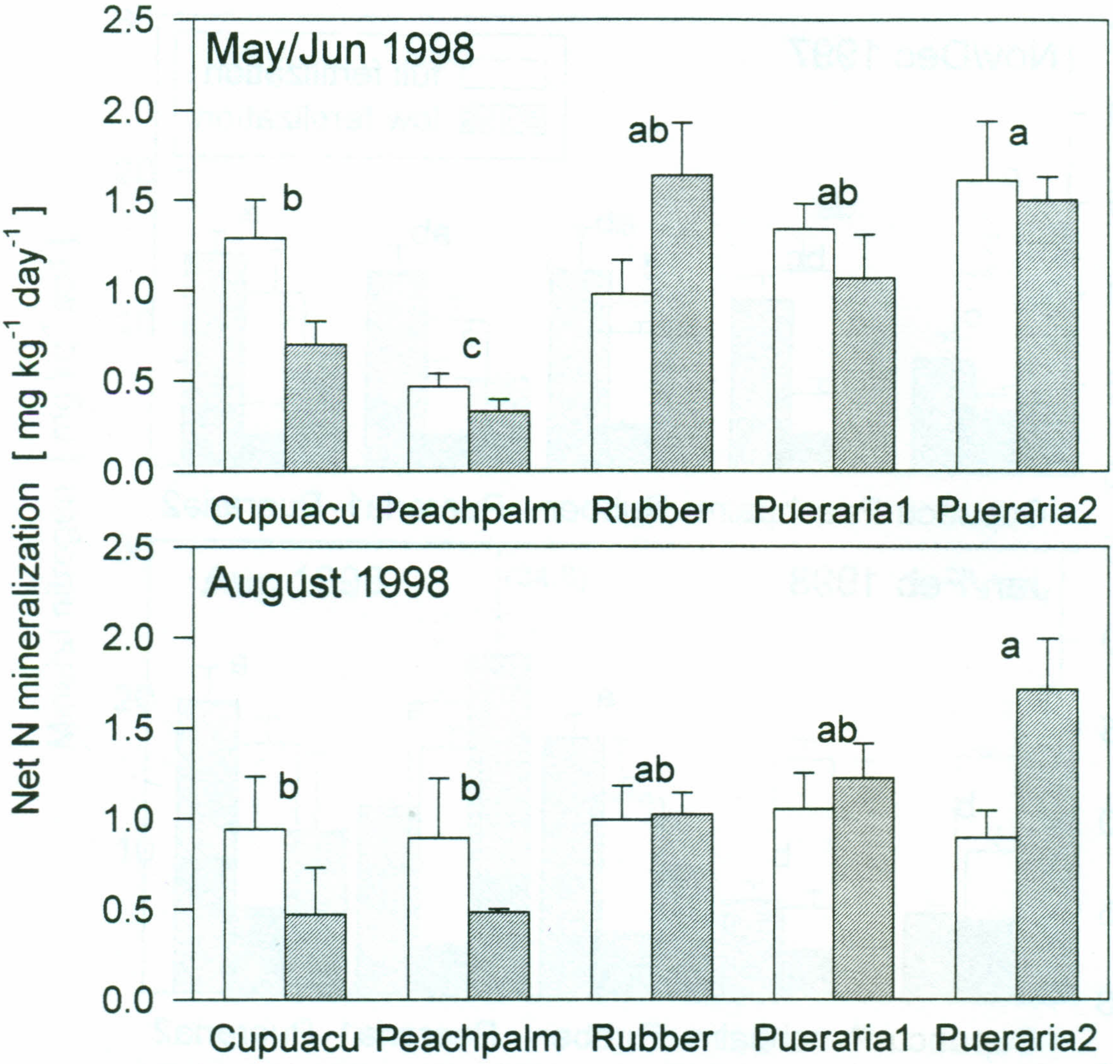


Figure 3: Net N mineralization (means and S.E.) in the topsoil (0-10 cm) of the study plots.

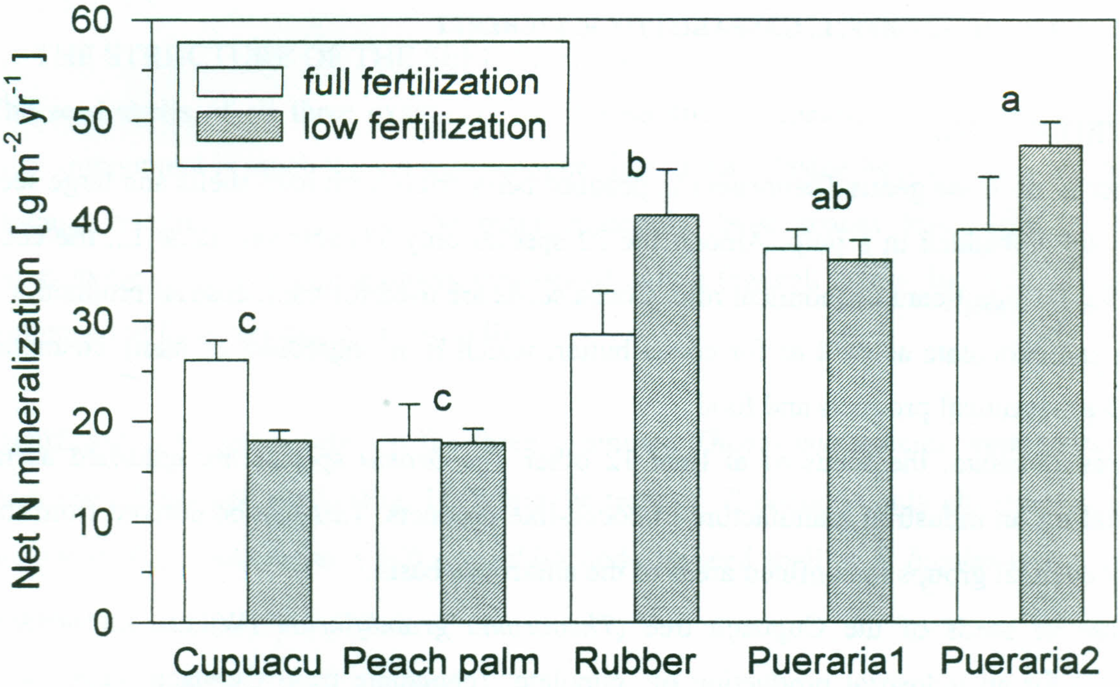


Figure 4: Cumulative net N mineralization (means and S.E.) during one year in the topsoil (0-10 cm) of the study plots.