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3) Significant subsoil accumulation of mineral nitrogen under perennial crops in a ferralitic Amazonian upland soil: effects of land use systems and single-tree patterns

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Introduction

Ferralsols (Oxisols) account for 50 % of the soils of humid tropical America and for 35 % of the soil cover of the humid tropics of the world (Szott et al., 1991). In the Amazon basin, the natural vegetation of these soils is typically rainforest. By definition, ferralsols are very poor in weatherable minerals and rich in caolinitic clay and sesquioxides, resulting in a generally low chemical fertility (van Wambeke, 1992). Where the soils are deep and the plant roots cannot reach the underlying rock or its less completely weathered residues, the nutrient supply of the vegetation depends strongly on the humus-enriched topsoil and, notably, on the nutrients in the biomass of the rainforest vegetation which are effectively recycled from decomposing organic materials by the dense, superficial roots and their mycorrhiza (Herrera et al., 1978; Stark and Jordan, 1978). As a consequence, the subsoils contain only small amounts of nutrients under these conditions and probably contribute little to the nutrient supply of the vegetation, despite the very deep roots of some forest plants (Chauvel et al., 1993; Nepstad et al., 1994).

After clearing the rainforest for agricultural use, the soil fertility declines rapidly when the soil is exposed to atmospheric forces without a protecting vegetation layer due to humus loss, structural degradation and, on some sites, surface erosion. Where the population density is too high for sustainable shifting agriculture, land use systems with perennial crops which provide a permanent soil cover and mimic to some extent the natural forest vegetation are therefore considered more suitable for these conditions than annual cropping systems (van Wambeke, 1992). However, because of the low chemical fertility of the soils, the correction of excessive acidity and nutrient deficiencies (e.g. phosphorus, calcium and micronutrients) as well as the replacement of nutrient

exports in the harvested biomass will often be necessary for permanent agriculture or agroforestry to be sustainable (Szott and Kass, 1993).

Under these conditions, the subsoil may play a different role than in the natural forest vegetation. As the nutrient availability in the topsoil is increased by fertilisation and the efficient nutrient recycling mechanisms of the forest are at least temporarily disrupted, the intensive rainfalls may wash higher amounts of nutrients into the subsoil, especially such mobile ones as nitrate. This nitrate can be retained to some extent in the subsoil through sorption to positively charged surfaces, thereby remaining within the reach of deep-rooting plants (Cahn et al., 1992; Hartemink et al., 1996). The amount of nutrient leaching and the degree to which these nutrients can be recycled by the vegetation obviously depend on the plant species present (e.g. their root distribution) and their management, especially the fertilisation rate and timing.

The objective of this study was to evaluate the potential contribution of the subsoil to crop nutrition in a ferralitic upland soil of western Amazonia. We determined the distribution of mineral and KCl-extractable organic N in the first two meters of soil at the beginning of the rainy season, comparing a perennial polyculture system composed of four common tree crop species of the region at two fertilisation levels with a monoculture plantation, spontaneous fallow and primary rainforest. Within the polyculture, we compared positions under the different tree crop species and under the cover crop. Our aim was to identify combinations of crop species and management practices which minimise nutrient losses into the subsoil and/or increase nutrient uptake from the subsoil, and which might be of use for the development of sustainable, permanent land use systems for the region, and for the humid tropics in general.

Materials and methods

Study site

The soil is a xanthic ferralsol according to the FAO/Unesco classification (1990) with a clay content of about 80%. It is moderately acidic with a very low cation exchange capacity and, in the natural state, high aluminium saturation (see fallow and primary forest profiles in comparison to the limed agricultural plots in Table 1). Available phosphorus contents are very low except in the top 10 cm in the fertilised plots. Total carbon and N decrease strongly with increasing soil depth, but are still detectable at 2 m depth (Table 1).

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 with bag plants in February/March 1993. The total experimental area was about 13 ha.

The centerpiece of the study was a polyculture system with four regionally important tree crop species: The palm *Bactris gasipaes* (peachpalm, Arecaceae) for the production of palmito (heart of palm); *Theobroma grandiflorum* (cupuaçu, Sterculiaceae), a small tree related to cacao whose fruit pulp is widely used in (and increasingly outside) the region for the preparation of juice, icecream and sweets; *Bertholletia excelsa*, the Brazil nut tree (Lecythidaceae) which, beside the well-known nuts, produces excellent wood; and *Bixa orellana* (urucum, Bixaceae) which is widely cultivated in the tropics for its non-toxic red dye. The trees were grown in rows with 4 m spacing between the rows. A row with peachpalm (at 2 m spacing within the row) alternated with a mixed row of cupuaçu and Brazil nut (at 6.7 m spacing between the trees within the row), a row of urucum (at 4 m spacing within the row) and again a mixed row of cupuaçu and Brazil nut, after which the next row of peachpalm followed. Between the trees, *Pueraria phaseoloides* (tropical kudzu, Fabaceae) was sown as a cover crop or developed from residual seed from the former rubber plantation (Figure 1). This system was studied at two fertilisation levels, full fertilisation according to local experiences and 30% of this fertilisation level (low input, Table 2). The fertiliser was applied in two doses per year in November/Dezember (beginning of the rainy season) and May/June. In the plots with the lower fertilisation level, 30% of the N fertiliser of the fully fertilised plots had been applied at all fertilisation events until May 1996. Thereafter, no N fertiliser was applied in these plots to test if the leguminous cover crop alone was able to supply sufficient amounts of N for the tree crops in the system (Table 2).

