Nitrogen cycling in coffee agroecosystems: net N mineralization and nitrification in the presence and absence of shade trees

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Abstract

Coffee (*Coffea arabica* L.) agroecosystems in Costa Rica receive relatively large inputs of N through fertilization (approximately 30 g N m^{-2} year^{-1}). However, little is known regarding the rate at which N is mineralization from organic matter and its subsequent transformation within the soil. We studied the seasonal and spatial variation of N transformations in coffee plantations with and without shade trees in the Central Valley of Costa Rica. Net N mineralization and net nitrification, assayed using an in situ incubation procedure, were measured at monthly intervals for 1 year. Both net N mineralization and net nitrification displayed marked seasonal variation; the significantly lowest rates occurred during the dry season (January – March). The mean annual rate of net N mineralization was 14.8 g N m^{-2} year^{-1} in shaded and 11.1 g N m^{-2} year^{-1} in unshaded plantations; 95% of mineralized N was oxidized to NO_3^- in both plantation types. Even though N availability was greater in unshaded plantations, related studies indicate that leaching losses are less than those from unshaded plantations. In combination, these results suggest that N is cycled more conservatively in shaded plantations than in unshaded plantations.

1. Introduction

Coffee agroecosystems are often subsidized by relatively large inputs of nitrogen (N) fertilizer. This practice is common throughout Latin America, particularly in Costa Rica, where applications of approximately 30 g N m^{-2} year^{-1} are used to increase coffee bean yield (Ministerio de Agricultura y Ganaderia, 1992). In addition to large inputs from fertilizer, soil N availability within these ecosystems is influenced by the rate at which soil microorganisms release inorganic N during the process of organic matter mineralization. This biologically-mediated process is regulated by the amount and chemistry of organic matter returned to the soil from above- and below-ground plant litter production. However, data regarding rates of net N mineralization in coffee agroecosystems are absent from the literature. As such, our understanding of the N budget of coffee agroecosystems is incomplete. Because N is the element most limiting the productivity of these ecosystems (Carvajal, 1984), and because N additions through fertilization are large, it is important to determine if soil N availability meets or exceeds plant demand. If nitrification is an important process within coffee agroecosystems, for example, then any N in excess of plant demand has the potential to be lost through leaching or denitrification.

Soil temperature, water potential, and substrate availability directly control the activities

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of soil microorganisms and rates of N transformation within soil. The physiognomy of coffee plantations differs greatly among management systems, a factor that has the potential to modify microbial activity within soil. In the recent past, coffee was primarily grown beneath the shade of one or several overstory tree species. However, recent trends favor the use of sun-tolerant coffee varieties planted in the absence of shade trees (Ministerio de Agricultura y Ganaderia, 1992). The presence or absence of overstory trees suggests that plant litter inputs, as well as soil temperature and water potential, could vary widely between shaded and unshaded coffee plantations. As such, the spatial patterns of controlling factors within shaded and unshaded coffee agroecosystems should be reflected in rates of N cycling processes .

The primary objective of our study was to quantify the spatial and temporal variability of net N mineralization and net nitrification in intensively managed coffee plantations in the presence and absence of overstory trees. Because spatial heterogeneity within coffee agroecosystems could be relatively high, we studied N transformations within the major micro-environmental conditions within these plantation types. We also summarize rates of N input and loss from these ecosystems to gain a clearer understanding of the N budget of intensively managed coffee agroecosystems.

2. Materials and methods

2.1. Study sites

Our experiment was conducted in intensively managed coffee plantations in the Central Valley of Costa Rica. Paired shaded and unshaded plantations, no more than 600 m apart, were selected in San Pedro de Barva (10° 9'N, 84° 8'W), Santo Domingo de Heredia (9° 58'N, 84° 5'W), and Barrio Socorro in San Jose (9° 57' N, 84° 4' W). These sites were located on a small altitudinal, temperature, and precipitation gradient. Elevation varied from 1142 to 1180 m among sites, and mean annual temperature ranged from 19 to 20.4°C. Precipitation averaged 2200 to 2800 mm year^{-1} among sites, with a seasonal peak in October and a dry season from December to April (Herrera, 1986). The unshaded plantation in San Pedro is the Centro de Investigaciones en Cafe (CICAFE) research station, and the others are privately-owned operational plantations.

Research plots (30 m×50 m) were established in the approximate geographic center of each paired shaded and unshaded plantation. Both plantation types contained *Coffea arabica* L. var. Caturra, intermixed with var. Catuai, and were between 8 and 14 years of age at the time of our study. The unshaded plantations contained coffee planted in rows at a density of 7000 plants ha^{-1}; coffee rows were pruned on a 5-year cycle. The shaded plantations had 10000 plants ha^{-1} and were pruned by plant, rather than by row. Primary shade trees were *Erythrina poeppigiana* (Walpers) O.F. Cook, or *Erythrina fusca* Loureiro (200 – 250 stems ha^{-1}). *Erythrina* were pruned during March or April, following coffee harvest, and again in September or October.

