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Response of Soil Inorganic Nitrogen to Land Use and Topographic Position in the Cofre de Perote Volcano (Mexico)

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Abstract This study addressed the effects of land use and slope position on soil inorganic nitrogen and was conducted in small watersheds. The study covered three land use types: tropical cloud forest, grassland, and coffee crop. To conduct this research, typical slope small watersheds were chosen in each land use type. Slopes were divided into three positions: shoulder, backslope, and footslope. At the center of each slope position, soil sampling was carried out. Soil inorganic nitrogen was measured monthly during a period of 14 months (July 2005–August 2006) with 11 observations. Significant differences in soil NH_4^+–N and NO_3^-–N content were detected for both land use and sampling date effects, as well as for interactions. A significant slope position-by-sampling date interaction was found only in coffee crop for NO_3^-–N content. In tropical cloud forest and grassland, high soil NH_4^+–N and low NO_3^-–N content were recorded, while soil NO_3^-–N content was high in coffee crop. Low NO_3^-–N contents could mean a substantial microbial assimilation of NO_3^-–N, constituting an important mechanism for nitrogen retention. Across the entire land use set, the relationship between soil temperature and soil inorganic N concentration was described by an exponential decay function ($N = 33 + 2459\exp^{-0.23T}$, $R^2 = 0.44$, $P < 0.0001$). This study also showed that together, soil temperature and gravimetric soil water content explained more variation in soil inorganic N concentration than gravimetric soil water content alone.

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Introduction

In terrestrial ecosystems, N availability is often a limiting factor that controls primary production (Vitousek and Howarth 1991), C storage (Shaver and others 1998), and N trace gas emissions (Davidson and others 1993). As the most limiting nutrient element in many forest ecosystems, N availability constrains ecosystem productivity (Reich and others 2006) and affects the biogeochemical cycles of other elements, mainly through the process of litter decomposition (Lin and others 2006). Soil is the primary and most immediate N pool for plants and microbes in forested ecosystems. In these ecosystems, litter dynamics constitute an important aspect of nutrient cycling and energy transfer, with the growth and productivity of forest ecosystems depending mainly on the amount, nature, and rate of forest litter decomposition (Lin and others 2006). Nitrogen mineralization rates and the total quantity of soil N are two important indicators of N availability, because they directly control soil NH_4^+–N and NO_3^-–N concentrations and the availability of inorganic N to plants (Owen and others 2003). However, soil nitrogen mineralization is considered to be particularly sensitive to changes in environmental conditions because of the small guild of microorganisms involved and the impact of soil chemistry, especially pH, on mineralization rates (Hayatsu and others 2008). Given the importance of soil inorganic nitrogen to earth system processes, quantification of its spatial-temporal behavior is receiving increased attention from the scale of agricultural fields and small watersheds to the global scale (Murty and others 2002; Soon and Malhi 2005).

Nitrogen mineralization is highly dependent on environmental conditions (Wang and others 2006). Some studies have shown that net N mineralization rates are positively correlated with seasonal temperature fluctuation but are less sensitive to soil water content (Sierra 1997). In contrast, results from other studies indicate that soil moisture is more important than soil temperature in regulating net N transformation rates (Owen and others 2003; Isaac and Timmer 2007). Variations in landscape features can result in differences in soil properties (Brubaker and others 1993), which can, in turn, affect patterns of soil organic matter distribution and litter production/decomposition. Many hydrological, and therefore soil-related, processes are associated with topographic attributes such as elevation, slope, and aspect (Martin and Timmer 2006). Landform segmentation enables rapid quantification and spatial analysis of the relationships, which can then be utilized for partitioning variability and ultimately predicting soil or other ecosystem properties. Segmentation procedures have been used to examine soil–landform relationships in several land uses and types, including agricultural systems (Norton and others 2003), grassland (Landi and others 2004), and forest plantations (Thwaites and Slater 2000). Integrated and simple comparison methods of soil inorganic nitrogen dynamics under different land use and slope position should be undertaken (Fu and others 2004). Land use change plays a very important role in regulating soil N mineralization and availability by altering soil biological, physical, and chemical properties. However, effects of land use on soil N mineralization still remain controversial (Wang and others 2006). In different land use scenarios, there have been reports of an increase (Frank and Groffman 1998; Frank and other 2000), decrease (Andersson and other 2002), and lack of changes (Goodale and Aber 2001). On this topic, Stark and Hart (1997) mention that the importance of NO_3^-–N in the internal nitrogen cycle of undisturbed ecosystems has not been widely recognized. Microbial immobilization of NO_3^-–N has been discounted as a significant process controlling NO_3^-–N pool sizes and as a nitrogen retention mechanism that results from disturbance in forest ecosystems (Stark and Hart 1997; Booth and others 2005; Booth and others 2006).

In Mexico, tropical cloud forest is the most diverse type of vegetation: it covers less than 1% of the country but contains approximately 10% of the plant species that grow preferentially or exclusively in this type of forest (Rzedowski 1996). Eighteen percent of the plant species are trees, more than 30% are epiphytes, and around 20% are ferns (Rzedowski 1996). In tropical cloud forest, most canopy trees are deciduous, whereas the understory is composed of small broadleaved evergreen trees and shrubs (Williams-Linera 2003). All forests in the humid tropics that are frequently covered by clouds or mist are considered cloud forests (Bubb and others 2004). Tropical cloud forests are unique among terrestrial ecosystems for their exceptional concentrations of biodiversity and as sources of freshwater due to the fact that they are strongly linked to regular cycles of cloud formation (Still and others 1999). One of the most significant characteristics of tropical cloud forests is their ability to strip water from wind-blown fog and clouds through contact with soil and vegetation surfaces, thus adding to the water supplies available downstream (Bubb and others 2004). Tropical cloud forests control the quality and natural flow regime of the streams and rivers emanating from them (Still and others 1999). On continental mountains, tropical cloud forests are typically found between 500 and 3500 m above sea level, with more frequent occurrence at altitudes of 1200–2500 m (Hamilton and others 1994). Due to the fact that tropical cloud forest occurs on a wide range of elevations, there is no soil type that characterizes them. In general, soils remain wet and have a high organic matter content, giving them a high infiltration capacity and nutrient budgets (Hamilton and others 1994).