For comparison, a peachpalm monoculture, planted at 2 by 2 m, and plots with spontaneous fallow vegetation of the same age as the agricultural plots were included in the study. The fallow plots were dominated by *Vismia* spp., which is a characteristic genus in the vegetation of young fallows and degraded lands in the region. The stem density was 1.95 ± 0.17 per m^2 in the *Vismia* plots. The peachpalm monoculture was fertilised at the same rate per tree as the peachpalm in the polyculture plots with full fertilisation (Table 2), and the fallow plots were unfertilised. In November/Dezember 1996, one year before the study, the fully fertilised plots and the monoculture, but not the low input plots, were limed with 2.1 Mg ha^{-1} of dolomitic lime.

In addition, we included two tree species from a nearby primary rainforest in the study: *Eschweilera* sp. („Matá-matá“, Lecythidaceae), a dicot tree, and *Oenocarpus bacaba* („Bacabeira“, Arecaceae), a palm. Both species are relatively frequent in this forest and are of commercial interest, *Eschweilera* for its wood and *Oenocarpus* for its fruits which are collected by the local population for the preparation of juice. For each species, three well-developed, adult specimens were included in the measurements.

The measurement plots with the exception of the rainforest sites were arranged in a randomised complete plot design with three replications. Plot size was 24 by 32 m in the peachpalm monoculture and 48 by 32 m in the polycultures and the fallow plots.

The peachpalm was managed by cutting the main stem about 1½ years after planting and harvesting the palmito three times per year when the offshoots reached a diameter of 8 cm at 1 m height. The urucum was cut back at about 1.5 m height once per year after the harvest between March and May to increase fruit production, removing all the leaves and small branches which were left to decompose under the trees.

Sample collection and analysis

Soil samples were collected between mid October and mid November 1997, i.e. at the end of the dry season. In the six polyculture plots (two fertilisation levels, three replications), five samples per plot were collected. One sample was collected at 50 cm from the trunk of a typical tree of each of the four species, respectively, and a further sample was collected under the *Pueraria* cover crop at maximum distance from the trees in the plots. The objective of this sampling design was not to measure an average situation within the polyculture systems, but rather to characterise the extreme points within the plots and to relate these to the properties and the management of the different tree species present (single-tree patterns). In the monoculture plots, one sample per plot was collected at 50 cm from a typical tree. In the fallow plots, one sample per plot was taken at a random position because of the close spacing of the trees. In the primary forest, one sample was taken at 50 cm from each of the six tree individuals (two species, three replications).

In each of the 42 sampling positions, soil was collected from the following depths: 0-10 cm, 10-30 cm, 30-50 cm, 50-100 cm, 100-150 cm and 150-200 cm. For the first depth, a cylindrical root corer was used to avoid loss of the fragile surface soil and to guarantee representative sampling of all subhorizons. The remaining depths were sampled with an Edelman auger.

Table 1: Soil fertility data from the study area from agricultural, fallow and primary forest plots (means of three replicate profiles)

Depth [cm]	C total [g kg ⁻¹]	N total [g kg ⁻¹]	pH (H ₂ O)	pH (KCl)	P avail. [mg kg ⁻¹]	CEC [cmolc kg ⁻¹]	BS [%]
<u>Agricultural plot (Brazil nut, full fertilisation)</u>							
0-10	25.9	2.2	4.5	4.0	20.9	0.737	55.9
10-30	13.2	1.2	4.4	4.1	2.8	0.363	26.6
30-50	9.5	1.0	4.4	4.1	0.8	0.304	17.7
50-100	5.3	0.7	4.5	4.3	0.2	0.252	28.7
100-150	3.6	0.5	4.7	4.5	0.1	0.215	52.6
150-200	2.7	0.4	5.0	4.7	0.1	0.136	61.5
<u>Fallow</u>							
0-10	18.9	1.6	4.5	4.0	6.3	0.486	33.0
10-30	12.0	1.1	4.4	4.1	1.4	0.336	20.9
30-50	8.5	0.9	4.7	4.2	0.4	0.254	16.3
50-100	5.5	0.7	5.0	4.3	0.2	0.158	14.8
100-150	3.5	0.5	5.1	4.4	0.1	0.108	13.8
150-200	2.6	0.4	4.7	4.5	0.1	0.076	23.5
<u>Primary forest (<i>Oenocarpus bacaba</i>)</u>							
0-10	27.8	2.0	4.2	3.6	3.9	0.599	23.5
10-30	10.8	1.0	4.4	4.1	0.9	0.316	16.4
30-50	7.7	0.8	4.7	4.2	0.4	0.257	16.3
50-100	5.0	0.6	4.9	4.3	0.2	0.162	11.9
100-150	3.0	0.4	5.0	4.4	0.1	0.108	12.2
150-200	2.3	0.4	5.4	4.6	0.1	0.076	27.3

