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ORIGINAL PAPER

Nitrogen dynamics and soil nitrate retention in a *Coffea arabica—Eucalyptus deglupta* agroforestry system in Southern Costa Rica

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Abstract Nitrogen fertilization is a key factor for coffee production but creates a risk of water contamination through nitrate (NO_3^-) leaching in heavily fertilized plantations under high rainfall. The inclusion of fast growing timber trees in these coffee plantations may increase total biomass and reduce nutrient leaching. Potential controls of N loss were measured in an unshaded coffee (*Coffea arabica* L.) plot and in an adjacent coffee plot shaded with the timber species *Eucalyptus deglupta* Blume (110 trees ha^{-1}), established on an Acrisol that received 180 kg N ha^{-1} as ammonium-nitrate and 2,700 mm yr^{-1} rainfall. Results of the one year study showed that these trees had little effect on the N budget although some N fluxes were modified. Soil N mineralization and nitrification rates in the 0–20 cm soil layer were similar in both systems ($\approx$280 kg N ha^{-1} yr^{-1}). N export in coffee harvest (2002) was 34 and 25 kg N ha^{-1} yr^{-1} in unshaded and shaded coffee, and N accumulation in permanent biomass and litter was 25 and 45 kg N ha^{-1} yr^{-1}, respectively. The losses in surface runoff ($\approx$0.8 kg mineral N ha^{-1} yr^{-1}) and N_2O emissions (1.9 kg N ha^{-1} yr^{-1}) were low in both cases. Lysimeters located at 60, 120, and 200 cm depths in shaded coffee, detected average concentrations of 12.9, 6.1 and 1.2 mg NO_3^--N l^{-1}, respectively. Drainage was slightly reduced in the coffee-timber plantation. NO_3^- leaching at 200 cm depth was about 27 ± 10 and 16 ± 7 kg N ha^{-1} yr^{-1} in unshaded and shaded coffee, respectively. In both plots, very low NO_3^- concentrations in soil solution at 200 cm depth (and in groundwater) were apparently due to NO_3^- adsorption in the subsoil but the duration of this

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process is not presently known. In these conventional coffee plantations, fertilization and agroforestry practices must be refined to match plant needs and limit potential NO_3^- contamination of subsoil and shallow soil water.

Keywords Nitrate leaching · Nitrate adsorption · N_2O emissions · N mineralization · Water contamination · Acrisol (Ultisol) · Coffee agroforestry

Abbreviations

AET	actual evapotranspiration
TDR	time domain reflectrometry
LAI	leaf area index
Masl	meter above sea level
N	nitrogen

Introduction

Intensively managed coffee (*Coffea arabica*) systems have been developed in Central America, particularly in Costa Rica where old coffee varieties, grown under a variety of shade trees, were replaced by more productive varieties (e.g., Caturra, Catuai) planted under heavily pruned leguminous trees or in unshaded monocultures (Babbar and Zak 1995). A suspected cause of increasing ground water nitrate (NO_3^-) concentration in the Central Valley of Costa Rica is the high fertilization rates (~250 kg N ha^{-1} yr^{-1}) of these coffee plantations grown on highly permeable soils under high rainfall intensities (Reynolds-Vargas and Richter 1995). Nitrogen fertilization can be the key factor for coffee growth and production (Carjaval 1984) but the efficiency of N fertilizer use is apparently low in these systems. Using ^{15}N labeled fertilizer, Salas et al. (2002) estimated that only 30–40% of the applied N was absorbed by the coffee plants.

In low-altitude and wet zones of Southern Costa Rica, fast growing timber trees like *Eucalyptus deglupta* Blume have been planted in unshaded coffee or have replaced the conventional leguminous shade trees in order to reduce labour cost (legume tree pruning) and increase the overall profitability of the system (Schaller et al. 2003). Introducing *E. deglupta* into these coffee plantations may increase evapotranspiration, biomass and nutrient accumulation and therefore reduce negative environmental impacts such as NO_3^- loss by leaching. Nevertheless, the timber trees may compete significantly with coffee for light, water and soil nutrients and reduce coffee production (Beer et al. 1998). Our research was conducted to understand potential controls on N loss and consequent effects on water quality in two contrasting coffee systems; i.e. unshaded coffee (*C. arabica*) and coffee shaded by *Eucalyptus* (*E. deglupta*) both of which received large annual additions of N through fertilization. In both systems (parallel case studies in adjacent commercial plantations established on a permeable Acrisol), soil N dynamics, N accumulation in biomass and litter and N losses from the system were measured.

Material and methods

Study site and experimental design

This study was carried out between February 2002 and April 2003 in a commercial coffee plantation in the Santa Fe farm, located 25 km South of the town of San Isidro del General, in the low wet Pacific southern zone of Costa Rica (9 16′°N, 83 33′°W; 600 masl). The average annual temperature is 23°C and annual precipitation 2,740 mm with a pronounced dry season from December to April. Rainfall during the study period totaled 2,622 mm (150 days of rainfall events; February to 15th December 2002) and the mean annual relative humidity was 87.5%. The soil is a fine textured Acrisol (Ultisol) derived from sedimentary rocks rich in mafic materials (Ustic, Paleumult). The commercial coffee plantation, shaded by 4- to 10-year-old *Eucalyptus* trees, occupied several micro-catchments, on a total area of approximately 750 ha. Only a few unshaded coffee plots (less than 1% of the area) existed in the Santa Fe farm at the beginning of the study. Two adjacent commercial coffee plots with the same site conditions (see results) and agricultural management, each 1 ha, were selected. One plot was shaded by *Eucalyptus* while the adjacent plot had no trees because it was located at the end of a landing strip. Both plots had slopes of about 1%. The coffee (*C. arabica* variety Costa Rica 95) was planted in 1988, in an area previously used for pasture, with a spacing of 2 × 0.85 m (5,900 plants ha^{-1}). In the shaded plot, the timber trees were planted in 1995 (within the coffee rows) at a density of 220 ha^{-1} and thinned in 2000 to a density of 110 trees ha^{-1} (approximate tree spacing of 9.5 × 9.5 m). In 2002 the average tree height was 19 m. Until 2000, these plots were heavily fertilized (average over 12 years; three or four split applications between April and October) with 250 kg N ha^{-1} yr^{-1} (180 kg Urea + 70 kg NH_4-NO_3), 30 kg P ha^{-1} yr^{-1} (triple superphosphate), 150 kg K ha^{-1} yr^{-1} (KCl) and 60 kg Mg ha^{-1} yr^{-1} (MgO). Fertilizer input was reduced in 2001, due to the coffee price decrease, to a total of 120 kg N (NH_4-NO_3) ha^{-1} yr^{-1} applied in two equal doses in May and July. In 2002, both plots received a total of 180 kg N ha^{-1} yr^{-1} (NH_4-NO_3) and 135 kg K ha^{-1} yr^{-1} (KCl) in two equal doses (May 22 and August 10), but no fertilizer was applied to the rest of the coffee plantation. Fertilizer was applied homogeneously between the coffee rows.