The soils in all plantations were classified as Typic Dystrandept (Pérez et al., 1978), equivalent to Udands. They exhibited good fertility for coffee production, and were on nearly level topographic positions. Soil texture and organic matter content did not significantly differ among plantations (Table 1; Babbar, 1993).

The plantations were managed following practices recommended by the Costa Rican Ministry of Agriculture (Ministerio de Agricultura y Ganaderia, 1992). Each plantation received 300 kg N ha^{-1} year^{-1} in three equal applications. The first two applications occurred in May and August with a complete formula (NPK; 18-5-15 or 18-3-10); the last application occurred in October or November as urea ($(NH_3)_2CO$). Fertilizer was applied by hand within a 40- to 50-cm radius surrounding each coffee plant. In addition, 1.5 – 2.0 t ha^{-1} of $CaCO_3$ had been added every 3 – 4 years to reduce soil acidity. Several fungicides and nematicides were sprayed as required, and weeding was conducted two to three times each year using manual and chemical methods. Manual control included scalping the inter-canopy areas, and placing organic matter

Table 1
General properties of the soils (0–10 cm) in shaded and unshaded coffee plantations in the Central Valley of Costa Rica. Carbon content is assumed to be 45% of soil organic matter (SOM). Data have been summarized from Babbar (1993)

Site	Management	Total				Texture		
		SOM (%)	N (%)	C:N	pH	Sand (%)	Silt (%)	Clay (%)
1	Shaded	6.23	0.40	7.0	4.7	54	12	34
	Unshaded	7.84	0.47	7.5	5.0	62	9	29
2	Shaded	9.04	0.52	7.8	4.9	52	12	37
	Unshaded	8.71	0.49	8.0	5.1	57	7	37
3	Shaded	7.04	0.43	7.4	5.1	57	7	37
	Unshaded	5.50	0.54	4.6	6.0	54	7	39

and small amounts of mineral soil beneath the coffee plants.

2.2. Soil sampling

In shaded plantations, we stratified our sampling by collecting soil between and beneath the canopy of *Erythrina*. We considered a radius extending 2 m around each *Erythrina* stem to constitute the beneath canopy area. We further stratified our sampling by collecting soil beneath the canopy of full-grown and recently-pruned coffee plants in the between and beneath canopy areas of *Erythrina*. Soil samples were collected no more than 40 cm from each coffee stem. In unshaded plantations, soil samples were collected beneath full-grown coffee plants, recently-pruned coffee plants, and from the bare soil between coffee rows. In each plantation type, we randomly selected four replicates of each micro-environmental condition and visually estimated the area encompassed by each. Soil samples were collected within each of these areas at 4-week intervals from mid-March 1990 to mid-February 1991.

2.3. Net N mineralization and nitrification

Soil samples consisted of 10 cm diameter cores extending from the surface of the mineral soil to a depth of 10 cm. Two intact soil cores were collected at each sampling point (i.e. micro-environmental condition) in shaded and unshaded plantations. One soil core was placed in a poly-ethylene bag and returned to its original position in the soil profile for a 28–30 day in situ incubation. The second core was transported to the laboratory for analysis. On the subsequent sampling date, incubated samples were removed from the soil profile, and the sampling procedure was repeated.

Within 24 h of field collection, incubated and unincubated soil cores were homogenized within their polyethylene bag, and a 10 g subsample of each was extracted with 20 ml of 1 M KCl. Filtrates were analyzed colorimetrically for NH_4^+-N and NO_3^--N using a Lachat Automated Ion Analyzer. Net N mineralization was calculated as the NH_4^+-N plus NO_3^--N in incubated samples in excess of initial amounts. Similarly, net nitrification was determined as the increase in extractable NO_3^--N during the in situ incubation. Values for these processes are expressed as a mean daily rate (mg N m^{-2} day^{-1}) during the incubation period. We weighted the mean daily rates within each micro-environmental condition by their respective area to provide an annual flux (g N m^{-2} $year^{-1}$) for each plantation type.

