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NITROGEN DYNAMICS IN SOILS OF FORESTS AND ACTIVE PASTURES IN THE WESTERN BRAZILIAN AMAZON BASIN

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Summary—To investigate the influence of forest conversion to pasture on soil N transformations, we compared soil inorganic-N pools and net mineralization and nitrification rates along two chronosequences of upland (*terra firme*) forest and pastures ranging in age from 4 to 82 years in the state of Rondônia in the western Brazilian Amazon Basin. Forest and pasture soils had similar total extractable inorganic-N pools at 0–5 and 5–10 cm depths. Ammonium-N and NO_3^--N pools were of similar magnitude in forest soils (2–10 μg N g^{-1} dry soil), while NH_4^+-N dominated pasture soil inorganic-N pools. Annual average net N mineralization rates for the two chronosequences at 0–5 cm depth in the forests were 1.31–1.88 μg N g^{-1} d.s. d^{-1} and exceeded the annual average net N mineralization rates measured in pastures of -0.11–0.02 μg N g^{-1} d.s. d^{-1}. Annual average net nitrification rates at 0–5 cm depth in forest (1.09–1.46 μg N g^{-1} d.s. d^{-1}) were also higher than in pastures (0.24–0.25 μg N g^{-1} d.s. d^{-1}). Pasture soils had lower net N mineralization and net nitrification rates than forest soils even though they had approximately equal or higher total C and total N content. Pasture age did not affect NH_4^+-N pools or net nitrification rates, but decreased NO_3^--N pools and net N mineralization rates. Net N mineralization rate was unaffected by soil moisture, but net nitrification rate decreased at higher soil moisture. Higher net mineralization and nitrification rates in forest soils suggest a higher potential for NO_3^--N losses either through leaching or gaseous emissions from intact forests compared with established pastures.

INTRODUCTION

The Brazilian Amazon Basin contains approximately one-third of the world's remaining tropical moist forest (Myers, 1991). The region also experiences very high deforestation rates of 1.5–2 million ha year^{-1} (Skole and Tucker, 1993; INPE, 1992). This large-scale alteration of natural tropical ecosystems has important consequences for soil processes and regional biogeochemistry. The state of Rondônia in the western Amazon has been the focus of rapid deforestation since the early 1980s (Fearnside and Salati, 1985; Skole and Tucker, 1993). The deforested area in Rondônia increased from 6300 to 24,000 km^2 between 1978 and 1988 (Skole and Tucker, 1993).

Pasture now represents the largest single use of converted forest land in the Brazilian Amazon Basin and in Rondônia (Fearnside, 1980; Skole *et al.*, 1994). Pasture creation has important effects on soil physical and chemical characteristics, rates of soil mineral cycling and the role of soils in long-term storage of C and N. The sustainability of pasture agriculture is now an important issue in Amazonia (Serrão and Toledo, 1990) and understanding the biogeochemical mechanisms that maintain pasture soil fertility will be important for predicting the biological and social consequences of deforestation and for implementing effective pasture management.

Rates of soil N mineralization and nitrification are also indicators of the ability of soils to supply N for plant growth and to retain N following disturbances. The microbial mineralization of NH_4^+-N from soil organic matter is the principal source of plant-available N in most forest ecosystems and rates of N mineralization can regulate the productivity of many forests (Nadelhoffer *et al.*, 1983; Pastor *et al.*, 1984). The rate of production of NO_3^- from NH_4^+ in the process of nitrification influences N losses through leaching and conversion to N gases (Bormann and Likens, 1979; Vitousek and Melillo, 1979; Melillo, 1981; Robertson and Tiedje, 1984). In temperate forests, cutting generally increases net mineralization and net nitrification rates and soil NH_4^+ pools (Bormann *et al.*, 1974; Krause, 1982; Vitousek and Matson, 1985). In the tropics, net N mineralization and net nitrification rates may also increase following forest clearing (Matson *et al.*, 1987; Montagnini and Buschbacher, 1989; Steudler *et al.*, 1991; Reiners *et al.*, 1994), but data is currently available for few tropical forests and almost nothing is known about rates in established pastures.

Laboratory soil incubations were used as an index of rates of net N mineralization and net nitrification

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along two chronosequences of forest and different-aged pastures in the western Brazilian Amazon Basin state of Rondônia to develop a better understanding of N transformations and their effects on soil fertility following tropical forest clearing, pasture creation and pasture aging. This information also provides insight into how land use change may alter regional biogeochemical links between soils and the atmosphere through the release of greenhouse N gases and between soils and aquatic systems by movement of inorganic N to streamwater.

METHODS

Study sites

We conducted field measurements along two forest-to-pasture chronosequences at Fazenda (Ranch) Nova Vida at km 472 of highway BR-364, 50 km southeast of Ariquemes (10°30′ S, 62°30′ W) in central Rondônia. The climate of the region is humid tropical, with a dry season from May to September. Annual rainfall is 2.2 m (Bastos and Diniz, 1982). Annual mean daily temperature is 25.6°C. Mean daily temperature for the warmest and coolest months varies less than 5°C and mean annual relative humidity is 89% (Bastos and Diniz, 1982).