Soil sampling and analysis

Soil samples were taken with an Edelman auger, on 2nd April 2002, at 10 cm depth intervals in the top 40 cm (composite of four adjacent sub-samples) and at 20 cm intervals between 40 and 200 cm depth (only one sub-sample per depth), from three random locations in each plot. Soil samples were collected along the coffee rows at 40–50 cm from a coffee plant (this position provides an integrated measure of soil properties for the entire spatially stratified coffee plot) and also, in the shaded plot, at 1.5–2 m from the base of a *Eucalyptus* tree. The distance to the timber tree was chosen to evaluate the effect of the trees on soil properties and may not reflect average values in the shaded plots.

The day after sampling, field-moist sub-samples, kept at 4°C until processing, were suspended in K_2SO_4 solution (1:10 soil to solution, 0.5 M K_2SO_4 concentration) and shaken for 1 h. After centrifuging and filtration, extracts (50 ml) were analysed for NH_4^+ and NO_3^- by the Kjeldahl method (Mulvaney 1996) and for Cl^- by colorimetry (Futura 2000, Alliance Instruments, Frépillon, France). Gravimetric water content was estimated simultaneously by drying a subsample at 105°C. Other subsamples were air-dried, sieved to <2 mm and analized for: soil organic carbon (SOC) by dry combustion using an automatic CHN analyser (Thermo Finnigan, Flash EA 1112, Milan, Italy). Cation exchange capacity (CEC) was determined by extraction with 1 M ammonium acetate at pH 7.0 (Summer and Miller 1996) and basic cations (Ca, Mg, K and Na) by atomic absorption spectrometry (Perkin Elmer, Analyst 100 spectrometer, Norwalk, Connecticut, US). Soil pH in water and 1 M KCl (soil solution ratio 1: 2.5) were measured with a standard pH electrode (Corning G-P Combowrj, Corning Inc, New York, US) and particle size distribution with the hydrometer (Bouyucous) procedure following dispersion with 10% sodium hexametaphosphate (Forsythe and Warren 1985). The soil bulk density was measured in both plots, using volumetric cylinders in a 200 cm deep soil pit 50 cm away from the coffee rows. Four cylinders (100 cm^3) were collected at 10 cm depth intervals (0–40 cm) and at 20 cm intervals (40–200 cm).

N export in coffee harvest

Coffee berries were harvested from three sub-plots (12 × 12 m) per system at the end of the rainy season (three dates). Samples (0.5–0.7 kg) from each harvest and sub-plot, were dried at 60°C to constant weight. After grinding the samples, total N concentration was determined by dry combustion (see above).

N accumulation in vegetation

Aboveground biomass of trees and coffee

An allometric relationship between *Eucalyptus* stem diameters at 1.30 m (D_{130}) and the biomass or N content of individual trees was determined in May 2002. Fifteen trees, representing all the diameter classes in the shaded plot, were cut in comparable stands around the study plots, and the following parameters measured:

- Stem diameter at 0.50 m ($D_{0.50}$) and every 2 m up to a diameter of 3 cm. Cross-sectional discs (thickness 4 cm) were taken at intervals of 2 m, weighed and oven-dried (65°C) to constant weight to estimate wood-bark proportions and water content. The N content of bark and wood of each tree stem was analyzed from a sample representing the distribution of biomass in the whole stem; i.e. an integrated measure of N content for the entire stem.

- For each sample tree, branches (>1 cm and 0–1 cm) and leaves were weighed. Sub-samples (about 500 g) of each component were taken from each tree to measure water and N content (dry combustion).

Stems, branches, foliage and fruits of thirty coffee plants per plot, of average height, were separated and weighed; nine composite samples per plot of each component were taken to measure water and N content (dry combustion).

Litter layer

In each plot, 8 composite litter samples (0.5 m^2; two quadrats of 50 × 50 cm) were collected in June 2002 by systematic sampling. One quadrate was placed beside a coffee plant and the other on the central line midway between coffee rows. All material above the mineral soil was collected, oven-dried (65°C) to constant weight, weighed and analyzed for N (dry combustion).

Roots were not measured; values of 25% for the belowground/ aboveground biomass ratio for coffee (Crouzet 2003) and 30% for *Eucalyptus* (Laclau et al. 2003) were assumed. Nitrogen accumulation in the permanent biomass and litter was quantified as N loss from soil. The mean annual increment of dry matter and N accumulation in the biomass was estimated in 2002 from the biomass and N content of the fourteen year old coffee plants and seven year old trees. The mean annual increment of the litter layer in the shaded plot, during the period 1988–1995, was assumed to be the same as for unshaded coffee (trees were planted in 1995); a different mean annual increment was calculated for the period 1995–2002 when trees were present.

Net N mineralization and nitrification in the topsoil

From April 2002 until April 2003, net N mineralization and nitrification was evaluated through 28–30 day "in situ" incubations of undisturbed soil samples (Anderson and Ingram 1993) collected within the coffee rows and in the open area midway between the rows (2 m from the timber trees in the shaded coffee plot). In each plot, we randomly selected six sampling areas; within each area two paired cores (cores of 8 cm diam., 20 cm deep) were collected: one pair from the coffee row and the other one midway between the rows. One soil core of each pair was transported to the laboratory to determine NH_4^+ and NO_3^- at the beginning of the incubation. The other core was incubated in a PVC tube in the original position in the soil profile (10 cm of the 30 cm tube above the soil surface) for 28–30 days, before collection and analysis of mineral N. The bottom of the tube was sealed with a 100 μm mesh sieve to maintain moisture equilibrium inside-outside but preventing root in-growth. The top of the tube was covered to prevent leaching of mineral N by rain but lateral holes under the polyethylene cap allowed air circulation. For mineral N extraction, soils were suspended in KCl solution (1:10 soil to solution, 1 M KCl); extracts were analysed for NO_3^- and NH_4^+ by colorimetry.

Nitrate leaching

Soil solution samples were collected every ten days during the 2002 rainy season using porous ceramic cups (12 ml volume; SDEC Tensionic, Reignac-sur-Indre, France; filled with distilled water before each sampling period) mounted on a rigid tube (2.5 cm diam.). In each plot, six, six and four porous cups were located at 60, 120 and 200 cm depth, respectively. In both plots the lysimeters were installed 40–50 cm from the base of a coffee plant and in the shaded plot 2–2.5 m from a *Eucalyptus* stem. The soil solution was collected every 10 days (no suction was applied) assuming an equilibrium between the mineral composition of the solution in the ceramic cup and the soil solution as it was demonstrated by Moutonnet et al. (1993). Nitrate-N loss was expressed on an area basis by multiplying the computed amount of drainage water by the soil water NO_3^--N concentration for the same sampling period.

Nitrate in groundwater

In the coffee-eucalyptus plantations of the Santa Fe farm, eight springs were selected for sampling during the dry and wet seasons of 2001 and 2002. Each site was sampled 13 times to compare NO_3^- concentrations in the soil solutions and in the aquifers, in relation to N fertilisation.