CEC = cation exchange capacity; BS = base saturation

Table 2: Fertilisation of four tree crops on a ferralitic upland soil in western Amazonia with N, P and K in May 1996, Dezember 1996 and May 1997 (the last three applications before the sample collection for the present study)

	Plants per ha	N ¹ P ¹			K ¹						
		[g plant ⁻¹]			[g plant ⁻¹] [g plant ⁻¹]						
		5/96	12/96	5/97	5/96	12/96	5/97	5/96	12/96	5/97	
<u>Polyculture, full fertilisation</u>											
Peachpalm	312.5	37	40	21	0	20	6	19	50	13	
Cupuaçu	93.3	28	20	47		0	34	39	23	25	62
Brazil nut	93.3	20	20	21		0	20	11	42	0	25
Urucum	156.3	23	40	42		0	34	20	43	50	75
<i>Sum [kg ha⁻¹]</i>		20	23	20		0	17	9	19	26	24
<u>Polyculture, 30% fertilisation</u>											
Peachpalm	312.5	11	0	0	0	6	2	9	15	4	
Cupuaçu	93.3	8	0	0		0	10	12	7	8	19
Brazil nut	93.3	6	0	0		0	6	3	13	0	8
Urucum	156.3	7	0	0		0	10	6	13	15	22
<i>Sum [kg ha⁻¹]</i>		6	0	0		0	5	3	7	8	7
<u>Monoculture</u>											
Peachpalm	2500	37	40	21	0	20	6	19	50	13	
<i>Sum [kg ha⁻¹]</i>		93	100	53		0	49	14	49	125	31

¹Fertiliser forms: N in 1996 as urea (40% N) and in 1997 as ammonium sulfate (21% N); P as triple super phosphate (22% P), except in 12/1996 (North Carolina Phosphate „Atifos“, 13% P); K as potassium chloride (50% K)

The samples were stored in plastic bags in the shade and were taken to the laboratory within a maximum of three hours. In the laboratory, from every soil 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 to suppress microbial activity, 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 to 3 hours. Filtration of the subsoil samples had been found almost impossible during preliminary tests because of the high clay content of the soils and had also been found to be a source of ammonium contamination.

The extraction solutions were either analysed the same day or were kept below 0°C until the analysis. Ammonium, nitrate (after reduction to nitrite) and total N in the extracts were analysed photometrically with a segmented flow analyser (Skalar, Netherlands) in the EMBRAPA laboratory. Total N was measured as nitrite after online UV-digestion in a potassium peroxodisulfate solution. The N contents were related to the dry soil, taking into account the water content of the extracted soil samples.

The samples for the general soil characterisation (Table 1) were collected with the same method in the central part of the experiment one year earlier (dry season 1996). Carbon and N were measured with a CNS elemental analyser. Phosphorus and basic cations were extracted with the Mehlich III-solution at a soil:solution ratio of 1:10 (Tran and Simard, 1993) and were measured photometrically with a segmented flow analyser (P) or by atomic absorption spectrometry. Exchangeable acidity was extracted with 1 M KCl at a soil:solution ratio of 1:15 by 10 minutes shaking, and a subsample of 25 ml was titrated with NaOH against a phenolphthaleine indicator. The pH was measured by glass electrode at a soil:solution ratio of 1:2.5 in distilled water and 1 M KCl.

Statistical analysis

Statistical comparisons were conducted separately for the different soil depths and for the sum of all depths. For summing the soil depths, a bulk density of 1.1 g cm⁻³ was used for the top 10 cm of soil and of 1.2 g cm⁻³ for all other depths (D. Haag, 1997, unpublished data). Separate analyses were calculated for the variables measured, a) ammonium-N, b) nitrate-N, c) mineral N

(the sum of a and b), d) total N in the KCl-extracts and e) organic N in the extracts (the difference between d and c).

We first tested for significant differences between the sampling positions (tree species and cover crop) within the polyculture systems at the two fertilisation levels, without taking the other systems (monoculture, fallow and forest) into account. We computed a two-factorial analysis of variance for a randomised complete block/split block design with the fertilisation level as the main plot factor and the plant species as the subplot factor (Little and Hills, 1978). In case of a significant F-test at $p < 0.05$, mean separations were computed by least significant difference tests at the same level of significance.

The system types (or main plots of the experiment, i.e. polyculture plots at full and 30% fertilisation, monoculture and fallow) were compared in a separate analysis for a randomised complete plot design (referred to as „systems comparison“ below). For this analysis, it was necessary to calculate a mean value from the different sampling positions in the polyculture plots which could be compared with the values from the monoculture and the fallow. Our sampling scheme had been designed for detecting extreme values within the plots and did not allow to define the area around a tree (or, for the cover crop, between the trees) for which each sample was representative. For this reason, it was not possible to calculate precise area averages for the different variables measured for the whole polyculture systems. Instead, we calculated the simple arithmetic mean of the five sampling positions within a plot for each variable and used these values in the comparison with the other system types. As before, means were separated by LSD test in case of a significant F-test at $p < 0.05$. The sampling positions in the primary forest were only compared qualitatively with the other positions and were not included in the analyses, because they were not part of the original experimental design and were not spatially interspersed with the experimental plots (Hurlbert, 1984).