Chronosequences were identified from Fazenda records and satellite images. Chronosequence 1 consisted of a forest tract and pastures cleared in 1989, 1987, 1983, 1979, 1972, 1951 and 1911. Chronosequence 2 contained a forest tract and pastures cleared in 1989, 1987 and 1972. Both chronosequences were on ultisols (Tropudults, Podzólicos Vermelho-Amarelo in the Brazilian classification). This soil type covers about 22% of the Brazilian Amazon Basin (Moraes *et al.*, 1995). Forest vegetation was typical of the open, humid tropical forests of Rondônia, with large numbers of palms (Pires and Prance, 1986). Selective logging in the forest removed about 3–4 trees ha^{-1} between 1987 and 1990. All pastures were created in a similar manner: brush was cut during March, trees were cut during June and July, slash was burned following the beginning of the rainy season in September or early October, and pasture grasses were planted following burning. Established pasture vegetation consisted of forage grasses planted widely in Amazonia. In Chronosequence 1, the pastures cleared in 1989, 1987, 1972 and 1911 were dominated by brachiarão (*Brachiaria brizantha* [Hochst] Stapf.), the pastures cleared in 1979 and 1951 contained colonião (*Panicum maximum* Jacq.) and the pasture cleared in 1983 contained predominantly *P. maximum* with some quicuio (*Brachiaria humidicola* [Rendle] Schweickt). In Chronosequence 2 the 1989 and 1987 pastures contained *B. brizantha* and the 1972 pasture contained predominantly *P. maximum*. All pastures were actively grazed at an average annual rate of ca. 1 animal ha^{-1}. Neither mechanized agricultural practices nor chemical fertilizers were used on any of the pastures. Pastures were burned every 4–10 years to control weeds.

Field and laboratory methodology

To characterize soils along the chronosequences, pH, bulk density, total C and total N were determined in five replicate soil samples collected from small soil pits to a depth of 10 cm. Soil was collected in volumetric 5 cm dia metal cylinders. Density was calculated from a soil subsample dried at 105°C. pH was determined in water (2.5:1) on air dried soil. Total C and N were determined on a Perkin-Elmer 2400 elemental analyzer from subsamples dried to 60°C. Soil for texture determination was collected at 0–10 cm from a deep soil pit at every site and analyzed by the hydrometer method after dispersion with hexametaphosphate.

Soil inorganic-N pools were measured on 10 dates between June 1992 and December 1993, spanning both wet and dry seasons. Net mineralization and net nitrification potential rates were determined from 7-day laboratory soil incubations approximately bimonthly from January to December 1993. Laboratory incubations were chosen based on studies at the site that indicated wide variation in soil moisture and rates measured with standard *in situ* incubation methods (Piccolo *et al.*, 1994).

Soils were collected from depths of 0–5 cm and 5–10 cm using a 5 cm dia corer or small pits (ca. 30 × 30 × 15 cm deep) at each site along the sequences. Pits were used during the dry season when soil hardness prevented effective coring. Five replicate cores or five replicate small pits were made 3 m apart in a line running the same direction from a chosen point. Each month the line was moved 1–2 m parallel to the original line to prevent resampling from disturbed soil. Samples were prepared the same day they were collected by mixing them by hand and removing roots and stones. One subsample of the homogenized soil, used to determine soil inorganic-N pools, was extracted for 24 h with 2 N KCl (10 g fresh soil per 50 ml KCl). A second subsample of ca. 50 g was kept for 7 days at room temperature (between 25 and 28°C). A third subsample was dried to constant weight at 105°C for gravimetric moisture determination. After 7 days, ca. 10 g of the incubated sample was extracted with 2 N KCl. Soil moisture was expressed as percentage of soil dry weight.

Extracts were centrifuged and a subsample was preserved with phenyl mercuric acetate and refrigerated. We analyzed the samples for NH_4^+-N and (NO_3^- + NO_2^-)-N (hereafter referred to as NO_3^--N) within 1 month using an automated flow injection system (Ruzicka and Hansen, 1981). NH_4^+-N was measured colorimetrically after Nessler reaction. NO_3^--N was measured colorimetrically as NO_2^- following reduction with a Cd catalyst. Limits of detection were 0.1 mg L^{-1} for NH_4^+-N and 0.01 mg L^{-1} for NO_3^--N.

Net N mineralization was calculated as the change in NH_4^+-N plus NO_3^--N concentrations during the incubation. Nitrification equaled final minus initial NO_3^--N concentrations. Mean inorganic-N pools were calculated as the mean of all sampling dates in 1992 and 1993. Mean net N mineralization and net nitrification rates were calculated as the mean of all sampling dates in 1993. We tested for differences of N pools, net N mineralization rates and net nitrification rates between sites using analysis of variance. Linear contrasts at a significance level of 0.05 (GLM procedure of SAS) were used to compare between forest and pasture group means (SAS Institute Inc., 1987). Effects of pasture age were tested using linear regression (REG procedure of SAS). One set of NH_4^+-N measurements from March 1993 was not included in the statistical analyses because of unusually high values, where the possibility of handling or laboratory error could not be ruled out.

Daily precipitation totals were recorded at a permanent weather station ca. 20 km away at Fazenda Rancho Grande.

RESULTS

Environmental conditions

Annual precipitation totals near Nova Vida of 2281 mm in 1992 and 2274 mm in 1993 were similar to the 10-year mean annual precipitation of 2229 mm. Precipitation was distributed with a seasonal maximum during January–March and a seasonal minimum during June–August (Fig. 1). Gravimetric soil moisture in forest and pasture soils showed the same seasonal pattern with a slight lag. Highest soil moistures (20–25%) occurred during January–May and lowest soil moistures (5–10%) during July–October (Fig. 2). Pasture soil moisture was generally higher than forest soil moisture and differences were greatest during wetter periods (Fig. 2). Pasture age affected soil moisture ($F = 3.60$, $P < 0.0065$), but linear regression of soil moisture against pasture age indicated that there was no significant trend in soil moisture with increasing or decreasing pasture age.