2.4. Statistical analyses

The influence of sampling date, plantation type, and coffee pruning (recently pruned vs. full

grown) on mean daily rates of net mineralization and nitrification were investigated using an analysis of variance (ANOVA) for a randomized complete block design; geographic location was the blocking variable. Mean annual rates of net mineralization and nitrification also were compared using an ANOVA for a randomized complete block design. Means in all cases were compared using a protected Fisher's LSD procedure with significance accepted at $\alpha = 0.05$. In addition, differences in mean daily rates of net mineralization and nitrification beneath and between the canopies of *Erythrina* and coffee plants were compared using a t-test for unpaired observations ($\alpha = 0.5$). All statistical analyses were performed using SYSTAT (Wilkinson, 1989).

3. Results

3.1. Net N mineralization and nitrification

Mean daily rates of net N mineralization and nitrification differed significantly among sampling dates. The lowest rates occurred during the dry season (January – March), whereas rates were generally greater during August to Novem-
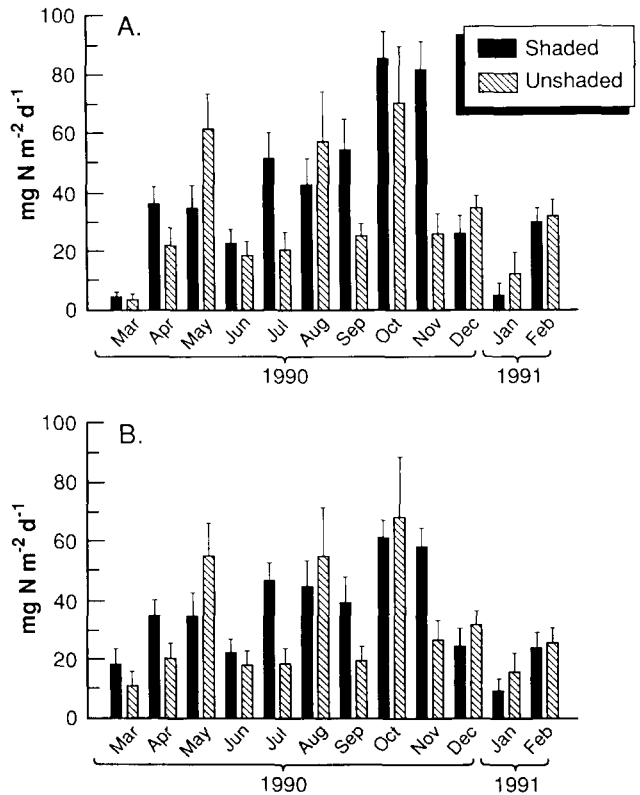

Fig. 1. Temporal variation of net N mineralization (A) and net nitrification (B) in shaded and unshaded coffee plantations. Values are means of three geographic locations in the Central Valley of Costa Rica. The length of each bar represents one standard error.

ber when monthly precipitation was relatively high (Fig. 1). Mean daily rates of net N mineralization and nitrification, averaged across sampling dates, did not differ significantly between shaded (38.9 mg N m^{-2} day^{-1}) and unshaded (29.4 mg N m^{-2} day^{-1}) plantations. These processes also were not significantly different beneath recently-pruned and full-grown coffee plants. Averaged across sampling dates, neither net mineralization nor nitrification were significantly different beneath or between the canopy of *Erythrina* and coffee plants (Table 2). In all cases, net nitrification was directly proportional to net N mineralization. Annual rates of net N mineralization were 14.5 g N m^{-2} year^{-1} in shaded plantations and 11.5 g N m^{-2} year^{-1} in the unshaded plantations; this difference was

Table 2
Mean daily rates of net N mineralization and nitrification under different micro-environmental conditions in shaded and unshaded coffee agroecosystems. Values are means with standard error enclosed within parentheses. Means within a column for a plantation type that have the same letter are not significantly different (t-test)

	Mineralization (mg N m^{-2} day^{-1})	Nitrification (mg N m^{-2} day^{-1})
Plantation Type		
I. Unshaded		
Beneath coffee canopy	33.6a	33.2a
	(4.2)	(4.0)
Between coffee canopy	25.1a	23.3a
	(4.2)	(4.4)
II. Shaded		
Beneath *Erythrina* canopy	40.2a	36.4a
	(3.9)	(3.1)
Between *Erythrina* canopy	37.5a	33.8a
	(3.7)	(2.9)

significant. In both plantation types, 95% of the annually mineralized N oxidized to NO_3^-.

4. Discussion

Coffee bean production in Costa Rica is often coupled to relatively large applications of N (Carvajal, 1984). The magnitude of these inputs, combined with rates of organic matter mineralization, suggest that N availability within these intensively-managed agroecosystems was relatively high. In our study, N availability was higher in shaded plantations compared with those without shade trees. More importantly, the majority of that N was present as NO_3^-. Nevertheless, a higher coffee density and the presence of a tree overstory seem to offset higher N availability in shaded plantations, leading to lower N losses via leaching and a more conservative cycling of N (Babbar and Zak, 1994).