Results

Figures 2 and 3 show the profiles of KCl extractable N for the 14 investigated combinations of land use system, plant species and management. Tables 3 and 4 give values for the whole profiles. In all cases, most of the mineral N in the profiles was nitrate. Significant amounts of ammonium were only measured in the surface soil; they decreased to low values already in the 10-30 cm depth. The highest ammonium concentrations were found in the primary forest under the palm *Oenocarpus bacaba*, where ammonium contributed 59% to the total mineral N in the

topsoil (Figure 3). For the whole profile, the effects of fertilisation level and land use system on the ammonium stocks were not significant (Tables 3 and 4), although at 0-10 cm depth, the lower fertilised polyculture plots had significantly ($p=0.026$) higher ammonium concentrations than the higher fertilised polyculture, the monoculture and the fallow (Figure 2). Also, there were significantly ($p=0.003$) higher ammonium values for urucum and Brazil nut than for peachpalm and *Pueraria* in the polycultures at 10-30 cm depth (mean of both fertilisation levels, Figure 2).

The nitrate concentrations in the soil decreased in all cases except the *Bactris* monoculture from the topsoil to some depth between 50 and 150 cm, as would be expected. With further increasing soil depth, however, there was an increase of the nitrate concentrations under all species, including the unfertilised fallow and the primary forest sites (Figures 2 and 3). Within the polyculture system, the fertiliser effect and the fertiliser-species interaction were again non-significant (although the fertiliser effect was significant when calculated only for the species cupuaçu and *Pueraria*, Table 3 and Figure 2). In contrast, the species effect was highly significant, with higher values for cupuaçu and *Pueraria* than for the remaining three tree species (Table 3). This was due to significant differences between species at 50-100 cm depth ($p=0.038$) and at 100-150 cm depth ($p=0.001$). (The 30-50 cm depth was slightly non-significant, $p=0.0502$; Figure 2). In the systems comparison, significantly higher nitrate values were found for the three fertilised (agricultural) systems than for the unfertilised fallow (Table 4). In particular, the fallow had much less nitrate in the subsoil than the fertilised plots ($p=0.011$ at 100-150 cm depth), the systems effect in the topsoil being slightly non-significant ($p=0.052$). As nitrate made up most of the mineral N in the profiles, the statistical results for total mineral N (ammonium + nitrate) were very similar to those for nitrate alone (Tables 3 and 4).