Emission of N_2O from the soil

N_2O fluxes were measured 51 and 1 day before N fertilization (11th August 2002) and 1, 2, 5, 7, 14, 21 and 110 days after N application. Five round polypropylene chambers (0.1 m^2) were installed in each plot on 21 June 2002, to a depth of 5 cm. In the shaded plot, chambers were installed 1.5 m from a Eucalyptus tree. Flux measurements were made by sampling through a small centre port, after a one hour enclosure period, into 1 L PTFE bags using a 1 L syringe. In addition, at least three samples of ambient air were taken when chambers were closed. Concentrations of N_2O were measured using a gas chromatograph (CP 9000, Crompack International, Middleburgh, NL) fitted with an electron capture detector. The analysis was usually completed (at CEH, Edinburgh, UK) within three weeks of sample collection, during which period the leakage rate of N_2O through the bag was insignificant. Fluxes of N_2O were calculated from the product of the volume of air enclosed (about 25 L) and the difference between N_2O concentration of ambient air and chambers divided by the chamber area and time of enclosure.

Water dynamics

Surface runoff was measured in both plots using three square sub-plots (1 × 1 m) surrounded by a half-buried galvanized frame, buried to 7 cm depth, with an opening at the lower side to drain runoff through a plastic pipe to a 30 l plastic container buried in the soil. Runoff volume was measured after every rain event and a representative sample (10% of the runoff volume) was collected and filtered (0.45 μm). Composite samples from a 15 day period were analyzed for inorganic N (NO_3^- and NH_4^+) by colorimetry.

Throughfall was monitored between April and August 2002, during 66 rainfall events, with troughs (length 6 m; longitudinal cut of 10 cm diameter PVC tube giving 4 cm wide collection slit, equivalent to 0.24 m^2 sampling area per trough). These troughs were replicated three and six times in unshaded and shaded coffee, respectively. According to recent measurements in Costa Rica's Central Valley (unpublished data), stemflow was estimated as 2% and 3% of precipitation in unshaded and shaded coffee respectively.

Seasonal changes in soil moisture (0–120 cm) were determined 12 times during the rainy season using three TDR probes (ESI MP 917, Victoria, BC, Canada), in each system at 50 cm from a coffee plant. Additionally gravimetric soil moisture was measured in each system five times between April and September 2002 (four soil cores every 10 cm from 0 to 200 cm depth). Field capacity, determined in the laboratory using a soil tension of 33 kPa, was close to the soil moisture content on May 29. Soil water content and water drainage were computed daily using a simple box model which involved the following steps (Imbach et al. 1989a): the precipitation, each day, was added to the soil water content, while runoff and AET (sum of interception and transpiration) for that day were subtracted. When the remaining amount of water was greater than the water retention capacity of the soil (field capacity), the excess was assumed to be lost by drainage. When the opposite occurred, it was assumed that there was no drainage and that the remaining value was the soil moisture content at the end of the day. The calculation was repeated successively for each following day, taking the final value of the previous day as the initial soil moisture content.

Statistical analysis

Descriptive statistics (averages, standard errors) for each system are presented in order to discuss differences between case studies (systems). For soil $NH_4^+ + NO_3^-$, soil N mineralization, NO_3^- in groundwater, all sampling dates were compared within each system by analysis of variance for a randomized block design with time as the repeated measurements factor.

Results

Soil characteristics

Physical (texture) and chemical (CEC, pH) soil properties in the top 200 cm were very similar in both plots (Table 1). The Acrisol (Ustic, Paleumult) in both plots had a sandy texture (59% sand, 19–22% silt and 19–22% clay) in the 0–20 cm layer; a clay-sandy texture (46% sand, 12% silt and 42% clay) in

Table 1 Physical and chemical characteristics of an Acrisol (Ustic Paleumult) in two adjacent coffee plots in Southern Costa Rica

Depth (cm)	Bulk density (t m^{-3})	Porosity (m^3 m^{-3})	Total C (g kg^{-1})	pH (H_20)	pH (KCl)	CEC[a] ($cmol_c$ kg^{-1})	BS[b] (%)	Sand (%)	Silt (%)	Clay (%)
Unshaded coffee plot										
0–20	0.77 (0.03)	0.69	71.3	6.1 (0.2)	5.2 (0.2)	29.3 (2.0)	74	59 (2)	19 (2)	22 (2)
20–40	0.86 (0.01)	0.66	44.5	5.3 (0.1)	4.5 (0.1)	17.5 (2.0)	14	46 (1)	12 (1)	42 (1)
40–60	0.99 (0.01)	0.62	20.8	5.1 (0.1)	4.4 (0.1)	12.4 (1.6)	10	34 (2)	9 (1)	57 (3)
60–80	1.07 (0.02)	0.60	14.5	4.8 (0.2)	4.5 (0.1)	11.3 (1.6)	8	19 (5)	10 (1)	72 (5)
80–120	1.08 (0.02)	0.59	11.6	4.7 (0.2)	4.8 (0.1)	16.6 (1.0)	10	16 (3)	7 (1)	77 (4)
120–160	1.12 (0.03)	0.58	9.2	4.7 (0.1)	5.0 (0.2)	19.8 (1.2)	8	11 (2)	7 (1)	82 (3)
160–200	1.17 (0.02)	0.56	6.7	4.8 (0.1)	5.2 (0.2)	22.0 (1.4)	6	8 (2)	11 (2)	81 (2)
Coffee—*Eucalyptus* plot										
0–20	0.78 (0.01)	0.68	74.6	6.2 (0.2)	5.3 (0.2)	30.1 (2.0)	74	59 (1)	22 (2)	19 (3)
20–40	0.87 (0.02)	0.66	51.2	5.3 (0.1)	4.5 (0.1)	20.2 (1.9)	15	46 (1)	12 (1)	42 (1)
40–60	1.00 (0.06)	0.61	22.0	5.1 (0.1)	4.4 (0.1)	14.1 (1.2)	9	29 (2)	12 (1)	59 (2)
60–80	1.02 (0.07)	0.61	14.1	5.0 (0.1)	4.7 (0.1)	12.7 (1.0)	7	12 (5)	9 (2)	79 (5)
80–120	1.03 (0.03)	0.61	11.2	4.8 (0.1)	5.0 (0.1)	15.3 (0.9)	8	9 (4)	8 (1)	83 (5)
120–160	1.03 (0.04)	0.61	8.9	4.7 (0.1)	4.9 (0.1)	21.5 (1.4)	9	8 (2)	7 (1)	85 (4)
160–200	1.04 (0.07)	0.61	7.0	4.8 (0.1)	5.0 (0.1)	20.0 (1.8)	9	11 (4)	7 (3)	82 (3)

Means (standard errors); [a] Cation exchange capacity; [b] base saturation

the 20–40 cm layer; and a clayey texture with low base saturation in the subsoil. Between 40 and 200 cm depth, clay increased from 57 to 82% and from 59 to 85% in the unshaded coffee and the shaded coffee plots, respectively. The soil was slightly acid in the topsoil with a decrease of pH with depth. Higher pH values in KCl than in water, below 80 cm, indicated that positive charges prevailed in the subsoil (Cahn et al. 1992; Qafoku et al. 2000). The organic C content decreased sharply with depth. Soil bulk density in the layer 0–120 cm was similar for both plots, increasing with depth from 0.77 to 1.07 t m^{-3}. By contrast, for the 120–200 cm soil layer, bulk density was higher in the unshaded (average value of 1.14 t m^{-3}) than in the shaded plot (average value of 1.03 t m^{-3}).