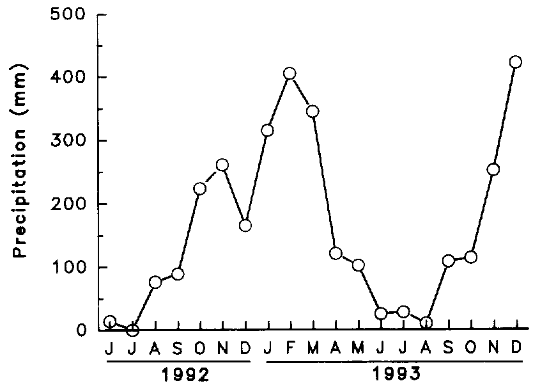

Fig. 1. Mean monthly rainfall during the study period of June 1992–December 1993. The typical regional dry season lasts from May to September. Data are from a permanent weather station located ca. 20 km from the study site.

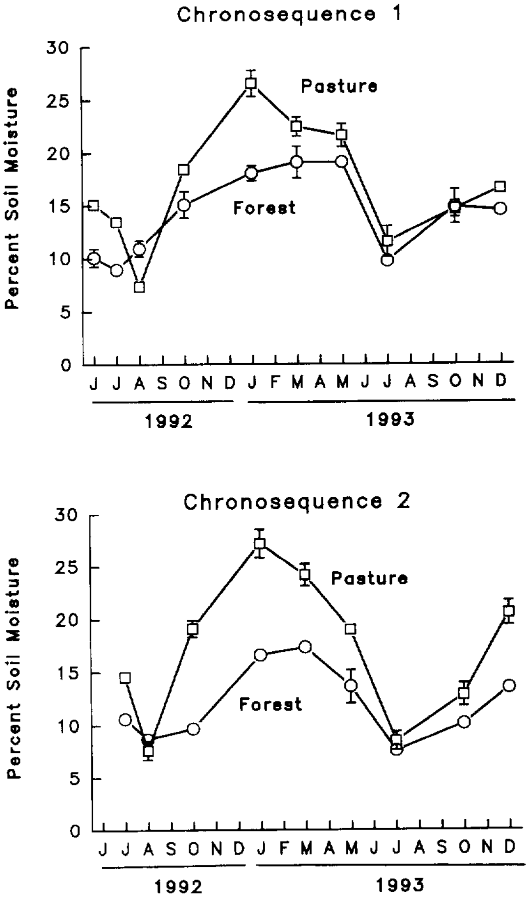

Fig. 2. Percentage gravimetric soil moisture (g H_2O g^{-1} d.s.) collected from forest and pasture soils at 0–5 cm along two chronosequences at Fazenda Nova Vida. There was no significant trend in soil moisture with pasture age and soil moistures for all aged pastures were combined. Pasture values represent the means of seven pastures in Chronosequence 1 and three pastures in Chronosequence 2. Pasture soils were wetter than forest soils during most of the year. Error bars represent ± 1 SE and are not shown when the error is smaller than the symbol.

Soil characteristics

The pH of the upper 10 cm of soil ranged from 4.91 to 5.00 in the forests and 5.12 to 7.14 in the pastures (Table 1). The 6-year-old pastures, cleared in 1987, had the highest pH. Clay content ranged from 14 to 29% (Table 1). The lowest measured soil bulk densities were in the forests (Table 1), but pasture soil densities were generally similar (Table 1). Soil C and N stocks in the upper 10 cm of pastures were generally similar to or greater than the stocks in the original forest (Table 1).

Inorganic-N pools

Forest extractable soil NH_4^+-N pools ranged between 2 and 10 μg N g^{-1} d.s. with a maximum during the dry season in July 1993 (Fig. 3). Forest

Table 1. Soil bulk density, total C and N concentrations at 0–10 cm depth along two chronosequences at Fazenda Nova Vida

Chronosequence	Land use	pH	Clay (%)	Density (g cm^{-3})	C stock (kg m^{-2})	N stock (kg m^{-2})
Chronosequence 1	Forest	4.91	21	1.28 ± 0.04	1.61 ± 0.31	0.138 ± 0.019
	Pasture 1989	6.60	19	1.36 ± 0.06	1.68 ± 0.27	0.121 ± 0.020
	Pasture 1987	7.14	29	1.36 ± 0.04	2.37 ± 0.89	0.180 ± 0.030
	Pasture 1983	5.99	25	1.50 ± 0.06	2.32 ± 0.38	0.174 ± 0.027
	Pasture 1979	6.04	19	1.38 ± 0.05	2.06 ± 0.19	0.134 ± 0.032
	Pasture 1972	5.60	29	1.31 ± 0.06	2.12 ± 0.29	0.147 ± 0.024
	Pasture 1951	5.75	25	1.36 ± 0.07	2.47 ± 0.32	0.176 ± 0.021
	Pasture 1911	5.53	15	1.33 ± 0.04	2.75 ± 0.38	0.211 ± 0.048
Chronosequence 2	Forest	5.00	23	1.22 ± 0.05	1.38 ± 0.29	0.081 ± 0.024
	Pasture 1989	5.12	26	1.30 ± 0.04	1.88 ± 0.35	0.139 ± 0.024
	Pasture 1987	6.28	18	1.29 ± 0.06	2.18 ± 0.74	0.146 ± 0.043
	Pasture 1972	5.93	14	1.28 ± 0.05	2.30 ± 1.05	0.111 ± 0.026

extractable soil NO_3^--N pools generally also ranged between 2 and 10 μg N g^{-1} d.s. with increasing NO_3^- pools during the transition between the wet and dry periods, from January to May (Fig. 3). Pasture soil NH_4^+-N pools showed the same seasonal peak in July (Fig. 3), but pasture soil NO_3^--N pools remained at concentrations 3–7 times lower than forest soil NO_3^- pools throughout the year (Fig. 3).