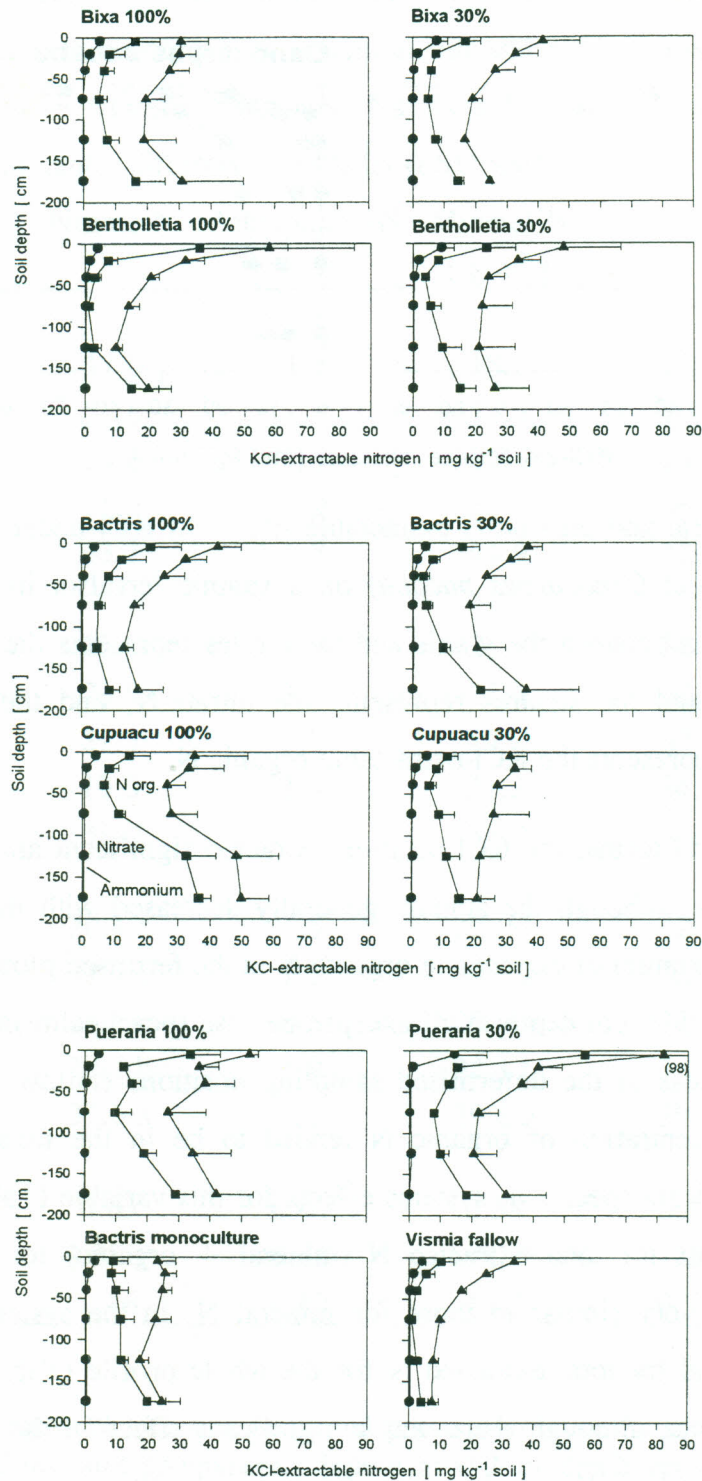


Figure 2: Profiles of mineral and organic N extractable with 1 M KCl under four different tree crop species and a cover crop in polyculture (full and 30% fertilisation) as well as peachpalm monoculture and *Vismia* fallow on a xanthic ferralsol in western Amazonia (means and S.E.). The area between the y-axis and the circles represents the ammonium-N, the area between the circles and the squares represents the nitrate-N, and the area between the squares and the triangles represents the KCl-extractable organic N.

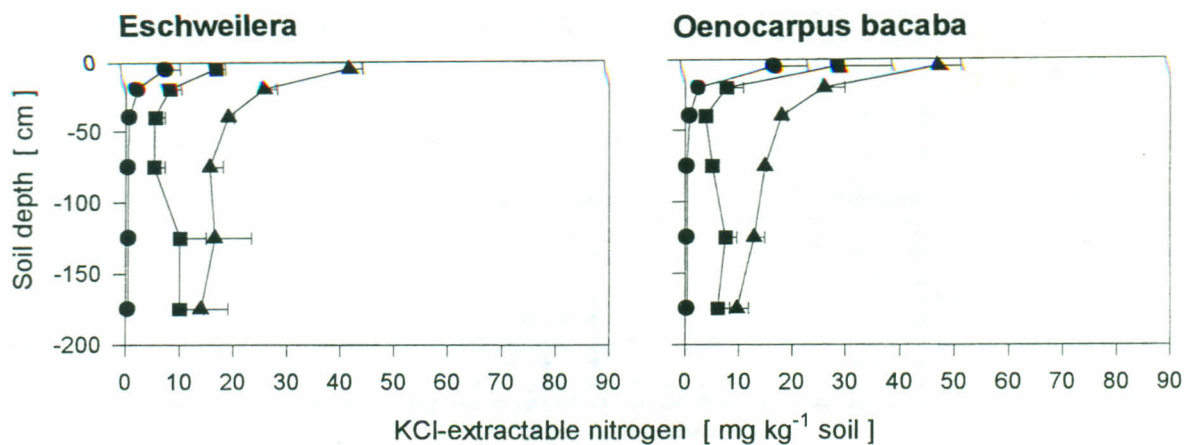


Figure 3: Profiles of mineral and organic N extractable with 1 M KCl under two primary forest species (*Eschweilera* sp. and *Oenocarpus bacaba*) on a xanthic ferralsol in western Amazonia (means and S.E.). The area between the y-axis and the circles represents the ammonium-N, the area between the circles and the squares represents the nitrate-N, and the area between the squares and the triangles represents the KCl-extractable organic N.

In addition to the mineral N forms, the KCl solution extracted significant amounts of organic N from the soil at all depths, although the amount generally decreased with increasing soil depth (Figures 2 and 3). The maximum of extractable organic N in the fertilised plots was not in the top 10 cm of soil, but in the 10-30 cm depth in all except one case (peachpalm in the fully fertilised polyculture system), whereas in the unfertilised sampling positions (fallow and primary forest sites), the maximum concentration of organic N tended to be in the topsoil. The statistical analysis detected no significant species or systems effects for this variable (Tables 3 and 4). As a result, the statistical results for total extracted N (mineral + organic) for the species in the polyculture systems were very similar to those for mineral N. In the systems comparison, no significant effect was found for total extracted N for the whole profile (Table 4), in contrast to nitrate and mineral N alone, although there was a significant effect in the 100-150 cm depth ($p=0.011$), with significantly higher values for the two polyculture treatments than for the fallow.

Table 3: KCl-extractable N forms in the soil under four different tree crop species and a leguminous cover crop in a polyculture system at full and 30% fertilisation at 0-2 m depth on a ferralitic upland soil in western Amazonia. Numbers followed by similar letters in the same column are not significantly different at $p < 0.05$ (LSD test).