N export in coffee bean harvest and N accumulation in vegetation

Coffee berry production was low in 2002 with values of 1.64 (s.e. 0.07) and 1.25 (s.e. 0.10) t dry matter ha^{-1} yr^{-1} in unshaded and shaded plots, respectively (40% of potential values for this production zone; ICAFE-CICAFE 2000). Nitrogen concentrations of coffee berries in the unshaded (20.9; s.e. 0.6 g N kg^{-1}) and shaded (19.9; s.e. 1.0 g N kg^{-1}) plots were similar. In comparison to unshaded coffee, N export in coffee berries from the shaded plots was reduced by 25%; i.e., 34.2 (s.e. 3.1) and 24.8 (s.e. 2.4) kg N ha^{-1} yr^{-1}, respectively, accounting for less than 20% of the N fertilizer input in 2002.

The mean annual increments in coffee biomass (without considering the berries) were similar for the two systems (1.62 t ha^{-1} yr^{-1}, Table 2) but the inclusion of the timber trees resulted in a high additional phytomass (biomass + litter) increment (+ 6.1 t ha^{-1} yr^{-1}). However, the inclusion of the timber trees resulted in a rather low additional N accumulation in phytomass (+20.1 kg N ha^{-1} yr^{-1}) because of the low N content of the trees and tree litter.

Water dynamics and budget

Precipitation, which began in February, was low until April 10th (<100 mm) and high from May to November (200–460 mm $month^{-1}$; Fig. 1). Rainfall was higher than 20 mm in 26% of the daily events, and daily precipitations of more than 50 mm were recorded 13 times, providing 34% of the total annual precipitation (2,624 mm).

Table 2 Annual increment of dry matter (DM), N concentration and annual N accumulation in the different components of biomass (except coffee berries) and litter of two coffee systems in Southern Costa Rica (coffee of 14 years old and eucalyptus tree of 7 years old)

Coffee system	Component	DM (t ha^{-1} yr^{-1})	N concentration (g kg^{-1})	N accumulation(kg ha^{-1} yr^{-1})
Unshaded coffee	Coffee leaves	0.20 ± 0.04	36.9 ± 0.1	7.2 ± 0.2
	Coffee branches	0.19 ± 0.04	9.9 ± 0.1	1.9 ± 0.4
	Coffee stems	0.87 ± 0.14	8.5 ± 0.1	7.4 ± 1.2
	Coffee roots	0.36		5.2
	Total coffee	1.62 ± 0.28		21.7 ± 3.8
	Litter	0.17 ± 0.04	20.0 ± 0.2	3.5 ± 0.8
Total unshaded coffee		1.79 ± 0.32		25.2 ± 4.6
Shaded coffee	Coffee leaves	0.16 ± 0.03	37.2 ± 0.1	6.0 ± 1.0
	Coffee branches	0.19 ± 0.03	7.4 ± 0.1	1.4 ± 0.3
	Coffee stems	0.92 ± 0.09	7.5 ± 0.1	6.9 ± 0.7
	Coffee roots	0.36		4.5
	Total coffee	1.63 ± 0.18		18.8 ± 2.1
	Tree leaves	0.18	23.1 ± 0.1	4.1
	Tree branches	1.30	1.7 ± 0.0	2.2
	Tree stem wood	2.39	0.8 ± 0.0	1.8
	Tree stem bark	0.15	4.2 ± 0.1	0.6
	Tree roots	1.21		2.6
	Total tree	5.22		11.3
	Litter	1.04 ± 0.13	15.5 ± 0.1	15.2 ± 3.1
Total shaded coffee		7.89		45.3

Means ± standard errors; root values are estimated from above ground biomass

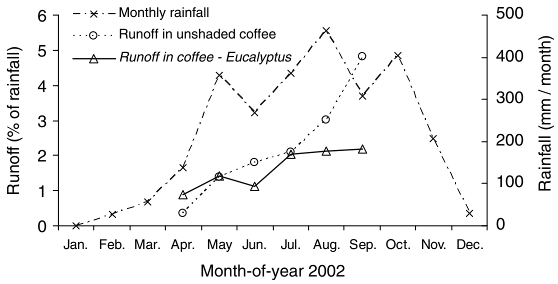

Fig. 1 Monthly rainfall in 2002 and monthly surface runoff expressed as percent of rainfall for the period April–September 2002 in unshaded and shaded coffee in Southern Costa Rica

Surface runoff, expressed as a percent of monthly rainfall, increased during the rainy season with no major differences between treatments until August (Fig. 1). Cumulative runoff from unshaded and shaded coffee was estimated at 3 and 2% of the rainfall during the period April–December, respectively (Table 3).

As already documented by Avila et al. (2004) for the same experiment, at the end of the dry season (2nd April), the soil water content of the 0–120 cm layer was higher under unshaded coffee than in the shaded plot, but from the 21st of May onwards, soil water content under shaded and unshaded coffee were similar (Fig. 2). Throughfall was calculated as a percentage of rainfall and results were grouped for different rainfall event classes (5 mm intervals). Mean throughfall varied from 56 to 93% for daily rainfall amounts of 1–5 to 60–65 mm, respectively (data not shown). For the throughfall monitoring period (April–August 2002; 66 rainfall events with a maximum event of 64 mm d^{-1}) regressions of throughfall (T; mm d^{-1}) versus rainfall (P_g; mm d^{-1}) were computed from daily values for each plot. The linear equations were $T = -0.859 + 0.873$ (s.e. 0.009) * P_g and $T = -0.795 + 0.865$ (s.e. 0.015) * P_g ($R^2 = 0.99$ in both cases) in unshaded and shaded coffee, respectively; i.e., regression parameters of throughfall versus rainfall were similar for the two systems.

Table 3 Components (mm) of the water balance of two coffee systems from April 2nd to December 27th 2002 on an Acrisol in Southern Costa Rica

Water flux	Unshaded coffee		Coffee-*Eucalyptus*	
	(mm)	(% of rainfall)	(mm)	(% of rainfall)
Rainfall	2,509	100	2,509	100
Throughfall	2,083	83	2,060	82
Stemflow	51	2	73	3
Interception (I) [b]	375	15	376	15
Transpiration (T) [a]	521	21	580	23
AET[c] (T + I)	896	36	956	38
Runoff	76	3	51	2
Soil water variation in the top 2 m layer (ΔS)	52	2	141	6
Water drainage	1,485	59	1,361	54

[a] Transpiration is the sum of the daily values obtained by van Kanten and Vaast (2006) in a nearby coffee plantation during the same study period, [b] Interception is the difference between precipitation and the sum of throughfall + stem flow [c] Actual evapotranspiration

Applying these relationships to the daily rainfall values for the whole study period, the total throughfall was estimated at 83 and 82% of total rainfall in unshaded and shaded coffee, respectively (Table 3). Transpiration of shade trees and coffee plants was monitored between January and December 2002 by van Kanten and Vaast (2006) using sap flow probes in a nearby coffee plantation shaded with *Eucalyptus* with similar LAI index values to these found in our shaded plot (2.26 and 1.23 m^2 m^{-2} for the coffee and the shade tree, respectively; total LAI of 3.49 m^2 m^{-2}). We used their transpiration values for the shaded plot and since there was a 20% lower LAI index in unshaded coffee (2.74 m^2 m^{-2}), and according to recent measurements done in the Central Valley of Costa Rica (Siles, personal communication), transpiration in the unshaded coffee plot was reduced by 10% compared to the shaded plot.