Tropical cloud forests are highly vulnerable to anthropogenic pressure and climate change (Bruijnzeel and Hamilton 2000; Bubb and others 2004). The greatest loss of tropical cloud forests is due to conversion to grassland, subsistence crops, and commercial crops such as coffee (Still and others 1999). The conservation status of these unique ecosystems is precarious, as they are among the most endangered of all tropical forest types (Still and others 1999). Drastic changes in land use have occurred in the eastern region of Mexico, where during the last 30 years more than 70% of the tropical cloud forest of central Veracruz has been converted to cropland and grassland (Rzedowski 1978; Williams-Linera 1992). Land use changes and landscape features can influence many natural phenomena and ecological processes (Fu and others 2004) including soil inorganic N dynamics, soil temperature, and soil water content interactions. Compared to almost all other major forest ecosystems, tropical cloud forests have been the subject of little research and even less long-term monitoring (Bubb and others 2004). Knowledge of how tropical cloud forest soils function remains limited despite the fact that it is critical to their effective management and long-term conservation. Soil organic nitrogen, the primary source of nitrogen to plants, is mineralized during the microbial oxidation of soil organic material. Thus, an understanding of soil inorganic nitrogen dynamics and their interactions with topographic position and land use are necessary for rational resource evaluation and planning as well as for proper management and conservation of the soil resource. The hypothesis, then, is that soil inorganic nitrogen dynamics are affected by topographic position, land use, and environmental variations such as soil temperature and water conditions.

The purpose of the study was twofold: (a) to quantify soil inorganic nitrogen variability resulting from land use by means of monitoring over time, and (b) to understand the relative role of topographic and soil environmental factors in controlling soil inorganic nitrogen. This research was part of a larger study carried out between 2005 and 2007 regarding anthropic disturbance, land use, water quality, ecosystem structure, and species composition and functions in the tropical cloud forest habitat.

Materials and Methods

Study Sites

This study was conducted on typical slopes of small watersheds found on the middle and slightly lower part of the eastern slope of the Cofre de Perote Volcano (Fig. 1). The characteristics of the small watersheds in the study area are provided in Table 1. In this region, the remaining tropical cloud forests are fragments of forest in grasslands and coffee crop landscapes (Williams-Linera 2003). Each watershed includes a small perennial stream fed by baseflow. The study covered three land use types: native vegetation, grassland, and coffee crop. Two adjacent small watersheds, covered with tropical cloud forest that represents native vegetation, were used for this project (Fig. 1). The best-represented arboreal species in this tropical cloud forest (Castillo-Campos 1991) are Platanus mexicana Moric., *Carpinus caroliniana* Walter, *Clethra mexicana* DC., *Quercus xalapensis* Bonpl., *Liquidambar macrophylla* Oerst., *Ulmus mexicana* (Liebm.) Planch., *Quercus germana* Schltdl. & Cham., *Eugenia xalapensis* (Kunth) DC., *Ostrya virginiana* (Mill.) K. Koch, *Turpinia insignis* (Kunth) Tul., *Ilex tolucana* Hemsl., *Meliosma alba* (Schltdl.) Walp., *Styrax glabrescens* Benth., *Quercus leiophylla* A. DC., and *Podocarpus matudae* Lundell. The most common tree fern species are *Alsophila firma* (Baker) D. S. Conant, *Lophosoria quadripinnata* (J. F. Gmel.) C. Chr., and *Sphaeropteris horrida* (Liebm.) R. M. Tryon (Bernabe and others 1999). The climate is humid subtropical with frequent fog, mainly during autumn and