	Nitrate-N	Ammonium-N	Mineral N [g m ⁻²]	Organic N	Total N
<u>Full fertilisation</u>					
Peachpalm	17.0	1.5	18.5	28.7	47.2
Cupuaçu	51.6	1.9	53.5	40.3	93.9
Brazil nut	16.0	1.5	17.5	27.4	44.9
Urucum	21.0	1.9	22.9	36.3	59.2
Pueraria	43.2	1.7	44.9	40.9	85.8
<u>30% fertilisation</u>					
Peachpalm	23.9	1.6	25.4	36.6	62.0
Cupuaçu	23.9	1.5	25.4	33.5	58.9
Brazil nut	21.5	2.2	23.7	37.1	60.8
Urucum	19.3	1.9	21.2	34.0	55.2
Pueraria	32.0	2.7	34.7	37.5	72.2
<u>Species means</u>					
Peachpalm	20.4 b	1.5	22.0 b	32.6	54.6 b
Cupuaçu	37.7 a	1.7	39.5 a	36.9	76.4 a
Brazil nut	18.7 b	1.8	20.6 b	32.3	52.8 b
Urucum	20.1 b	1.9	22.1 b	35.1	57.2 b
Pueraria	37.6 a	2.2	39.8 a	39.2	79.0 a
F (Fertil. level)	0.63	6.01	0.58	0.52	0.32
F (Species)	8.25**	0.63	8.92**	1.10	7.60**
F (Fertil. x Species)	1.46	0.62	1.49	0.79	1.43

** = $p < 0.01$

Table 4: KCl-extractable N forms in perennial polyculture systems at full and 30% fertilisation, peachpalm monoculture and spontaneous fallow at 0-2 m depth on a ferralitic upland soil in western Amazonia. Numbers followed by similar letters are not significantly different at $p < 0.05$ (LSD test).

	Nitrate-N	Ammonium-N	Mineral N [g m ⁻²]	Organic N	Total N
Polyculture 100%	29.8 a	1.7	31.5 a	34.7	66.2
Polyculture 30%	24.1 a	2.0	26.1 a	35.8	61.8
Monoculture	29.1 a	1.3	30.4 a	22.5	52.9
Fallow	5.9 b	1.6	7.5 b	21.6	29.1
F	10.52**	2.39	10.91**	1.05	3.22

Discussion

Sources of mineral N in the subsoils

This study brought evidence for the accumulation of very significant quantities of mineral N in the subsoil of a ferralitic Amazonian upland soil under perennial crops at the beginning of the rainy season, shortly before the fertilisation of the crops. From the distribution of the mineral N in the soil profiles it is clear that more N could have been found below the sampling depth of 2 m (Figure 2). Most of the mineral N in the subsoils was nitrate. This indicates that nitrification was rapid despite the low pH values, in agreement with measurements at a nearby site under rainforest (Vitousek and Matson, 1988), and this facilitated N leaching from the topsoils (Robertson, 1989). Significant nitrate leaching under annual crops at the same site has been reported by Cahn et al. (1993).

The subsoil accumulation of mineral N was much lower in the fallow plots than in the agricultural plots, despite a similar site history prior to the installation of the experiment. This excludes residual N from the previous rubber plantation and N leached after slashing and burning the secondary forest for the establishment of the present experiment as major sources for the mineral N in the agricultural plots. Also, there was no evidence that the decomposition of soil organic matter following the conversion of the secondary forest to the experimental plantation had contributed to the release of mineral N as this would have also affected the fallow plots. In the agricultural soils, the total N contents were not lower than those under primary forest and were even higher than in the fallow plots (Table 1).

One source of the subsoil N in the agricultural plots was certainly leached fertiliser. In the 30% fertilised plots, no N fertiliser had been applied since May 1996, i.e. for about 16 months before the sampling (Table 2). The infiltration speed of tritiated water was about 3.5 m in one year at a nearby site under forest (Chauvel et al., 1993). So, the downward movement of the nitrate through the soil was retarded in comparison to its transport medium water, as would be expected because of the considerable nitrate sorption especially of the subsoils at this site (Cahn et al., 1992).

A second probable source of mineral N in the subsoils, especially in the polyculture plots, was biologically fixed N from decomposing biomass of the leguminous cover crop. This would explain the large accumulation of N in the subsoil under the *Pueraria* despite the fertiliser placement near the stems of the trees. The monoculture and the fallow plots, on the other hand,

had no significant understorey vegetation due to the close spacing of the trees, and biological N fixation was presumably irrelevant in these systems.

The spatial patterns of the distribution of mineral N within the polyculture plots were to some extent related to the fertilisation level of the respective tree species (Table 2). Cupuaçu received the highest N fertilisation in May 1997 and had also the highest accumulation of mineral N in the subsoil. It was followed by urucum in both regards. However, the difference in subsoil N between the fully fertilised and the 30% fertilised plots was less than what might have been expected from the difference in fertilisation. This may have been due to higher N losses beyond 2 m soil depth in the fully fertilised plots and eventually to a higher contribution of biologically fixed N at the lower fertilisation level.