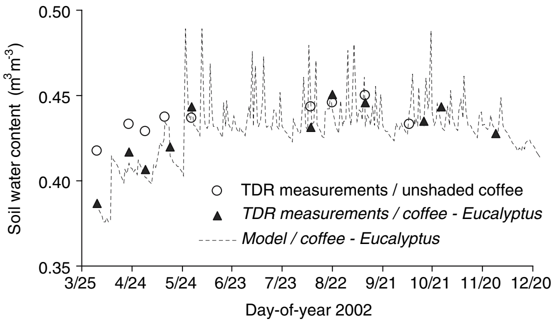

Fig. 2 Measured and modelled soil water contents in the 0–120 cm layer of an Acrisol in unshaded and shaded coffee in Southern Costa Rica

Modeled soil water contents in the shaded plot agreed well with measured values (Fig. 2). The higher estimated annual drainage under unshaded coffee (1,485 mm y^{-1}) than under shaded coffee (1,361 mm y^{-1}) was due to the combined effect of lower transpiration during the rainy season (Table 3) and a lower amount of rainfall required at the beginning of the rainy season in order that soil water content reached field capacity under unshaded coffee.

Net N mineralization in the top soil

During the study period, on average 96% (s.e. 4) of the total mineralized N in the 0–20 cm soil layer was in the NO_3^- form. The daily net N mineralization rates, calculated for a period of 28–30 days, were in the range of 0.2–0.9 mg N kg^{-1} d^{-1} and showed seasonal patterns with significantly lower values ($P < 0.05$) in February and March at the end of the dry season (Fig. 3a). Within each plot, daily rates for each sampling date did not differ significantly beneath or midway between the coffee rows, and no difference was observed between shaded and unshaded coffee. Similar net N mineralization values of 282 and 285 kg N ha^{-1} yr^{-1} were calculated from the daily net N mineralization rates for unshaded and shaded coffee, respectively. However there appeared to be different seasonal patterns of soil mineral N concentrations ($NH_4^+ + NO_3^-$) in the topsoil (0–20 cm) in the two coffee systems (Fig. 3b). Under unshaded coffee, soil mineral N contents were higher ($P < 0.05$) during the dry periods of March 2002 and January 2003 (23–24 mg N kg^{-1}) compared to the remaining dates (8–17 mg N kg^{-1}) whereas no significant differences between sampling dates occurred under shaded coffee. During the dry periods (March, April, December 2002, January and March 2003), the soil mineral N content appeared to be lower under shaded than unshaded coffee whereas no difference occurred between the systems during the wet season (Fig. 3b). Soil NH_4^+-N values were in the range of 0.1–3.8 mg N kg $soil^{-1}$ and tended to be higher under shaded than unshaded coffee. Soil NO_3^--N contents

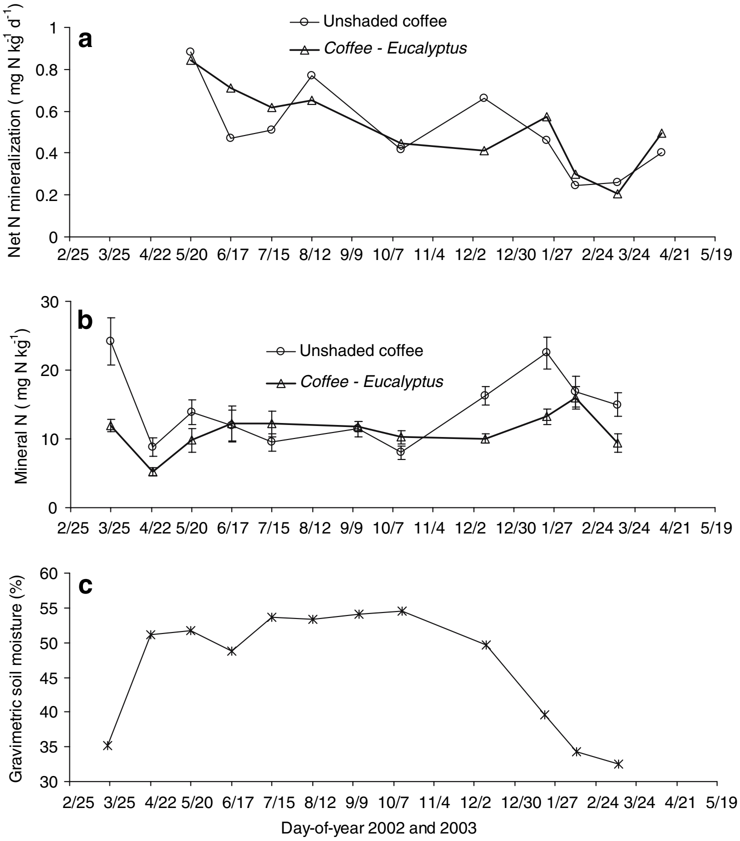

Fig. 3 Net N mineralization (**a**), mineral N (NH_4^+ + NO_3) dynamics (**b**) and soil moisture (**c**) in the top soil (0–20 cm) in unshaded and shaded coffee on an Acrisol in Southern Costa Rica. Vertical bars for (**b**) denote ± SE. For Mineralization data (**a**), standard errors were on average 50% (20–90%) of the average flux

showed the same patterns as mineral N with lower values under shaded (10 mg N kg soil^{-1}) than unshaded coffee (22 mg N kg soil^{-1}) in March 2002 and January 2003. Annual average values of soil NH_4^+/NO_3^- ratio were 0.12 and 0.28 under unshaded and shaded coffee, respectively, with the lowest values during the rainiest months.

N loss in runoff

The mineral N loss in runoff was low. Nitrate + NH_4^+ concentration in the runoff was on average 1.1 (s.e. 0.3) and 1.6 (s.e. 0.7) mg N l^{-1} under unshaded and shaded coffee, respectively. The total loss was 0.86 and 0.85 kg N ha^{-1} yr^{-1} from unshaded and shaded coffee, respectively, which accounted for about 0.5% of the annual N fertilizer input.