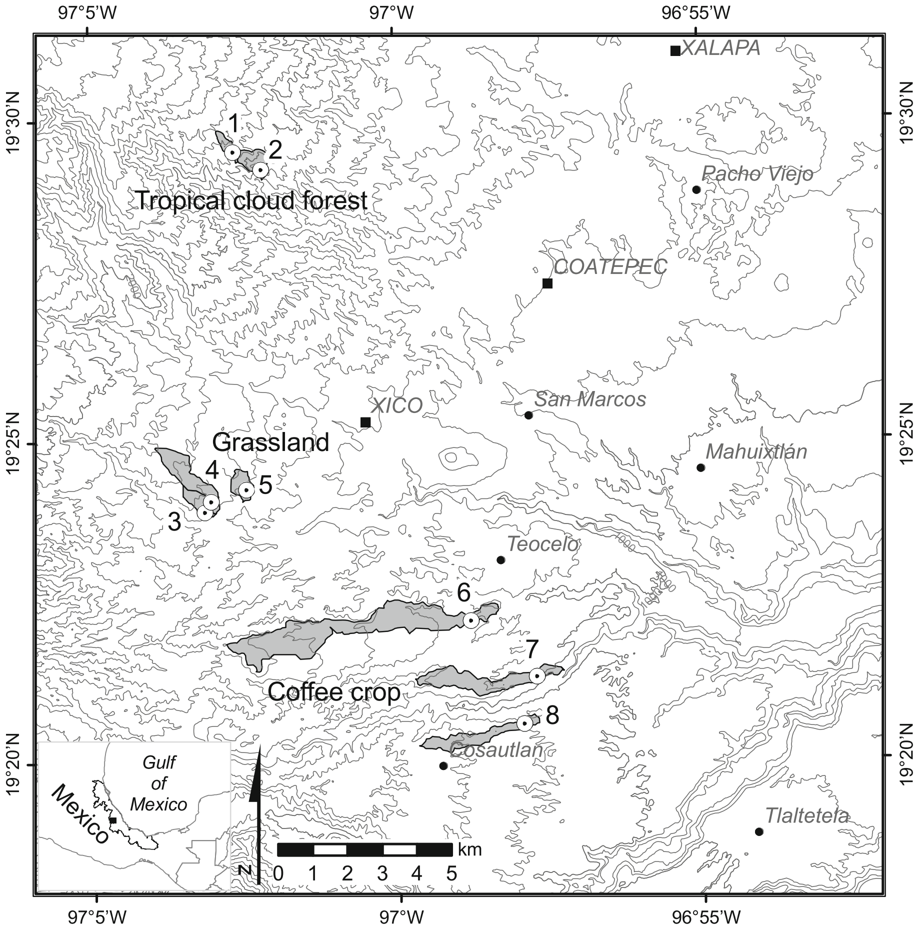

Fig. 1 Location map of the study site

Table 1 Characteristics of the small watersheds in the study area

Land use	Watersheds		Latitude	Longitude	Altitude (m. a. s. l.)	Mean temperature (°C)[b]	Annual rainfall (mm)[b]	Slope (deg)	Soil type
	Site number[a]	Size (ha)							
Tropical Cloud Forest	1	24.7	19°29′28″N	97°02′24″W	2169	15	2830	21	Histic umbric
	2	52.8	19°29′36″N	97°02′41″W	2059	15	2830	20	Andosol
Grassland	3	32	19°23′54″N	97°03′04″W	1474	16.1	2710	14	Umbric
	4	118	19°24′05″N	97°03′06″W	1533	16.1	2710	12	Andosol
	5	41	19°24′17″N	97°02′31″W	1480	16.1	2710	13	
Coffee Crop	6	380	19°22′09″N	96°58′50″W	1125	23	1700	10	Ferric
	7	177	19°22′12″N	96°58′22″W	1089	23	1700	12	Acrisol
	8	80	19°20′29″N	96°58′27″W	1147	23	1700	9	

[a] From map of the Fig. 1

[b] From Muñoz-Villers and Equihua 2007

winter. Soils are derived from volcanic ash and are classified as histic umbric Andosols (IUSS 2006).

Three adjacent small watersheds covered with grasslands were selected for study (Fig. 1; Table 1). The general environmental conditions that prevail in these sites are similar to those of tropical cloud forest; however, at this altitude vast areas of native vegetation have been replaced by grasslands. Grassland is a grazed mixed-grass prairie dominated by *Pennisetum clandestinum* Hochst. ex Chiov., *Paspalum notatum* Flüggé, and *Cynodon dactylon* (L.) Pers.; it maintains cattle throughout the year and has a stocking rate of 1.0 animal unit per hectare (Hoffmann 1993). Inorganic fertilizer is not applied to grassland. Soils are derived from volcanic ash and are classified as umbric Andosols (IUSS 2006).

Three adjacent small watersheds covered with coffee crop were selected for this project (Fig. 1; Table 1). Here, coffee (*Coffea arabiga* L.) crop covers most of the landscape; this is the area on the study site that has been used for agricultural activity for the longest time. The climate is tropical. For coffee crop, the following is applied three times a year (in January, June, and September): 144 kg N ha^{-1}, 42 kg P ha^{-1}, and 40 kg K ha^{-1} in the form of urea, triple superphosphate, and potassium chloride, respectively. Soils are derived from volcanic ash and are classified as ferric Acrisols (IUSS 2006).

Sampling and Measurements

To conduct this research, three typical slopes in the two small watersheds were chosen for each land use. In tropical cloud forest, slopes have a gradient of 40°, 25°, and 20° and a length of 194, 254, and 105 m, respectively. In grassland, slopes have a gradient of 20°, 28°, and 13° and a length of 70, 140, and 250 m, respectively. In coffee crop, slopes have a gradient of 20°, 8°, and 12° and a length of 110, 130, and 140 m, respectively. Slopes were divided into three positions according to their topography: shoulder (SH), backslope (BS), and footslope (FS). All slope transects extended to baseflow. At the center of each slope position, soil was sampled. The study was carried out over a period of 14 months with 11 observations from July 2005 to August 2006. Measurements of soil inorganic N concentration were made once mid-month during the entire research period. To determine soil inorganic N concentration, soil samples were taken in triplicate to a 10 cm depth between 10:00–13:00 h, approximately. Soil samples, field moist, were stored at −4°C until analysis. On each sampling date, measurements were taken of soil temperature in triplicate with a thermometer and soil water content to a 10 cm depth. Soil water was determined gravimetrically after core samples had been oven dried at 105°C for 24 h. Volumetric water content was derived using bulk density.

To determine inorganic N content, soil was extracted for 1 h with 2 M KCl (1:10 w/v soil:solution ratio) in a reciprocating shaker at 180 reciprocations per min. After shaking, samples were centrifuged (4 min; 3500 rev min^{-1}) and the supernatant filtered through Ahlstrom 94 paper. The soil extract was treated with 0.2 g MgO and Devarda alloy and immediately taken for steam distillation. NH_4^+ and NO_3^- were determined in the distillate by titration with 0.005 M H_2SO_4 (Bremner 1965). Soil water content was determined simultaneously with extraction in order to calculate the dry weight of the extracted soil. Ammonium and nitrate values (mg kg^{-1}) were converted to kg ha^{-1} using soil bulk density.