Need for improved fertilisation practices

The obvious N losses from the topsoil under all species point to two interrelated problems with the fertilisation of Amazonian tree crops. Firstly, there is a need to develop species- and site-adapted fertiliser recommendations for the investigated (and many other) species for the Brazilian Amazon, as scientifically based recommendations are practically inexistent for this region, despite the importance of tree crops for its agricultural (or agroforestry) development. For example, the fertilisation of cupuaçu followed mainly experiences with its relative cacao in other states of Brazil (Bahia, São Paulo). For cacao, very low leaching rates of N fertiliser have been reported from other humid tropical regions (Santana and Cabala-Rosand, 1982; Seyfried and Rao, 1991), whereas for cupuaçu, the full fertilisation level resulted in the highest subsoil accumulation of mineral N which was measured in our study (Figure 2 and Table 3). The cupuaçu yields did not respond to the higher fertilisation level, indicating that the species was unable to absorb the additional nutrients. The same was true for Brazil nut with respect to height and diameter growth. Peachpalm showed a weak and usually insignificant yield response to higher fertilisation, whereas urucum produced significantly higher seed yields at the higher fertilisation level (J. Macedo and R. Lima, unpublished results). However, the yield response of urucum was not necessarily to the increased N application but possibly to another nutrient such as P. The complete growth and yield data will be presented in a subsequent publication.

Secondly, the fact that N accumulated in the subsoil under all species even at the lower fertilisation level indicates that under the high rainfall and permeable soil conditions of our site, the splitting of the annual fertiliser dose into two applications was insufficient, and the timing of the applications may have been wrong. There is a need to develop optimum fertilisation schemes

for these conditions which balance the additional cost of frequent applications of small amounts of fertiliser with the increased leaching losses when the fertiliser is applied at too high quantities at a time, or in asynchrony with plant demand.

Accessibility of mineral N for tree crops

The presence of large amounts of mineral N in the soil profile shortly before the crops were fertilised (*i.e. the beginning of the rainy season*) also illustrates the great interest of basing recommendations for N fertilisation on a previous evaluation of the plant-available N in the respective soil. For this, it would obviously be necessary to know how much of the N in the soil profile is actually accessible to the tree crops. This requires on the one hand information on the lateral extension of the tree root systems and their relative competitiveness in comparison to the roots of the cover crop for the nutrients in the intertree spaces; and on the other hand knowledge of the vertical extension of the tree roots into the subsoil and their efficiency in capturing nutrients before these are leached to inaccessible soil depths. Information on the relative nutrient uptake from different soil depths and distances from the trunk which are available for some tropical tree species of greater international importance (IAEA, 1975) have not yet been produced for the tree crops of this study. However, root excavations 1½ years before the soil sampling for the present study at the same site showed that at 0-10 cm soil depth, the coarse roots of peachpalm extended laterally about 3.5 m from the plants, and those of urucum extended about 2.5 m from the plants. The lateral extension of the cupuaçu and Brazil nut roots was less (Haag, 1997), which means that only part of the N in the intertree spaces would have been accessible for the trees at this age. Vertically, most of the fine roots of the trees were concentrated in the upper 30 to 60 cm of soil, although some roots attained the maximum sampling depth of 150 cm under all species, and possibly more (Haag, 1997). Although these results show that the acidic subsoils were no impermeable barrier to the root development of these local tree crop species, they also indicate that the trees had restricted access to nutrients below 1 to 1.5 m soil depth at this age. Despite some additional root growth in the 1½ years between the two studies, this probably explains the increase in the mineral N concentration in the soil that was often observed at this depth (Figure 2).

The considerable stock of mineral N under the unfertilised cover crop suggests that the potential of the leguminous *Pueraria* with respect to the N nutrition of the tree crops was strongly under-utilised in the investigated systems. Considering the limited lateral extension of the roots of most of the tree species into the intertree spaces, this is not surprising, especially as all the trees in the systems were apparently even unable to use the fertiliser N applied close to their trunks. So,

competition between the trees and the cover crop for surplus N may have been minimal. One way of increasing the root interactions between trees and cover crop would be to reduce the spacing of the trees, either permanently or temporarily through the inclusion of semi-perennial crops. In addition, it is likely that a reduction of the N fertilisation of the trees would not only reduce directly the N leaching, but would also increase the competition between the trees and the cover crop for N in the intertree spaces. The advantages may be severalfold: a reduced need for N fertilisation of the tree crops which may in some cases even become unnecessary; reduced nitrate leaching (and consequently soil acidification) under the cover crop; and eventually even an increased fixation of atmospheric N by the cover crop when the availability of mineral N in their rooting zone is reduced by the tree roots.