Land use of forest or pasture had a strong influence on mean annual soil NH_4^+-N and NO_3^--N pools (Table 2). Pasture soils had higher NH_4^+-N pools at 0–5 cm depth compared with forest soils (Table 3). This pattern was present but weaker at the 5–10 cm depth. NO_3^--N pools were higher in forest soils at all depths (Table 3).

Chronosequence had no significant effect on soil inorganic-N pools (Table 2). Depth significantly affected soil NH_4^+-N and NO_3^--N pools (Table 2). Pools were higher at the 0–5 cm depth (Table 3). There was a significant interaction between chronosequence and land use for NO_3^--N pools, but the pattern of lower NO_3^- pools in pasture compared with forest was

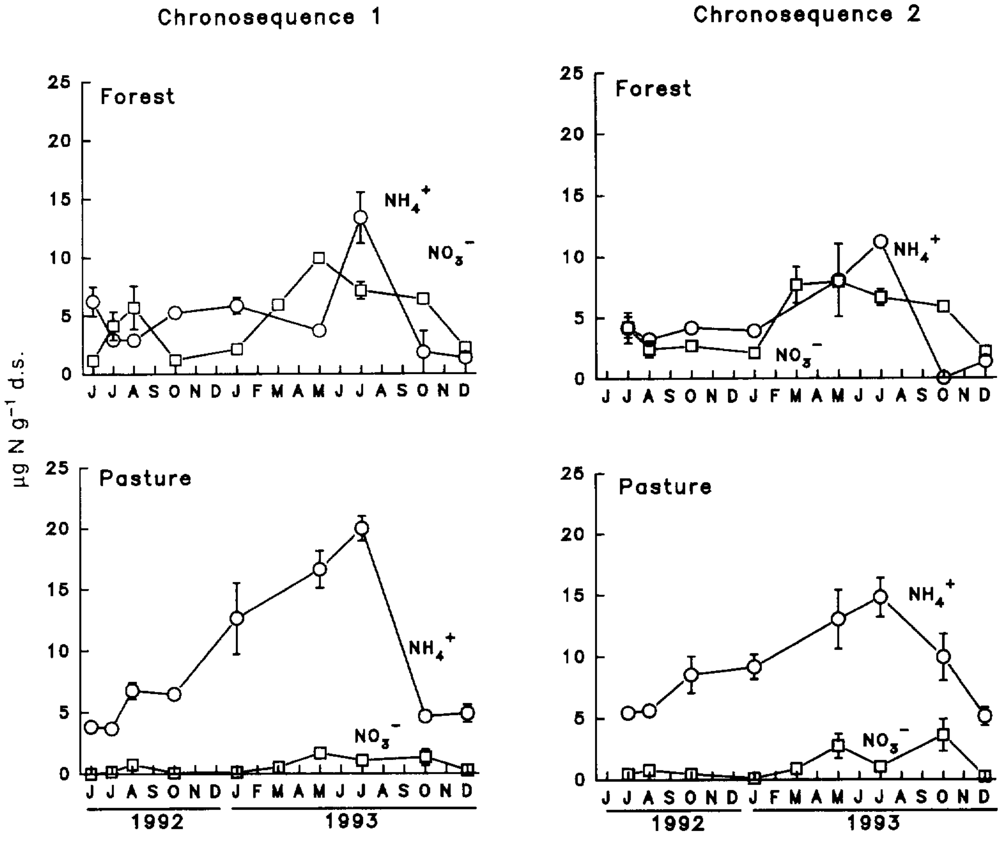

Fig. 3. Seasonal pattern of soil extractable NH_4^+-N and NO_3^--N pools in forest and pasture at 0–5 cm depth along two chronosequences at Fazenda Nova Vida. Pasture values represent the means of seven pastures in Chronosequence 1 and three pastures in Chronosequence 2. Extractable forest soil NO_3^--N pools did not show the same wet season maximum. Pasture soil NO_3^--N pools remained at concentrations from one-third to one-seventh less than forest soil NO_3^--N pools throughout the year. Error bars represent ± 1 SE and are not shown when the error is smaller than the symbol.