As complementary measurements to characterize topsoil, three soil samples (10 cm depth) were collected from each experimental site and analyzed using conventional procedures (Carter 1993). Soil samples for chemical analyses were air dried and ground to pass through a 2 mm sieve. Soil pH was measured from a saturated paste mixture (1:2 ratio of soil to H_2O). Organic carbon was determined by the wet oxidation method and total nitrogen by the micro Kjeldahl digestion procedure. Exchangeable bases were extracted with 1 M NH_4OAc (pH 7); Ca and Mg in the extracts were measured by AAS, while Na and K were estimated by flame photometry. Exchangeable aluminum (Al) was determined by leaching the soil with 1 M KCl and titrating aliquots with 0.01 M NaOH. Extractable P was determined by the Bray and Kurtz 1 method. Bulk density was determined using the soil core method.

Experimental Design and Data Analyses

The experimental design was repeated measurements. Treatments consisted of three land use types (tropical cloud forest, coffee crop, and grassland) and three slope positions (shoulder, backslope, and footslope) for each land use. Soil inorganic N concentration was measured on 11 occasions to detect treatment effects. Three typical slopes chosen for each land use type were used as replicates. To analyze the effects of land use types and sampling dates on soil inorganic N content, a repeated measures GLM (general linear model) was used. To analyze the effects of slope position for each land use type and sampling date on soil inorganic N content, repeated measures GLM was also used. Measurements taken repeatedly within of same experimental unit were averaged prior to statistical analysis to prevent pseudo-replication. All statistical analysis was done using SAS (2000). Differences between treatments were considered significant at $P \leq 0.05$.

Results and Discussion

Topsoil Properties and Environmental Conditions

The major topsoil properties of study sites are given in Table 2. There was no significant difference between slope positions within each land use type. Overall, tropical cloud forest was more acidic and contained more carbon, nitrogen, potassium, and phosphorus than grassland and coffee crop. Average bulk density was 5 and 6.8 times greater in the grassland and coffee crop than in the tropical cloud forest, respectively. In contrast, average exchangeable aluminum (Al) was 2.3 and 3 times greater in the tropical cloud forest than in grassland and coffee crop, respectively.

Figure 2a and b show monthly soil temperature and soil water content for each land use during the research period. Soil temperature was higher in spring and summer and

Table 2 Means and standard errors (in parentheses) of main topsoil characteristics at the study sites ($n = 3$)

Site/slope position	pH	C (%)	N (%)	C/N	Ca ($cmol_c$ kg^{-1})	Mg ($cmol_c$ kg^{-1})	K ($cmol_c$ kg^{-1})	Na ($cmol_c$ kg^{-1})	Al ($cmol_c$ kg^{-1})	P (mg kg^{-1})	BD (g cm^{-3})
Tropical cloud forest											
Shoulder	3.4 (0.2)	26.7 (2.6)	2.0 (0.1)	13.2 (0.7)	11.6 (6.1)	2.2 (0.5)	1.0 (0.04)	0.18 (0.02)	3.8 (1.3)	102 (29)	0.14 (0.01)
Backslope	3.5 (0.1)	31.6 (1.2)	2.1 (0.2)	15.2 (2.0)	12.5 (4.5)	3.3 (0.6)	1.4 (0.2)	0.38 (0.06)	2.5 (0.9)	106 (22)	0.11 (0.03)
Footslope	3.6 (0.2)	26.4 (2.6)	1.9 (0.2)	13.8 (0.3)	5.9 (4.2)	1.9 (1.0)	1.8 (0.8)	0.33 (0.18)	4.0 (1.4)	121 (61)	0.13 (0.01)
Grassland											
Shoulder	4.3 (0.3)	10.6 (0.7)	0.7 (0.1)	19.3 (7.9)	2.7 (0.7)	1.1 (0.4)	0.6 (0.2)	0.27 (0.2)	1.7 (0.6)	0.2 (0.1)	0.65 (0.03)
Backslope	4.4 (0.4)	9.2 (1.2)	0.7 (0.1)	13.8 (3.3)	2.8 (0.9)	1.2 (0.3)	0.5 (0.2)	0.02 (0.02)	1.7 (0.9)	0.1 (0.06)	0.60 (0.03)
Footslope	4.4 (0.2)	9.3 (0.7)	0.8 (0.1)	11.2 (1.0)	3.4 (0.7)	1.3 (0.06)	0.7 (0.2)	0.03 (0.03)	1.0 (0.1)	0.4 (0.1)	0.56 (0.06)
Coffee crop											
Shoulder	4.4 (0.6)	5.3 (1.6)	0.6 (0.1)	9.0 (2.6)	5.5 (2.6)	3.0 (1.7)	0.9 (0.5)	0.19 (0.1)	1.6 (0.7)	2.1 (1.2)	0.76 (0.1)
Backslope	4.9 (0.3)	4.5 (1.4)	0.4 (0.1)	10.5 (1.4)	5.8 (2.1)	4.9 (2.4)	0.4 (0.1)	0.09 (0.05)	0.6 (0.4)	1.1 (0.8)	0.83 (0.01)
Footslope	4.8 (0.8)	5.8 (1.6)	0.5 (0.08)	10.0 (1.7)	7.8 (3.4)	3.6 (2.1)	0.7 (0.2)	0.15 (0.07)	1.2 (0.5)	13.2 (10)	0.87 (0.09)