Nitrate leaching

At each depth, NO_3^--N concentrations in leached water tended to be higher under unshaded than shaded coffee but there was a high variability (Fig. 4). Annual average NO_3^--N concentrations at 60, 120 and 200 cm depth under unshaded and shaded coffee, were 15.2 ± 4.2, 9.2 ± 1.5 and 1.9 ± 0.7 mg N l^{-1}, and 12.9 ± 2.8, 6.1 ± 1.4 and 1.2 ± 0.5 mg N l^{-1}, respectively. Thus NO_3^--N concentrations were high above 60 cm depth but decreased steadily between 60 and 200 cm. At 200 cm depth, the concentrations were very low and similar to the groundwater NO_3^--N concentrations (1.8 ± 0.6 mg N l^{-1}). Large and rapid variations (+10 to +20 mg N l^{-1}) of NO_3^--N concentration in leached water occurred at 60 cm depth 1–2 months after N fertilizer application whereas much lower and smoother variations occurred later at 120 and 200 cm depth (Fig. 4). As a result, NO_3^--N fluxes at 60 cm depth were 2.5–12 times greater the NO_3^--N fluxes at 120 and 200 cm depth, respectively. At 60 cm depth, NO_3^--N fluxes (268 and 201 kg N ha^{-1} yr^{-1} under unshaded and shaded coffee, respectively) were higher than the amount of N fertilizer supplied. At 120 cm depth, for the same systems, the respective

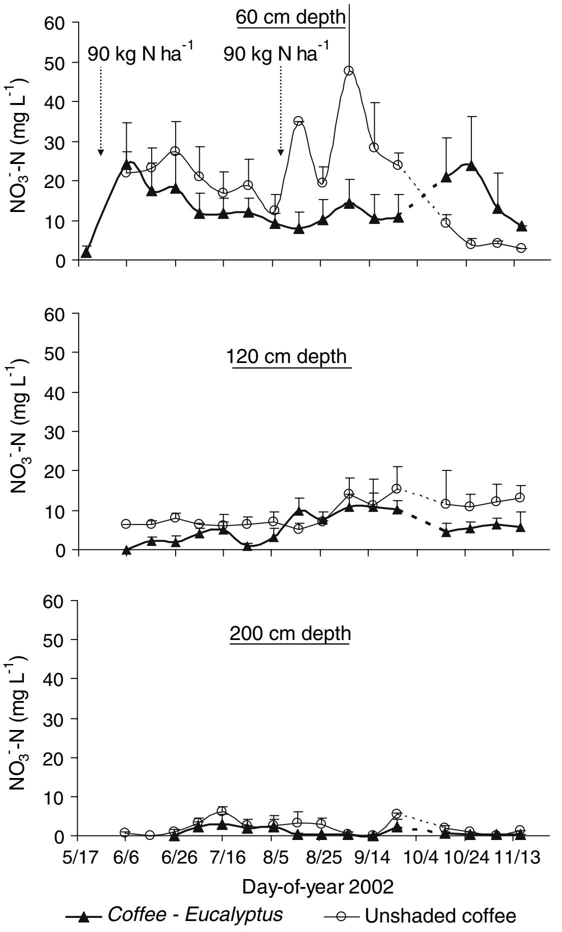

Fig. 4 Nitrate-N concentrations in leached water at depth 60, 120 and 200 cm between May and November 2002 in unshaded and shaded coffee in Southern Costa Rica. The vertical arrows indicate the dates and amounts of fertilizer input in 2002. Vertical bars denote ± SE

NO_3^--N fluxes were 113 and 70 kg N ha^{-1} yr^{-1} and at 200 cm depth, much lower NO_3^--N losses were observed (27 ± 10 and 16 ± 7 kg N ha^{-1} yr^{-1}, respectively).

Nitrate in groundwater

As coffee cultivation was the only land use system managed for more than 10 years in several micro-catchments within the farm, it could have influenced directly the NO_3^--N concentration of the shallow aquifers of these watersheds. A survey conducted in 2001 and 2002 indicated that NO_3^--N concentrations in groundwater averaged 1.8 ± 0.6 mg N l^{-1}. Seasonal patterns were observed with significantly lower values during the dry seasons (0.8–0.9 mg N l^{-1} in March 2001 and 2002, respectively) (Fig. 5). In 2001, the increase in groundwater NO_3^--N concentrations at the beginning of the rainy season was associated with a rise of the water level in the shallow aquifers to a maximum position at the beginning of June (Renderos Durán et al., 2002). Thereafter, small differences between sampling dates during the two rainy seasons were observed, except the relatively high NO_3^--N concentration (5.1 ± 1.0 mg l^{-1} l) which occurred on the 12th of August 2002, just one year after the last fertilizer application to the whole coffee farm.

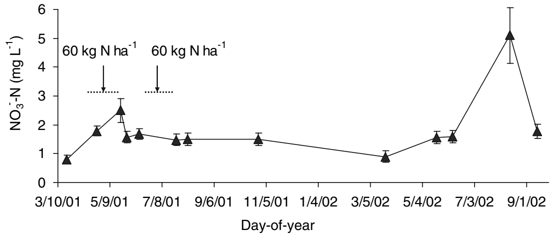

Fig. 5 Nitrate-N concentrations (mg N l^{-1}) in spring waters in the Santa Fe coffee farm between March 2001 and September 2002. The vertical arrows indicate the dates and amounts of fertilizer input; in 2002 no fertilizer was applied except in the experimental plots. Vertical bars denote ± SE

Soil NH_4^+-N + NO_3^--N and Cl^- accumulation in the top 200 cm

At the end of the dry season (April 2, 2002), NH_4^+ accumulation was found in the soil (0–50 cm) at relatively low values (less than 6 mg NH_4^+-N kg soil^{-1}) with no differences between systems (Fig. 6a). Below 160 cm depth, NH_4^+ contents were very low (<0.22 mg NH_4^+–N kg soil^{-1}). Nitrate contents in 0–20 cm were relatively high (39 and 24 mg NO_3^--N kg soil^{-1} under unshaded and shaded coffee, respectively) and decreased until 60 cm depth. Below 60 cm, NO_3^--N contents increased with depth to reach maximum and relatively constant values (about 50 mg NO_3^--N kg soil^{-1}) between 100 and 200 cm in both systems. Below 80 cm depth, accumulation of fertilizer derived Cl^- also occurred. A possible anion adsorption, due to the dominance of positive charges below 80 cm depth was suggested by higher pH values in KCl than in water (Table 1). In fact, 630 (s.e. 90) kg N ha^{-1} of NO_3^--N had accumulated in the first 200 cm of the soil profile (Table 4).

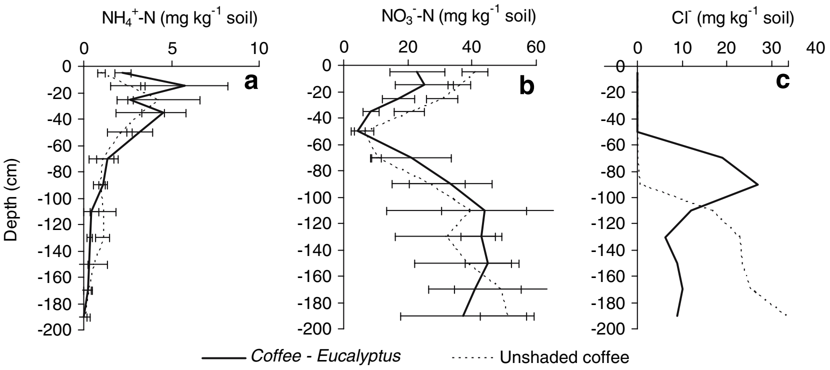

Fig. 6 NH_4^+-N (**a**), NO_3^--N (**b**) and Cl^- (**c**) accumulation in an Acrisol (0–200 cm) under unshaded and shaded coffee in Southern Costa Rica (April 2nd, 2002). For Cl^- data (**c**), standard errors were on average 70% (30–120%) of the average accumulation