Temporal variation in net N mineralization and net nitrification reflected rainfall patterns in the Central Valley; the lowest rates occurred during the driest months (January–March) and highest rates occurred during the wettest months (August – November). Soil moisture is known to directly control N mineralization (Andren et al., 1988). In addition, several studies have reported a 'Birch effect' in seasonal climates; net N mineralization decreases during the dry season, followed by a rapid increase in microbial activity and mineralization at the initiation of the rainy season (Birch, 1964; Sanchez, 1976). Even though rates were relatively low, it is important to note that there was considerable mineralization and nitrification during the dry season. Reynolds (1991) determined that intensively fertilized Andisols present the potential for significant mineralization even at water potentials less than − 1.5 MPa. Patterns of fertilizer application and organic matter additions, and soil removal by weeding may also contribute temporal variability, a factor that we are unable to precisely quantify.

Micro-environmental conditions within shaded and unshaded plantations exhibited relatively small differences in net N mineralization and net nitrification. For example, rates of both processes were similar beneath and between *Erythrina* canopies. However, other studies have demonstrated rapid N transformation rates beneath *Erythrina* (Santana and Cabda-Rostand, 1982; Vilas 1990). Although not statistically significant, the largest differences related to microenvironmental effects occurred between and beneath coffee canopies in unshaded plantations. The between-canopy areas had rates almost 30% lower than those beneath coffee canopies. This result was not unexpected because the between-canopy areas are lower in organic matter content and often become compacted due to foot traffic (L.I. Babbar, personal observation, 1990). Periodic contributions of litter and runoff from the fertilizer bands surrounding coffee plants may contribute to some of the variability we observed within these areas. The between canopy areas constitute 30% of the area within unshaded plantations, and their contribution to N cycling on an ecosystem level should be considered in future studies on coffee agroecosystems.

We fully expected rates of net N mineralization to differ between management practices because substrate quantity and quality, likely higher in shaded plantations, are known to influence organic matter mineralization (Douglas and Magdoff, 1991). The annual rates we report represented approximately 30% of the N available for plant uptake in both plantation types. Our data also indicate that approximately 45 and 41 g N m^{-2} year^{-1} (i.e. fertilizer N + mineralized N) are available for plant uptake in shaded and unshaded plantation, respectively; the majority of that N was NO_3^-. Despite the greater quantities of N available for plant uptake in the shaded plantations, these agroecosystems have significantly lower rates of N loss via leaching (0.9 g N m^{-2} year^{-1} in shaded plantations vs. 2.4 g N m^{-2} year^{-1} in unshaded plantations), which leads to a greater use-efficiency of N fertilizer (Babbar, 1993; Babbar and Zak, 1994). These differences are a likely result of greater N uptake by vegetation in shaded plantations (i.e. 30% higher coffee density and *Erythrina*) and storage of part of that N in plant litter. Even though N availability was somewhat lower in unshaded plantations,

relatively high rates of N loss suggest that N availability exceeds plant demand.

Although annual rates of N mineralization and nitrification differed significantly between management practices, high variability and a small sample size may be partially responsible for the lack of significant differences in mean daily rates. Averaged over sampling dates, mean daily rates of net N mineralization rates in both plantations types (shaded = 0.50 μg N g^{-1} day^{-1}; unshaded = 0.45 μg N g^{-1} day^{-1}) were higher than those obtained by Vilas (1990) in shaded plantations, but lower than those of Reynolds (1991) for the unshaded plantations during the dry season. Rates were comparable with arable Ultisols in the humid tropics (Arora et al., 1986) and to coconut and cacao plantations (Bopaiah and Shetty, 1991), but twice those measured in tea (Wickramasinghe et al., 1985). In addition, the rates we report are well within the range of tropical dry forests (Raghubanshi, 1992), but were higher (Marrs et al. 1988; Montagnini and Bushbacher, 1989) or lower (Matson et al., 1987) than other tropical humid forests.

5. Summary

Patterns of N availability within the coffee agroecosystems we studied reflected seasonal patterns of precipitation, fertilizer additions, and organic matter additions to the soil. Spatial variability within both plantation types was important, but it was much less than that related to the aforementioned temporal factors. Although N availability was highest in shaded plantations, related studies indicate that NO_3^- leaching from shaded plantations is significantly less than that from unshaded plantations (Babbar and Zak, 1994). The presence of shade trees and a greater coffee planting density in shaded plantations seems to reduce the potential for N loss, even though large quantities of N are rapidly cycled on an annual basis. Our data highlight the need for understanding the patterns of N retention and loss in these intensively managed agroecosystems because they occupy large land areas throughout tropical America.

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