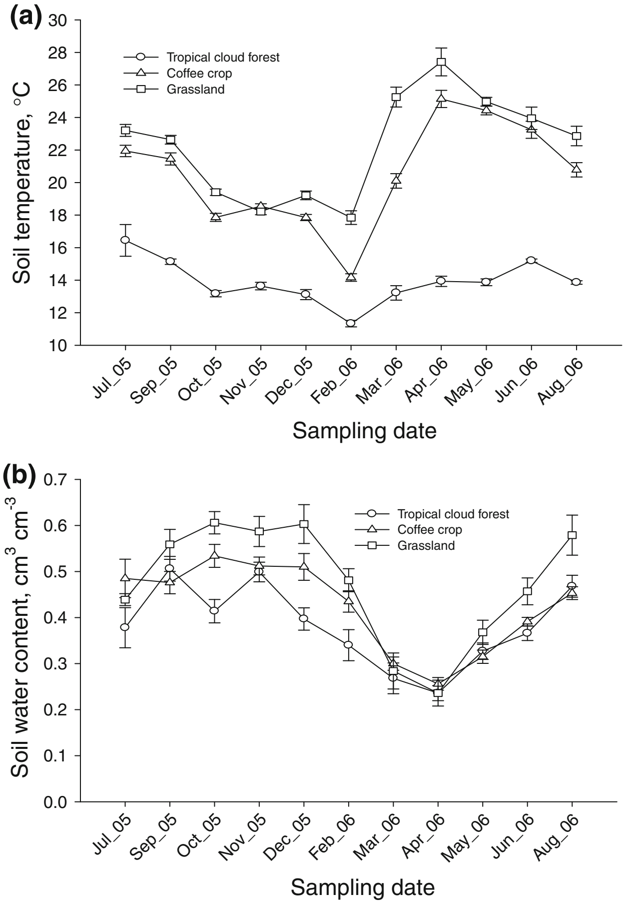

Fig. 2 Seasonal soil temperature (**a**) and water content (**b**) variation during the July 2005–August 2006 period at the three study sites. *Vertical bars* indicate standard error of the mean

decreased progressively from autumn to winter, peaking in February. In tropical cloud forest, soil temperature changed little during the research period, revealing a response to tree biomass. In the case of soil water content, this was higher in summer and autumn, during which time it began to decline, reaching its lowest level in April.

Repeated measures analysis showed a significant land use-by-sampling date interaction for separate analyses of soil temperature and soil water content (Table 3). A significant interaction between land use and sampling date means that the effect of sampling date on soil temperature and soil water content depends on land use type.

Soil Inorganic N Content in Response to Land Use

The dominant inorganic N form varied with land use. In tropical cloud forest (Fig. 3a), the highest soil NH_4^+–N content was observed at the end of autumn, with a peak in December followed by a decrease in winter and a gradual increase starting in early spring with a peak in May. This coincides with the transition from dry to wet seasons, when soil water content increases. The marked increase in soil NH_4^+–N content at the end of autumn and early spring may result from the high nutrient concentrations and low C:N ratio of tropical cloud forest litter (Table 2), coupled with high soil water availability and adequate soil temperature conditions for microbial activity. Kirschbaum (2006) mentions that in many systems, litter fall occurs primarily in autumn, so that substrate availability is higher in autumn and winter and counteracts the unfavorable temperature at this time of year. On the other hand, as can be seen in Fig. 3a, the soil NO_3^-–N content changed little during the research period, peaking in July, when soil water content began to rise and soil temperature was higher. The higher NH_4^+–N than NO_3^-–N contents recorded in tropical cloud forest were attributed to litter layers that, according to Schlesinger (1997), produce high concentrations of ammonium during the decomposition process. In contrast, nitrification is frequently inhibited in low pH soils (Schlesinger 1997). In the case of grassland (Fig. 3b), the seasonal pattern of NH_4^+–N content was characterized by a high level in the summer, when soil temperature and soil water content were relatively high, as well as in the autumn, when soil water content was high and soil temperature started to drop, peaking in June, July, and December. Neill and others (1997) and Fang and others (2007) also found that NH_4^+–N was the dominant form in unmanaged pastures and prairie, respectively. Soil NO_3^-–N content changed little during the research period, showing higher peaks in June and July, when soil temperature and water content were high. In coffee crop (Fig. 3c),

Table 3 Repeated measures analysis of variance of soil temperature and soil water content by land use and sampling date

Source of variation	Soil temperature				Soil water content			
	DF	MS	F	*P* value	DF	MS	F	*P* value
Replication	8	10.3			8	0.06		
Land use	2	1926.5	473.2	<0.001	2	0.20	8.5	0.003
Sampling date	10	151.7	159.6	<0.001	10	0.27	62.1	<0.001
Land use × sampling date	20	24.9	22.7	<0.001	20	0.01	4.7	<0.001
Residual	160	1.1			160	0.003		
Total	296	21.1			296	0.01		