Table 4 Nitrate N accumulation in the top 200 cm of an Acrisol in Southern Costa Rica (April 2nd 2002) under unshaded and shaded coffee

Depth (cm)	Unshaded coffee (kg NO_3^--N ha^{-1})	Coffee—*Eucalyptus*
0–60	104 ± 18	68 ± 24
60–120	164 ± 80	200 ± 70
120–200	391 ± 116	336 ± 84
Total profile	658 ± 190	603 ± 68

Means ± standard errors

Nitrous oxide emission

Maximum emissions of 53 and 65.8 µg N_2O-N m^{-2} h^{-1}were measured one and two days after N fertiliser application under shaded and unshaded coffee, respectively (Fig. 7). The increase in N_2O emission between 14 and 21 days after fertilizer application (all plots) could not be explained by changes in rainfall pattern, soil moisture content or soil temperature. On the nine measurement days, the soil temperature at 10 cm depth only varied by less than 2°C (24.1–25.6°C), with the shaded plantation soil being slightly cooler (<1°C) on some of the measurement days. Average gravimetric soil moisture contents were the same for the two sites (53.3 ± 3.9% (w/w)) and only varied from 48 to 61% (w/w) during the June–November 2002 N_2O study period (Fig. 3c).

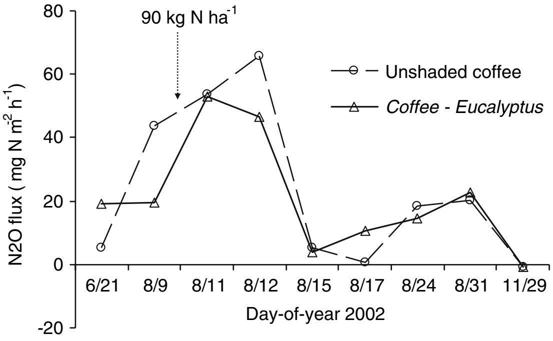

Fig. 7 Nitrous oxide emissions from unshaded and shaded coffee that received N fertiliser on the 11.08.2002. Each data point is the median of 4–5 chamber measurements; standard errors were on average 70% (16–258%) of the median flux

Table 5 Net annual N budget (2002) in unshaded and shaded coffee plantations on an Acrisol in Southern Costa Rica

N Flux	Unshaded coffee (kg NO_3^--N ha^{-1} yr^{-1})	Coffee—*Eucalyptus*
Fertilizer input	180	180
N accumulation in permanent biomass and litter	25.2	45.3
N losses		
N export in coffee beans harvest	34.2	24.8
N_2O-N emission	1.9	1.9
Mineral N loss in runoff	0.9	0.8
Nitrate N leaching 200 cm depth	26.9	15.6
Input—output N fluxes from the soil [a]	90.9	91.6

[a] The difference between fertilizer input and output N fluxes from the soil (including N accumulation in biomass and litter) contributed to soil N accumulation

N budget

A tentative N budget (Table 5) was calculated to compare N input in mineral N fertilizer and N outputs by accumulation in plants, harvest export, leaching, N_2O emission and runoff. N loss through erosion was not measured, but according to the literature, 2–3% runoff should be associated with less than 3 t ha^{-1} yr^{-1} of soil loss (Barthes et al. 2000) and consequently less than 15–20 kg N ha^{-1} yr^{-1}. This possible loss could be partly or totally offset by atmospheric N deposition estimated at 6.8 kg N ha^{-1} yr^{-1} in Monte Verde, Costa Rica (Clark et al. 1998) and at 26.5 kg N ha^{-1} yr^{-1} in a sugar cane production site (burnt annually) in Turrialba, Costa Rica (Imbach et al. 1989a). The difference between the measured input and output fluxes (90 kg N ha^{-1} yr^{-1}) was about half of the N fertilizer input during 2002. This amount, contributing to soil N accumulation, constituted the major flux of the N cycle. In comparison to unshaded coffee, the higher value of N accumulation in biomass and litter of shaded coffee was associated with reduced N leaching (Table 5).

Discussion

N dynamics

Annual average concentrations of NO_3^--N in leached water at 60 cm depth were higher than 10 mg N l^{-1}; a health hazard according to the World Health Organisation. Babbar and Zak (1995) also reported similar high NO_3^--N concentrations at the same depth under shaded (*E. poeppigiana*) and unshaded coffee plantations on a Andosol in Costa Rica where N fertilizer was applied at a high rate (ca. 300 kg N ha^{-1} yr^{-1}). In our study, as a result of high drainage, the corresponding NO_3^--N fluxes accounted for more than 100% of the 2002 N fertilizer input. Nitrogen fertilization and soil N mineralization exceeded by far N accumulation and use (coffee harvests) by the plants indicating a high leaching potential. The measured annual N mineralization (280 kg N ha^{-1} yr^{-1}) was much higher than N fertilization in 2002 but part of this mineralized N may have been derived from previous microbial immobilisation of chemical N fertilizer. Positive fertilizer-mineralization interactions were reported by Kolberg et al. (1999) for cropping systems and by Lee and Jose (2006) for tree plantations. The method used, although adequate to compare adjacent plots, may over-estimate absolute values because roots are cut (Jussy et al. 2004). Nevertheless, daily net mineralization rates (annual average of 0.52 mg N kg $soil^{-1}$ d^{-1}), are within the range of rates reported by other authors from Amazonian topsoils (Schroth et al. 2001; Montagnini and Bushbacher 1989).

In similar conditions of high rainfall and soil permeability, in intensive annual (corn) cropping systems on the Loyalty Islands (New Caledonia), Duwig et al. (1998, 2000) also reported high drainage (488 mm during 100 days) and high rates of NO_3^- leaching at 40 cm depth during the entire growing period, accounting for 128% of the N supplied (104 kg ha^{-1}). However in our trial, nitrate leaching strongly decreased with increasing depth, coinciding with NO_3^- and Cl^- accumulation in the subsoil below 80 cm. Higher pH values in KCl than in water indicated that positive charges prevailed below 80 cm, retarding and mitigating the movement of anions through the soil (Cahn et al. 1992; Qafoku et al. 2000; Qafoku and Sumner 2001; Lehmann et al. 2004). Plant uptake could also contribute to low NO_3^- drainage at 200 cm depth. However, to explain the reduction in NO_3^- drainage between 60 and 120 cm depth, plant uptake should be at least 131–155 kg ha^{-1} yr^{-1} which is very unlikely and not supported by our data on N export and accumulation in biomass and litter. Between 120 and 200 cm depth, where less than 4% of the total fine root mass was located (visual estimate), NO_3^- leaching decreased by 86 and 54 kg NO_3^--N ha^{-1} yr^{-1} under unshaded and shaded coffee, respectively. On the other hand, the accumulation of NO_3^- in this 120–200 cm soil layer ($\approx$360 s.e. 65 kg NO_3^--N ha^{-1}) was between four and six times the difference between the annual NO_3^- fluxes at 120 and 200 cm depth. Thus the reduction in NO_3^- leaching with depth appears to be primarily the result of NO_3^- adsorption in the subsoil.