Consequences for systems design

Reducing N fertilisation rates, better synchronising them with plant demand, reducing tree spacing and encouraging lateral tree root spreading into the interspaces between the trees would certainly reduce the unproductive N losses. However, the inspection of the N profiles in the soil under the two rainforest tree species, *Eschweilera* sp. and *Oenocarpus bacaba*, shows that even the unfertilised and undisturbed natural vegetation lost nitrate into the subsoil (Figure 3). This confirms the conclusion that „soil N availability in such forests is at least adequate“ (Vitousek and Matson, 1988), but discourages expectations that a vegetation with relatively high N availability (either through fertilisation, biological N fixation or, as in the rainforest, rapid internal N cycling between soil, litter and vegetation) could be made completely „tight“ for highly mobile nutrient forms such as nitrate under conditions of high rainfall and permeable soils. Much lower subsoil nitrate contents than in the agricultural plots were only found under the impoverished fallow vegetation. Under the pedoclimatic conditions of this study, productive agricultural systems which require a certain level of nutrient availability in the soil will probably always lose nutrients into the subsoil.

This shows that under these conditions, there is a considerable interest to design and manage agricultural systems with the explicit objective of recycling leached nutrients from the subsoil. For annual crops, this can be achieved through rotation with deep-rooted fallow species (Hartemink et al., 1996), but this is obviously no viable solution in systems with perennial crops. Instead, the fertilised crops could be associated with deep-rooted trees which form a „safety-net“ of tree roots under the crop root systems (van Noordwijk et al., 1996). The question is if, and under which conditions, the deep-rooting characteristic of certain tree species would persist in an association with fertilised crops, where the nutrient availability is usually much higher in the

topsoil than in the subsoil (Schroth, 1995). With respect to the development of agroforestry as a technique for the reduction of unproductive nutrient losses and improved nutrient use on infertile soils, the results of the present study were in fact somewhat disappointing. The investigated tree crops were typical examples for species to be included in agroforestry systems in the region, yet all of them were apparently sources of subsoil nutrients instead of being sinks as would be required for accomplishing a „safety-net“ function.

The role that tree species play within a cropping system is determined both by their specific properties and by their management. Certainly, trees which are grown with the aim of capturing and recycling subsoil nutrients should not be fertilised with mobile nutrients (especially with N) in order to increase their demand for the nutrients which have been (or are being) leached into the subsoil, although fertilisation with phosphorus and eventually micronutrients may be necessary to ensure satisfactory growth on the soils in question. Tree species like Brazil nut with an inherent tendency to form a deep tap root system on the soil of our study site (Haag, 1997) may develop a denser root system in the subsoil when they are not supplied with fertiliser nutrients in the topsoil, especially when certain amounts of fertiliser nutrients are continuously leached into the subsoil from the cover crop and from associated, fertilised crop species. Their root development in the subsoil may also be favoured by a certain amount of root competition in the topsoil through close spacing with competitive, but shallow-rooted tree crop and/or cover crop species (Comerford et al., 1984; Schroth, 1995), although the efficiency of this measure requires verification.

Importance of soluble organic N fraction

In addition to the mineral N in the soil, we also measured a KCl-extractable organic N fraction. The exact nature and importance of this fraction are not clear. The fact that it could be extracted with a salt solution indicates that it is composed of water-soluble, low-molecular N forms. Our hypothesis that this fraction could be related to properties of the plant species and vegetation types, giving hints to the involvement of organic N forms in the transport and turnover of N in the soil, were not confirmed, as there were no significant differences between species and systems with regard to this variable. Also, this soluble organic N did not seem to play a major role in the vertical N transport in the soil profile, as it generally decreased with increasing soil depth, whereas the nitrate levels increased in the subsoil (Figures 2 and 3). There were indications for a difference in the depth distribution of this labile organic N between fertilised and unfertilised plots, the reasons and implications of which might be explored in future research. However, from

our data the fraction seems to be relatively insensitive as a parameter of species and management specific processes of the soil N economy.

Conclusions

The finding of considerable amounts of mineral N in the subsoil under perennial polyculture and monoculture systems on a ferralitic upland soil of the Brazilian Amazon indicates that there is a considerable scope for the capture and recycling of subsoil nutrients by deep-rooted tree species under these conditions, despite the inherently low fertility of the highly weathered subsoils. Even in well-designed perennial cropping systems, the high rainfalls and permeable soils which are typical for large areas in the humid tropics make it unlikely that the leaching of mobile nutrients into the subsoils can be completely avoided. However, the fact that all tree species in our study were sources, and not sinks, for mineral N in the subsoil shows that not every tree species/management combination is suitable for the reduction of nutrient leaching and the recycling of subsoil nutrients. Not only must the species possess suitable characteristics such as the tendency to form a deep root system under the given soil conditions, but the management of the trees must also favour such tendencies for increasing the nutrient uptake from subsoil horizons.

In addition to the improvement of cropping systems by the inclusion of "catch crop" trees and the increase of nutrient exchange between the cover crop and the tree crops, there is an urgent need to develop site- and species-specific fertiliser recommendations for perennial crops for the Brazilian Amazon, including lesser-known species which may nevertheless be of high importance for the agricultural development of the region. Failure to do so may result in unproductive nutrient losses and eventually groundwater pollution. Soil analyses as a basis for N fertilisation of tree crops should include the subsoil, as significant amounts of previously applied fertiliser nutrients may still be within the reach of the crop roots, especially in the case of older trees with well-developed root systems.

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