Table 2. Effects of chronosequence, forest or pasture land use and depth (0–5, 5–10 cm) on N pools and N transformation rates along two chronosequences at Fazenda Nova Vida. Error *df* are 1038 for NH_4^+ and NO_3^- pools and 592 for net N mineralization and net nitrification rates

		NH_4^+ pool		NO_3^- pool		Mineralization rate		Net nitrification rate	
Source	*df*	*F*	$P \ll$	*F*	$P \ll$	*F*	$P \ll$	*F*	$P \ll$
Chronosequence (C)	1	0.93	NS	0.64	NS	10.64	0.0012	3.43	NS
Land use (L)	1	25.61	0.0001	283.02	0.0001	111.52	0.0001	265.29	0.0001
Depth (D)	1	16.23	0.0001	15.85	0.0001	0.36	NS	31.51	0.0001
C·L	1	0.67	NS	4.85	0.0278	1.52	NS	3.47	NS
C·D	1	0.90	NS	0.21	NS	0.17	NS	1.04	NS
L·D	1	4.27	0.0390	10.13	0.0015	8.29	0.0041	16.40	0.0001
C·L·D	1	0.03	NS	0	NS	0.31	NS	1.40	NS

NS = not significant.

generally similar for both sequences. A land use by depth interaction was significant for both NH_4^+-N and NO_3^--N pools (Table 2). NH_4^+-N pools were similar between depths in the forest but greater at shallower depth in pasture. NO_3^--N pools were greater at the shallower depth in forest soils but not were not different between depths in pasture soils (Table 2).

Pasture age had no consistent effect on NH_4^+-N pools but NO_3^--N pools decreased in older pastures (Fig. 4). A chronosequence by age interaction also indicated that the effects of pasture age on NO_3^--N pools differed between the chronosequences, with pasture age having more influence on NO_3^--N pools in Chronosequence 2 than in Chronosequence 1.

Overall, soil moisture was positively related to NH_4^+-N pools ($F = 20.00$, $P < 0.0001$) but negatively related to NO_3^--N pools ($F = 6.56$, $P < 0.0105$).

Net mineralization and net nitrification rates

Forest soil net N mineralization and net nitrification rates showed little seasonal pattern, although net N mineralization rates were highest in January (Fig. 5). Forest net N mineralization rates ranged between 0 and 3.5 μg N g^{-1} d.s. d^{-1}. Forest net nitrification rates ranged between 0 and 2 μg N g^{-1} d.s. d^{-1}. Pasture soil net N mineralization rates were lower and also showed little seasonal variability (Fig. 5). Pasture soil rates of net nitrification also showed no seasonal trend but always remained near 0 (Fig. 5).

Average annual net N mineralization and net nitrification rates at 0–5 cm depth were higher in the forest than in the pastures (Table 3). Net mineralization and net nitrification rates at 5–10 cm depth showed the same pattern of higher rates in forests (Table 3).

Chronosequence, depth, pasture age and soil moisture all influenced net mineralization and net nitrification rates. Chronosequence significantly affected net N mineralization rate but not net nitrification rate (Table 2). Net N mineralization rates were higher in Chronosequence 2 (Table 3). Over an annual cycle, net mineralization rates were similar between soil depths, but depth affected net nitrification rates (Table 2), which were higher at 0–5 cm. There was an interaction of the effects of depth and land use on both net mineralization and net nitrification rates (Table 2). Rates were higher at 0–5 cm depth in forest soils but not in pasture soils (Table 3). Overall, pasture age was negatively related to net mineralization rate, and the oldest (82-year-old) pasture showed net N immobilization (Fig. 4). Net nitrification rate was not affected by pasture age (Fig. 4). Net N mineralization rates were not correlated with soil moisture, but net nitrification rates were inversely related to soil moisture ($F = 7.80$, $P < 0.005$).

DISCUSSION

Forest net N mineralization and nitrification rates

Rondônia forest soils showed rapid cycling of mineral N. Mean annual net N mineralization and net nitrification rates measured in surface soils (0–5 cm) from both chronosequences fell within the range of ca. 0.5–2.0 μg N g^{-1} d.s. d^{-1} reported by others using both field and laboratory incubations in a variety of tropical forest sites from Mexico to the Brazilian Amazon (Robertson, 1984; Vitousek and Denslow, 1986; Matson *et al.*, 1987; Livingston *et al.*, 1988; Montagnini and Buschbacher, 1989; García-Méndez *et al.*, 1991; Luizão *et al.*, 1992).

Table 3. Mean inorganic-N pools and mean net N mineralization and net nitrification rates from forest and pasture soils along two chronosequences at Fazenda Nova Vida, Rondônia. Pools were collected approximately every 2 months from June 1992 to December 1993. Rates were measured from January to December 1993. Pasture values are the means of seven pastures in Chronosequence 1 and three pastures in Chronosequence 2. Forest values represent one forest in each chronosequence. Different superscript letters for NH_4^+-N or NO_3^--N within each row indicate a significant difference (ANOVA, $P < 0.05$)

		NH_4^+-N pools (μg N g^{-1} d.s.)		NO_3^--N pools (μg N g^{-1} d.s.)		Net N mineralization rate (μg Ng^{-1} d.s. d^{-1})		Net nitrification rate (μg N g^{-1} d.s. d^{-1})	
		Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture
Chronosequence 1	0–5	4.86^a	8.72^b	4.53^a	0.58^b	1.31^a	-0.11^b	1.09^a	0.25^b
	5–10	4.35^a	5.55^a	3.34^a	0.54^b	0.91^a	0.05^b	0.79^a	0.17^b
Chronosequence 2	0–5	4.46^a	9.10^b	4.60^a	1.15^b	1.88^a	0.02^b	1.46^a	0.24^b
	5–10	2.62^a	5.00^b	2.91^a	0.95^b	1.44^a	0.42^b	0.83^a	0.17^b