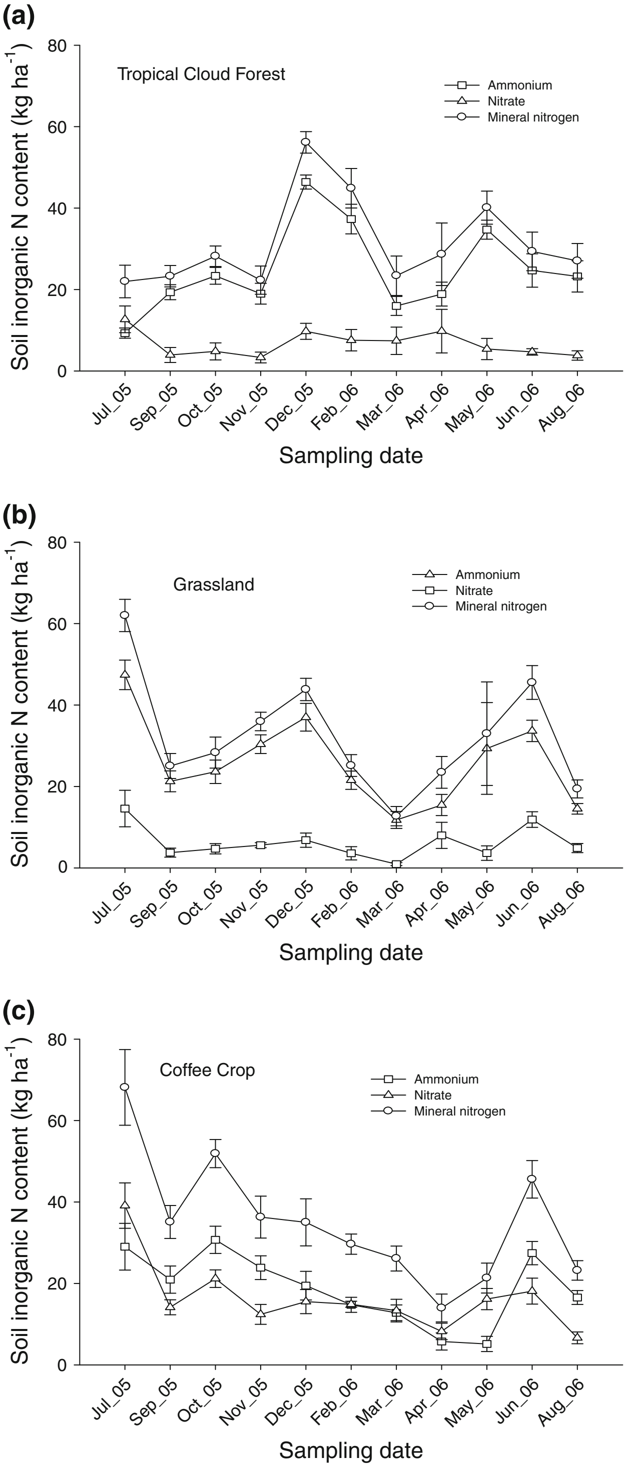

Fig. 3 Seasonal patterns of NH_4^+–N, NO_3^-–N, and total inorganic N contents during the July 2005–August 2006 period in tropical cloud forest (**a**), grassland (**b**), and coffee crop (**c**). *Vertical bars* indicate standard error of the mean

NH_4^+–N and NO_3^-–N contents followed a heterogeneous seasonal pattern during the study period. The seasonal dynamics of soil NH_4^+–N content, compared to NO_3^-–N content, were characterized by a high level from autumn until mid-winter with a peak in October, when soil water content was higher and soil temperature was lower. In contrast, NO_3^-–N content was higher in spring, when soil water content was lower and soil temperature was higher. The increase in NO_3^-–N content during the spring can be explained by agricultural practices such as fertilization, low soil water content (more aerated soil), and high soil temperature, factors that stimulate aerobic N transformation, resulting in the nitrification of NH_4^+–N.

Repeated measures analysis revealed a significant land use-by-sampling date interaction for separate analyses of soil NH_4^+–N and NO_3^-–N contents (Table 4). This means that on different sampling dates, soil NH_4^+–N and NO_3^-–N content responses generally differed depending on land use.

The results of this study showed that in spite of high ammonification (the transformation of organic N to NH_4^+–N) recorded in tropical cloud forest and grassland, NO_3^-–N contents tended to be low. It may be, however, that low NO_3^-–N contents recorded in these sites mean that soil microbial communities had the capacity to rapidly immobilize much of the NO_3^-–N produced. This explanation is supported by the results of Stark and Hart (1997), who demonstrated that the soil microorganisms in most of the ecosystems that they studied had the capacity to assimilate even more NO_3^-–N than that produced by nitrification. On the other hand, the increase in nitrification observed in coffee crop is probably due to a reduction in NO_3^-–N assimilation by soil microbial communities, maintaining high NO_3^-–N contents. On this point, Booth and others (2006) mention that NO_3^-–N production and consumption in soils that are tilled will be mediated more by carbon less than by the direct effects of disturbance; this is because as labile carbon is respired away, heterotrophs become less competitive and nitrifiers more competitive for NH_4^+–N (Hart and others 1994), resulting in increases in the size of the NO_3^-–N pool. Following earlier work by Booth and others (2006) mention that soils that experience frequent N inputs from fertilizer and that therefore support relatively large nitrifier communities should be particularly prone to NO_3^-–N accumulation or loss following disturbance. Therefore, the results of this study could be interpreted as corroboration for Stark and Hart (1997) in that nitrification is significant in undisturbed ecosystems, suggesting that microbial assimilation of NO_3^-–N constitutes an important mechanism for nitrogen retention in tropical cloud forest soils.

Soil Microclimate and Soil Inorganic N Content in Response to Slope Position

Soil Microclimate in Response to Slope Position

Repeated measures analysis showed a significant slope position-by-sampling date interaction only in coffee crop

Table 4 Repeated measures analysis of variance of soil NH_4^+–N and NO_3^-–N content by land use and sampling date

Source of variation	NH_4^+–N				NO_3^-–N			
	DF	MS	F	*P* value	DF	MS	F	*P* value
Replication	8	199.5			8	129.8		
Land use	2	1476.4	7.4	0.005	2	3245.3	15.7	<0.001
Sampling date	10	1121.5	11.3	<0.001	10	547.2	11.2	<0.001
Land use × sampling date	20	821.1	8.8	<0.001	20	170.7	3.8	<0.001
Residual	160	92.4			160	44.1		
Total	296	196.2			296	103.6		

for soil water content (Table 5). On the other hand, in all cases significant differences were observed for sampling date effects (Table 5). An explanation of these results could be that slope lengths, which ranged between 70 and 254 m, were not long enough to cause significant change in the microclimate (soil temperature and water) through slope gradient during the study period. As expected, these data consistently showed that soil temperature decreased progressively from the shoulder to the footslope position, and vice versa for water content.