Other factors, such as the loss of NO_3^- in water runoff and the N_2O emissions, had no significant effect on the N balance and NO_3^- leaching. As a result of low runoff fluxes, losses of NO_3^- in runoff were low. In other agroforestry systems with similar runoff rates, Lal (1989) reported losses of NO_3^--N generally lower than 1 kg ha^{-1} yr^{-1}. The loss of N as N_2O (1.9 ± 2.1 kg ha^{-1} yr^{-1}) also was insignificant compared with NO_3^- leaching. These N_2O losses were similar to those measured in non- fertilized agricultural corn and papaya (1.4 kg N_2O–N ha^{-1} yr^{-1}) but much smaller than those reported from equivalent fertilized corn and papaya plots (25.6 kg N_2O–N ha^{-1} yr^{-1}; Crill et al. 2000) or new pastures in Costa Rica (33–52 kg N_2O–N ha^{-1} yr^{-1}; Keller et al. 1993). The low N_2O emission at Santa Fe should be related to the high porosity and infiltration capacity of this Acrisol.

Whereas Babbar and Zak (1994) found higher net mineralization rates under the canopies of leguminous *Erythrina poeppigiana* shade trees (8–14 yr^{-1}; 200–250 trees ha^{-1}) compared to unshaded coffee plantations, in our study, the *Eucalyptus* shade trees (7 years) did not affect soil N mineralization of the highly fertilized coffee plantation. Lower soil mineral N contents under shaded compared to unshaded coffee during the dry season could be attributed to increased N absorption by the timber tree, which, by this means could reduce NO_3^- leaching. However, NO_3^- leaching rates in the top soil and at 200 cm in the shaded plots suggest that the shade trees were a secondary factor influencing NO_3^- leaching. Moreover, annual accumulation of N in the *Eucalyptus* trees was quite low compared to the amounts of applied N, mineralized N and N found in leached water at 60 cm depth. Furthermore the accumulation of NO_3^- in the sub-soils of both plots was similar (Table 5) suggesting little overall effect of the trees on N leaching.

Agroforestry systems are assumed to cycle nutrients in a more conservative manner than pure monocultures (Schroth et al. 1995; Beer et al. 1998). Increased N accumulation in *Eucalyptus* wood and litter and slightly lower NO_3^- leaching losses in the shaded plantation apparently support this premise. However, coffee berry production (and hence N export in berry harvest) was reduced by 25% under shade in 2002, because shade reduced the flowering intensity and hence the fruit load (Vaast et al. 2005). The coffee production in this zone can be 2.5 times as large as the value measured in 2002 (ICAFE-CICAFE 2000); the bi-annual variation in coffee production may be a major factor influencing N leaching. In years of high production, the negative effect of shade on coffee production could reduce N export in the coffee harvest by 20–30 kg ha^{-1} offsetting the advantage of N accumulation in trees as a means of reducing leaching.

Despite low NO_3^--N concentrations in leached water at 200 cm depth (1.2–1.9 mg N l^{-1}), high drainage rates resulted in significant amounts of leached NO_3^--N (15–27 kg N ha^{-1} yr^{-1}). These NO_3^- concentrations were similar to the average NO_3^- concentration in springs in the different microcatchments of this coffee farm. High precipitation should enhance the leaching of biologically produced and fertilizer derived NO_3^- during the rainy months. However, monthly variations in NO_3^--N concentrations in spring waters were independent of N fertilization dates and corresponded generally to the seasonality of the hydrological cycle (Fig. 5); i.e. the highest concentrations occurred in the rainy season as was observed by Reynolds-Vargas and Richter (1995) in the Central Valley of Costa Rica. During the dry season, the decrease in NO_3^- concentrations in spring waters could be due to NO_3^- retention by positively charged mineral surfaces in the subsoil when the ground water table decreases. More generally, adsorption-desorption processes of NO_3^- anions in the deep soil layers could result in a decrease of NO_3^- concentrations of spring waters in the dry season and an increase at the beginning at the rainy season. The relatively high average NO_3^--N concentration of spring waters (5.1 mg l^{-1}) in the coffee plantation (outside the experimental plots) on August 12th, 2002, in the middle of the rainy season, was probably due to NO_3^- desorption from deep soil layers as no fertilizer had been applied to this coffee plantation for more than one year except in the study plots.

Water dynamics

During the dry season, the lower soil water content in the shaded plot (Avila et al. 2004) was due to increased transpiration resulting from the inclusion of the *Eucalyptus* shade trees (van Kanten and Vaast 2006). Compared to the unshaded system, this higher water uptake of the multistrata system was associated with higher N uptake during the dry period. The other effect of the tree was a reduction of drainage resulting from increased transpiration. Transpiration rates ($\approx$2 mm d^{-1}) as well as interception rates ($\approx$15% of total rainfall) in our coffee plantations were similar to the values reported by Imbach et al. (1989b) for a *C. arabica–Cordia alliodora* system in Turrialba (Costa Rica) in similar site conditions (650 masl; rainfall of 2,000 mm yr^{-1}).

High drainage values (54–59% of rainfall) and low surface runoff (2–3% of rainfall) are explained by the high permeability of soils (average porosity of 63%), minimal slope and intense rainfall events. The runoff values are in agreement with the results reported by Lal (1989) for different alley cropping systems (2–5% of rainfall) and no tillage cropping systems (1.3% of rainfall) in Southern Nigeria (slope of about 7%). Compared to unshaded conditions, the trend toward lower runoff values under shade was probably a result of better protection of the soil surface (from rain splash) by the accumulated litter.

Conclusions

In highly fertilized (≥ 180 kgN ha^{-1} yr^{-1}) coffee plantations cultivated on a Acrisol in Southern Costa Rica, the inclusion of *E. deglupta* as a shade tree (110 trees ha^{-1}; age 7 years; height 19 m): (1) did not affect soil N mineralization; (2) increased N uptake during the dry season and N accumulation in litter and permanent biomass; and (3) slightly reduced water drainage. As a result, these trees contributed to reduce NO_3^- leaching. However in both shaded and unshaded plantations, the coffee and timber trees used only a small fraction of fertilizer and mineralized N, resulting in high N losses through leaching below 60 and 120 cm depth. Accordingly, there is a high risk of NO_3^- contamination when streamwater comes from shallow soil water particularly on slopes and at the bottom of microcatchments. Fertilizer practices in conventional coffee plantations should be refined to match plant needs and reduce nitrate leaching. Furthermore, coffee producers should be encouraged to maintain or switch back to cost effective and environmentally sound N inputs such as the establishment and/or conservation of leguminous shade trees in addition to the use of timber trees.

In the present study, NO_3^- leaching to groundwater at 200 cm depth, and in spring waters, was drastically reduced because of a strong anion retention in the subsoil at this site. This process may delay and mitigate groundwater contamination in large areas of Central and South America where Acrisols are heavily fertilized. On the other hand, environmental damage, caused by excessive fertilizer use on these soils, may not be detected promptly and deleterious effects could continue long after management practices have been corrected.

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