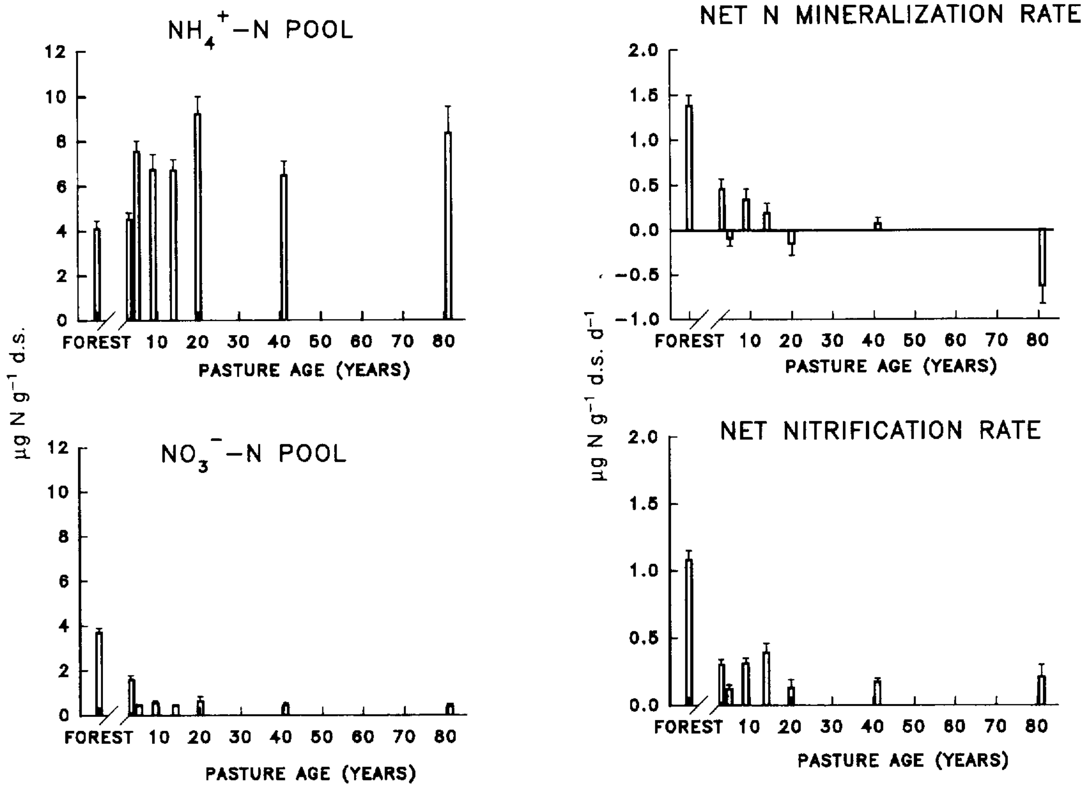

Fig. 4. The effect of pasture age on mean soil extractable NH_4^+-N and NO_3^--N pools and mean net N mineralization and net nitrification rates. For this analysis, similar aged pastures in both chronosequences were combined. Depths 0–5 and 5–10 cm were also combined. Mean NH_4^+-N and NO_3^--N pools for the two forests are shown for comparison. Pools were measured between June 1992 and December 1993; rates were measured from January to December 1993. Pasture age was correlated with soil NO_3^--N pools ($F = 9.68$, $P < 0.0019$) and net N mineralization rate ($F = 40.71$, $P < 0.0001$), but not related to NH_4^+-N pools or net nitrification rate. Error bars represent ±1 SE.

Mean annual net nitrification rates for the Rondônia forests of 1.09–1.46 µg N g^{-1} d.s. d^{-1} were similar to but slightly higher than rates measured at other moist tropical forest sites. Luizão *et al.* (1992) measured a mean annual nitrification rate of 0.6 µg N g^{-1} d.s. d^{-1} from Amazon Basin forest at Manaus. In Costa Rica, Matson *et al.* (1987) found nitrification rates lower than 1 µg N g^{-1} d.s. d^{-1} and Reiners *et al.* (1994) reported net nitrification rates of ca. 2 µg N g^{-1} d.s. d^{-1}. On Oxisols and Ultisols at Rio Negro in Venezuela, Montagnini and Buschbacher (1989) measured net nitrification rates of 0.1–0.5 µg N g^{-1} d.s. d^{-1}. Livingston *et al.* (1988) found higher rates on ridge and slope soils in Brazil, also near Manaus, but the data were from a single sampling.

Mineral-N pools and net N mineralization rates in tropical forest soils are often relatively aseasonal, despite large temporal variation of precipitation and soil moisture (Vitousek and Denslow, 1986; Matson *et al.*, 1987; Steudler *et al.*, 1991). Our data from Rondônia, which experiences a 3–4 month dry season, are consistent with this pattern. Our data showed a dry season maximum of NH_4^+-N and NO_3^--N pools similar to that found by García-Méndez *et al.* (1991) in a highly seasonal dry tropical forest in Mexico. In contrast, the wetter and less seasonal environment of Manaus in the Brazilian Amazon had generally higher N pools during the wet season but showed another local maximum at the end of the dry season (Luizão *et al.*, 1992). The highest net mineralization and net nitrification rates at Manaus occurred near the end of the wet season (Luizão *et al.*, 1992).