Soil Inorganic N Content in Response to Slope Position

A significant slope position-by-sampling date interaction was found only in coffee crop for soil NO_3^-–N content (Table 6). Morris and Boerner (1998) mention that nitrification is considered to be particularly sensitive to changes in environmental conditions because of the small guild of microorganisms involved and the impact of soil chemistry, especially pH, on nitrification rates. On the other hand, in all cases except NO_3^-–N content in grassland, significant differences were observed for sampling date effects (Table 6). In the case of tropical cloud forest, average NH_4^+–N and NO_3^-–N contents followed the trends footslope > shoulder > backslope and footslope > backslope > shoulder, respectively (Fig. 4a, b). For grassland, average NH_4^+–N and NO_3^-–N contents decreased in the order footslope > backslope > shoulder and backslope > shoulder > footslope, respectively. With respect to coffee crop, both average NH_4^+–N and

Table 5 Repeated measures analysis of variance of soil temperature and soil water content by slope position and sampling date

Source of variation	DF	Soil temperature		Soil water content	
		F value	*P* value	*F* value	*P* value
Tropical cloud forest					
Replication	2				
Slope position	2	22.433	0.007	0.971	0.453
Sampling date	10	12.823	<0.001	14.562	<0.001
Slope position × sampling date	20	1.168	0.329	1.265	0.257
Residual	40				
Total	98				
Grassland					
Replication	2				
Slope position	2	8.599	0.036	2.815	0.173
Sampling date	10	27.625	<0.001	38.148	<0.001
Slope position × sampling date	20	1.322	0.221	1.201	0.303
Residual	40				
Total	98				
Coffee crop					
Replication	2				
Slope position	2	6.18	0.060	5.008	0.081
Sampling date	10	59.5	<0.001	24.097	<0.001
Slope position × sampling date	20	1.25	0.26	3.638	<0.001
Residual	40				
Total	98				

Table 6 Repeated measures analysis of variance of soil NH_4^+–N and NO_3^-–N content by slope position and sampling date

Source of variation	DF	NH_4^+–N *F* value	NH_4^+–N *P* value	NO_3^-–N *F* value	NO_3^-–N *P* value
Tropical cloud forest					
Replication	2				
Slope position	2	2.041	0.245	5.647	0.068
Sampling date	10	14.690	<0.001	2.812	0.024
Slope position × sampling date	20	0.741	0.762	1.148	0.345
Residual	40				
Total	98				
Grassland					
Replication	2				
Slope position	2	1.380	0.350	0.837	0.497
Sampling date	10	9.074	<0.001	2.219	0.062
Slope position × sampling date	20	0.882	0.609	1.099	0.388
Residual	40				
Total	98				
Coffee crop					
Replication	2				
Slope position	2	2.261	0.220	2.474	0.200
Sampling date	10	6.233	<0.001	5.255	<0.001
Slope position × sampling date	20	0.714	0.789	3.155	<0.001
Residual	40				
Total	98				

NO_3^-–N contents followed the trend footslope > backslope > shoulder (Fig. 4a, b). In each case, slope position effect did not result in statistically significant differences in average NH_4^+–N and NO_3^-–N contents. The results presented here suggest that for each land use type, slope position was not a significant source of variation for soil inorganic nitrogen dynamics, at least during the research period. However, it is well-recognized (Fu and others 2004; Martin and Timmer 2006; Luizão and others 2004; Yimer and others 2006) that topographic attributes have a marked effect on ecological processes, including soil nutrient and water interactions. These data suggest that slope lengths (ranging from 70 to 254 m) are not long enough to cause important changes in the microclimate (soil temperature and water) that would significantly affect soil inorganic N content along slope gradients during the research period. Soil fertility is also vital to the organic matter mineralization process, but soil chemical and physical properties examined in this study exhibited little variability in relation to slope position for each land use type (Table 2).

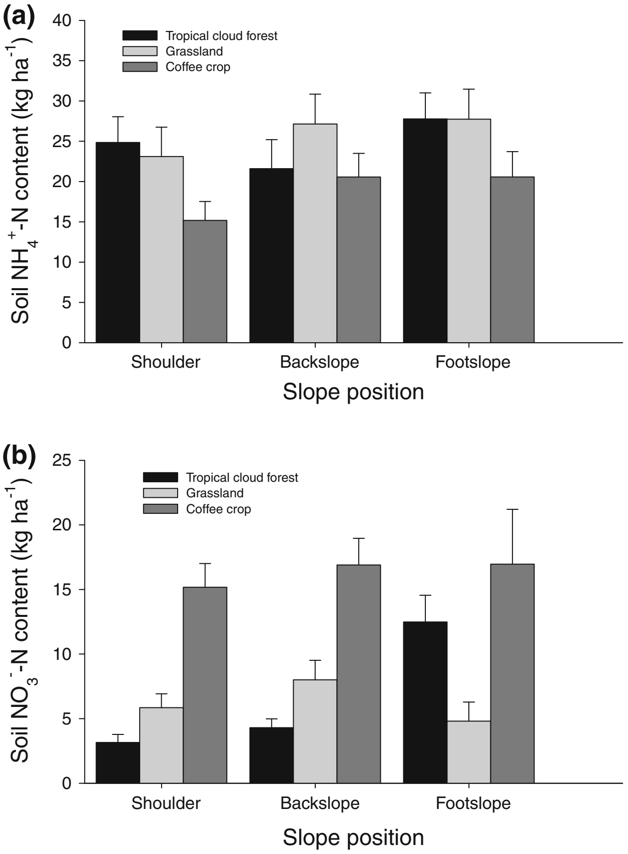

Fig. 4 Effect of slope position on soil NH_4^+–N (**a**) and NO_3^-–N (**b**) content at the study sites. *Vertical bars* indicate standard error of the mean

Relationship Between Soil Inorganic Nitrogen and Soil Environmental Factors

When all data collected in this study were combined, the relationship between soil inorganic nitrogen concentration and soil temperature was best described by a three-parameter single exponential decay model (Fig. 5). The present regression results showed that 44% of the variation in soil inorganic N concentration was explained by soil temperature. Based on the results presented in Fig. 5, it appears that soil inorganic N dynamics adapt to the environmental conditions of each land use, but probably also to the quality and quantity of prevailing soil organic matter. Therefore, the decrease in soil inorganic N concentration coupled with the increase in soil temperature (Fig. 5) indicate that there is a risk of soil organic matter loss from land use change, but also from warming climate conditions. Liu and others (2009) mention that elevated temperature generally stimulates soil carbon turnover and consequently activates the microbial carbon pool. Therefore, these results should be viewed in relation to the wide range of environmental conditions present in the study area.