Soil moisture may be an important controller of soil inorganic-N pools and N transformation rates leading to the availability of NO_3^-, but the relationship may be complex and mediated by the balance between net N mineralization and N immobilization as soil microorganisms respond to soil wetting and drying. Luizão *et al.* (1992) hypothesized that wetting induces net immobilization, as inputs of labile C with high C-to-N ratios fuel rapid microbial growth, and dry periods favor net mineralization because the only soil organic matter that has sufficient water to allow decomposition is clay associated organic matter with a low C-to-N ratio. Because our data represents net N mineralization, it does not allow us to evaluate these potentially interesting mineralization–immobilization relationships.

Net nitrification rates decreased with increased soil moisture, probably related to decreased O_2 availability at higher soil moistures. Lower rates of net nitrification with increasing soil moisture have been observed in other seasonal tropical forest systems (Steudler *et al.*, 1991; García-Méndez *et al.*, 1991).

Conversion of forest to pasture

Deforestation and conversion of land to pasture agriculture changed the distribution of soil inorganic-N pools from relatively equal parts of NH_4^+-N and NO_3^--N in natural forest to predominantly NH_4^+-N in pasture soils. Matson *et al.* (1990) and Luizão *et al.* (1992) both working near Manaus in Brazil and Reiners *et al.* (1994) in Costa Rica reported similar changes following forest conversion to pasture.

We observed lower mean annual net N mineralization and net nitrification rates in established pasture compared with intact forest. Despite the enormous scale of pasture creation in the Amazon Basin, there are few comparable measurements of changes to soil cycling rates. Reiners *et al.* (1994) found lower rates of net N mineralization and net nitrification in 10 to 36-year-old active pastures in Costa Rica, compared with the original forest. In contrast, no differences of net mineralization and net nitrification rates between forest and pasture land use were found near Manaus by Matson *et al.* (1990) and Luizão *et al.* (1992). Matson *et al.* (1990) measured net mineralization and net nitrification rates of ca. 1 μg N g^{-1} d.s. d^{-1} during one period at the height of the wet season in a fertilized 3-year-old pasture. Net N mineralization was -0.1 μg N g^{-1} d.s. d^{-1} in the 1-year-old pasture examined by Luizão *et al.* (1992) over an annual cycle, compared with an annual mean of 0.4 μg N g^{-1} d.s. d^{-1} in forest, but very high variability which ranged from high net mineralization to substantial net immobilization resulted in insignificant differences between land uses. The mean annual net nitrification rate of 0.6 μg N g^{-1} d.s. d^{-1} recorded by Luizão *et al.* (1992) for forest was lower than we found for Rondônia, while the average annual pasture net nitrification rate of 0.5 μg N g^{-1} d.s. d^{-1} was higher than we measured. A different trend of higher net N mineralization and net nitrification rates in 3-year-old pasture compared with forest were found by Montagnini and Buschbacher (1989) in southwestern Venezuela. Net N mineralization and net nitrification rates measured by Montagnini and Buschbacher were similar in magnitude to those measured near Manaus and in our study, and in the range of 0–0.3 μg N g^{-1} d.s. d^{-1} for net mineralization and 0.1–0.4 μg N g^{-1} d.s. d^{-1} for net nitrification.

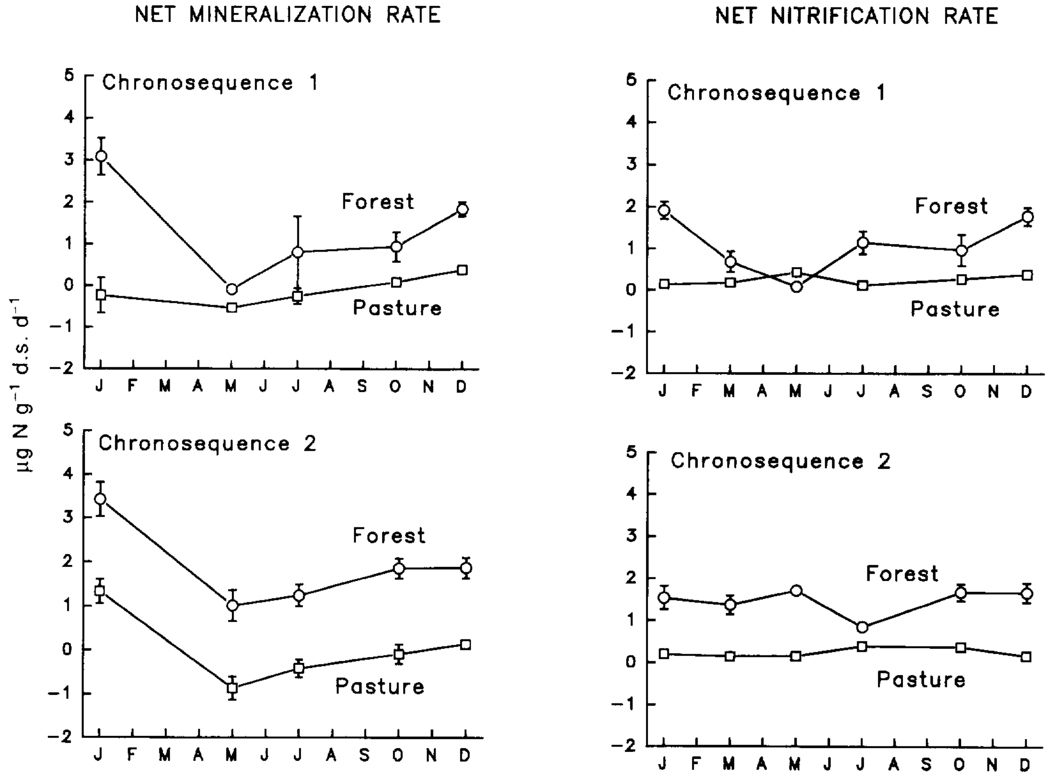

Fig. 5. Seasonal patterns of net N mineralization rate and net nitrification rate from 0–5 cm depth along two chronosequences at Fazenda Nova Vida during 1993. There was no clear seasonal trend in net nitrification rate in both forest and pasture soils, although forest net N mineralization rates were highest during January for both chronosequences. Rates of net nitrification in the pasture always remained near zero. Error bars represent ± 1 SE and are not shown when the error is smaller than the symbol.

In many forest ecosystems, the pulse input of biomass-N caused by cutting and burning of tropical forest increases soil NO_3^- concentrations, net N mineralization and net nitrification rates, and leaching NO_3^- losses (Bormann *et al.*, 1974; Matson and Vitousek, 1981). Similar increases were measured in cut or cut-and-burned tropical forests (Uhl and Jordan, 1984; Matson *et al.*, 1987; Montagnini and Buschbacher, 1989; Steudler *et al.*, 1991). The time after burning during which N cycling rates remain elevated varies from several months (Matson *et al.*, 1987; Vitousek and Matson, 1988) to 2–3 years (Uhl and Jordan, 1984; Montagnini and Buschbacher, 1989). Near Manaus, rates of net N mineralization and nitrification rates were not elevated compared with the original forest in a 6-month-old slash-and-burn site (Matson *et al.*, 1990) and a slash-and-burn site where sampling was initiated 2 months after burning (Luizão *et al.*, 1992). Because the youngest pastures we examined were 3–4 years old, our data did not capture possible shorter-term changes in NO_3^--N availability or net N mineralization and net nitrification rates that might occur immediately following forest conversion to pasture, but our data show that any increases in N transformation rates that may have occurred following forest cutting were no longer apparent after 4 years in pasture.

The decrease in net N mineralization and net nitrification rates that we measured between intact moist tropical forest and pastures 4 years old or older occurred despite greater total C and N stocks in older pastures. This could be caused by a general slowing down of N cycling rates as pastures age, or greater N immobilization in pasture compared with forest soils. C input to soil from pasture grass roots can be an important source of soil organic matter in tropical pastures (Fisher *et al.*, 1994). If immobilization is fueled by inputs to the soil of C from pasture plant roots, the timing of a 7-day laboratory measure of potential net N mineralization may not be appropriate to capture the N that is immobilized upon soil collection and sample preparation. Experiments with labeled N designed to measure gross N mineralization rates in pasture soils or to trace added N into microbial biomass would aid in interpretation of potential net N mineralization rates.

Ecosystem implications of net mineralization and net nitrification rates

Our finding of significant rates of net nitrification in the acidic soils of intact moist tropical forest has important implications for both land–water and land–atmosphere interactions and our understanding of the consequences of tropical land use change. Changes in patterns and rates of N cycling following conversion of tropical forest to pasture are of considerable importance to regional N cycles because of the explosive growth in total pasture area in Rondônia and other areas of the Amazon Basin.

High soil NO_3^- pools and nitrification rates in intact moist forest suggest that the potential for N losses from regional *terra firme* forests may be considerable. NO_3^- concentrations in the Amazon River suggest that forest soil nitrification may be an important source of NO_3^- on the scale of the entire Basin because the mass of NO_3^- leaving the Amazon River at the mouth exceeds inputs to the Basin by about 30% on an annual basis (Martinelli *et al.*, 1992), implying an internal source. Martinelli *et al.* (1992) provide evidence that N_2 fixation by floodplain (várzea) vegetation and subsequent nitrification in the floodplain may be a component of this input. Our findings of high rates of net nitrification in *terra firme* forests suggest that nitrification in intact Basin forests could also play an important role as a Basin-wide NO_3^- source.

N transformation rates, through the processes of nitrification and denitrification, are also linked to emissions of the greenhouse gas N_2O. Nitrification in both forest and pastures suggests gaseous N_2O losses could occur during both nitrification and denitrification. The finding of lower rates of net nitrification in soils of pastures compared with the original forest raises the interesting possibility that the severe disturbance of conversion of forest to pasture decreases the potential for N loss from established pastures. Several studies have identified increased N_2O losses with the disturbance associated with forest cutting and natural disturbances such as hurricanes, at least in the short term (Keller *et al.*, 1986, 1993; Matson *et al.*, 1987; Luizão *et al.*, 1989; Steudler *et al.*, 1991). Measured fluxes of N_2O from older pastures, however, can be lower than from the original forest (Keller *et al.*, 1993). Our data suggest that lower rates of net nitrification from pastures could result in lower emissions of N_2O from established pastures of 4 years or older.

The overall effect of forest clearing for pasture on N losses as NO_3^- and gaseous N_2O emissions will depend on: (1) direction and magnitude of the changes to soil N dynamics in the first 2–3 years following forest cutting and pasture establishment, and (2) the length of time land remains used as pasture. If net N mineralization and net nitrification rates immediately following deforestation are high, the early losses may balance reduction of losses that result from decreased net mineralization and net nitrification rates in pastures aged 4 years or older. Persistence of pastures over the long term and increasing total area of older pastures would appear to decrease net nitrification rates and decrease the overall potential for N losses.

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