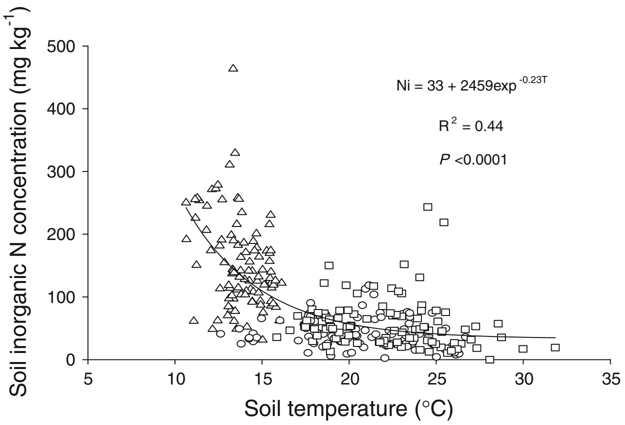

Fig. 5 Soil inorganic N concentration (mg kg^{-1}) as a function of soil temperature (°C) for the entire study period. *Triangles*, *squares*, and *circles* represent tropical cloud forest, grassland, and coffee crop, respectively

Across the entire data set, soil inorganic N concentration showed a significant ($P < 0.0001$) positive linear relationship with gravimetric soil water content (Fig. 6), where the value of correlation coefficient R^2 was 0.32. It is noteworthy that gravimetric water content performed better than volumetric water content in the regression model. A multiple linear regression model indicated a significant ($P < 0.001$) relationship across land use systems between soil temperature, soil inorganic N concentration, and gravimetric soil water content: soil inorganic N = 167 − 6.0 (soil temperature) + 26.7 (gravimetric soil water content), and explained more variation ($R^2 = 0.43$) than the regression model with gravimetric soil water content alone (Fig. 6).

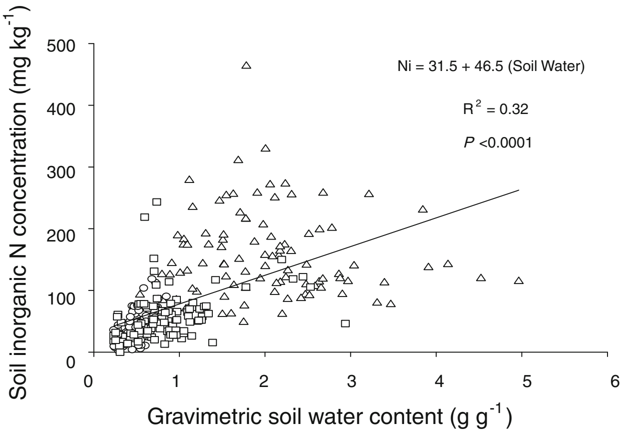

Fig. 6 Effect of gravimetric soil water content (g g^{-1}) on soil inorganic N concentration (mg kg^{-1}) for the entire study period. *Triangles*, *squares*, and *circles* represent tropical cloud forest, grassland, and coffee crop, respectively

Conclusions

The dominant inorganic N form varied with land use type. The seasonal patterns of soil inorganic nitrogen showed that in tropical cloud forest and grassland, soil NH_4^+–N content was much greater than soil NO_3^-–N content. One explanation for this behavior, supported by the results of Stark and Hart (1997), could be that microbial assimilation of NO_3^-–N is substantial in these soils, maintaining low NO_3^-–N concentrations. Based on the work of Booth and others (2006), the higher rates of soil NO_3^-–N production in coffee crop are probably ascribed to a higher availability of NH_4^+–N to autotrophic nitrifiers or to a reduction in available carbon, resulting in lower microbial assimilation of NO_3^-–N. These results suggest that at least in the short term, soil disturbance and N inputs from fertilizer may increase NO_3^-–N flux in coffee ecosystems. Careful study of N cycling in coffee crop is therefore advisable in order to synchronize fertilizer applications with the plant demands, thus reducing both N losses to the environment and costs to farmers while enhancing the productivity of coffee crop. As has been found in other studies (Stark and Hart 1997; Booth and others 2006), microbial immobilization of NO_3^-–N may constitute an important process for nitrogen retention in tropical cloud forest soils.

The results of this study showed that slope position was not an influential factor in the seasonal pattern of NH_4^+–N and NO_3^-–N contents for different land uses. The interpretation for these results is that at the scale studied (slope length ranging from 70 to 254 m), changes in the microclimate as well as in soil chemical and physical properties along the slope gradient were probably insufficient to significantly affect NH_4^+–N and NO_3^-–N contents. Further studies are required to refine the scale in order to fully understand the interactive relationships among topographic attributes such as aspect, gradient, and position and the seasonal pattern of NH_4^+–N and NO_3^-–N contents in various management scenarios.

During the study period, the results showed that the effect of soil temperature on soil inorganic nitrogen concentration followed an exponential decay pattern across the land use, revealing that soil inorganic N dynamics adapt to the environmental conditions of each land use and probably also to the prevailing soil organic matter quality and quantity. Based on these results, it is clear that tropical cloud forest can conserve soil properties and moderate soil temperature and moisture, therefore regulating soil inorganic nitrogen dynamics. However, the labile soil organic matter pool under tropical cloud forest appears to be strongly affected by the conversion of forest to managed ecosystems, due to increased soil temperature and stimulation of soil nitrogen mineralization potential.

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