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ORIGINAL PAPER

Fluxes of greenhouse gases from Andosols under coffee in monoculture or shaded by *Inga densiflora* in Costa Rica

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Abstract The objective of this study was to evaluate the effect of N fertilization and the presence of N_2 fixing leguminous trees on soil fluxes of greenhouse gases. For a one year period, we measured soil fluxes of nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4), related soil parameters (temperature, water-filled pore space, mineral nitrogen content, N mineralization potential) and litterfall in two highly fertilized (250 kg N ha^{-1} $year^{-1}$) coffee cultivation: a monoculture (CM) and a culture shaded by the N_2 fixing legume species *Inga densiflora* (CIn). Nitrogen fertilizer addition significantly influenced N_2O emissions with 84% of the annual N_2O emitted during the post fertilization periods, and temporarily increased soil respiration and decreased CH_4 uptakes. The higher annual N_2O emissions from the shaded plantation (5.8 ± 0.3 kg N ha^{-1} $year^{-1}$) when compared to that from the monoculture (4.3 ± 0.1 kg N ha^{-1} $year^{-1}$) was related to the higher N input through litterfall (246 ± 16 kg N ha^{-1} $year^{-1}$) and higher potential soil N mineralization rate (3.7 ± 0.2 mg N kg^{-1} d.w. d^{-1}) in the shaded cultivation when compared to the monoculture (153 ± 6.8 kg N ha^{-1} $year^{-1}$ and 2.2 ± 0.2 mg N kg^{-1} d.w. d^{-1}). This confirms that the presence of N_2 fixing shade trees can increase N_2O emissions. Annual CO_2 and CH_4 fluxes of both systems were similar (8.4 ± 2.6 and 7.5 ± 2.3 t C-CO_2 ha^{-1} $year^{-1}$, -1.1 ± 1.5 and 3.3 ± 1.1 kg C-CH_4 ha^{-1} $year^{-1}$, respectively in the CIn and CM plantations) but, unexpectedly increased during the dry season.

Keywords Agroforestry · CH_4 · CO_2 · Mineralization · N_2O · Water-filled pore space (WFPS)

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Introduction

Agricultural activities account for about 13.5% of global greenhouse gas (GHG) emissions (Rogner

et al. 2007). The dominant greenhouse gases nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) are mainly products of microbial processes in soils and ruminants (Baumert et al. 2005). Denitrification and nitrification are the main processes to form N_2O. Denitrification is the anaerobic reduction of NO_3^- and NO_2^- to N_2O and N_2 and nitrification is the aerobic oxidation of NH_4^+ to NO_2^- and NO_3^-, with N_2O production under either oxic or anoxic (nitrifier denitrification; Wrage et al. 2001; Chapuis-Lardy et al. 2007) conditions (Hergoualc'h et al. 2007). The soil atmosphere CH_4 flux is the result of the balance between the two offsetting processes of methanogenesis (CH_4 production) and methanotrophy (bacterial oxidation of CH_4) (Verchot et al. 2000). The CO_2 emitted from the soil surface results from (1) metabolic activity of roots and associated mycorrhizae, (2) heterotrophic respiration from microbial communities using recently added organic material as an energy substrate, and (3) decomposition of older, more recalcitrant carbon compounds (Ryan and Law 2005).

Many studies have revealed that N fertilization in agriculture increases N_2O emissions from soil (Stehfest and Bouwman 2006) and decreases the uptake of atmospheric CH_4 (Chu et al. 2007; Hütsch et al. 1993). Soil respiration may or may not be stimulated by N fertilization (Raich and Schlesinger 1992). N_2 fixing leguminous trees are commonly used in coffee agroforestry to provide shade, which moderates the microclimate for the benefit of the understorey crop and/or bring N and organic matter to the system (Vaast et al. 2008; Verchot et al. 2008). The suspected contribution of N fixing species to increase soil emissions of N_2O (Rochette and Janzen 2005; Verchot et al. 2008) and reduce the soil CH_4 sink (Palm et al. 2002) is a growing concern in the sustainable development framework. To date results in the literature are contradictory (Verchot et al. 2008).

In the last few decades, in Central America, old coffee (*Coffea arabica*) varieties have been replaced with more productive varieties (e.g. Caturra, Catuai) planted under heavily pruned leguminous trees (e.g. *Erythrina poeppigiana, Inga* sp.), timber trees or in unshaded monocultures (Babbar and Zak 1994). Accompanying this change was the increased use of N fertilizers, particularly in Costa Rica where annual fertilizer input are between 150 and 350 kg N ha^{-1} $year^{-1}$. These intensively managed coffee plantations show low efficiency in N fertilizer use, with more than 50% of the annual N fertilizer added lost through nitrate leaching (Harmand et al. 2007a; Harmand et al. 2007b). Nowadays coffee monocultures and agroforestry systems with legume or timber trees represent 40 and 60% of all cultivations, respectively in Costa Rica (Vaast and Harmand 2002).

Although coffee agriculture represents 7.5% of the world's permanent crops (FAO 2005), very few studies have quantified its contribution to GHG emissions. The aim of this paper was to investigate GHG emissions under two types of coffee cultivation (monoculture vs. shaded culture by N_2 fixing leguminous trees) in intensively managed systems in the tropics. We compared the two coffee cultivation plantations by examining seasonal variations in GHG fluxes, related soil parameters and litterfall. We analyzed the variables determining GHG fluxes as well as the impact of N fertilization on GHG emissions.

Materials and methods

Site description and experimental design

The study area was located at the Research Station of the Coffee Institute of Costa Rica (Icafé), in the Central Valley at San Pedro de Barva, 10 km west of San José, Costa Rica (10°02′ N, 84°08′ O; 1,180 m above sea level). The mean annual air temperature was about 21°C and the annual precipitation was about 2,300 mm with a pronounced dry season from January to April. From 1/10/04 until 30/09/05, the total rainfall was 2,886 mm. According to the rainfall pattern (Fig. 1e), the dry season began on 4/11/04 and ended on 27/03/05. The soil, typically well structured, deep and permeable derived from the weathering of volcanic ashes; belonged to Andosols [IUSS (International Union of Soil Sciences) Working group WRB 2006] and was classified as a Dystric Haplustands (Mata and Ramírez 1999). The slope of the site was about 5%.

We worked in two adjacent 1,300 m^2 coffee plantations. One was a monoculture (CM), and the other one was shaded by the N_2 fixing leguminous tree *Inga densiflora* (CIn). Both systems were established in June 1997. Landuse for at least the previous 10 years was a coffee monoculture in the case of CIn

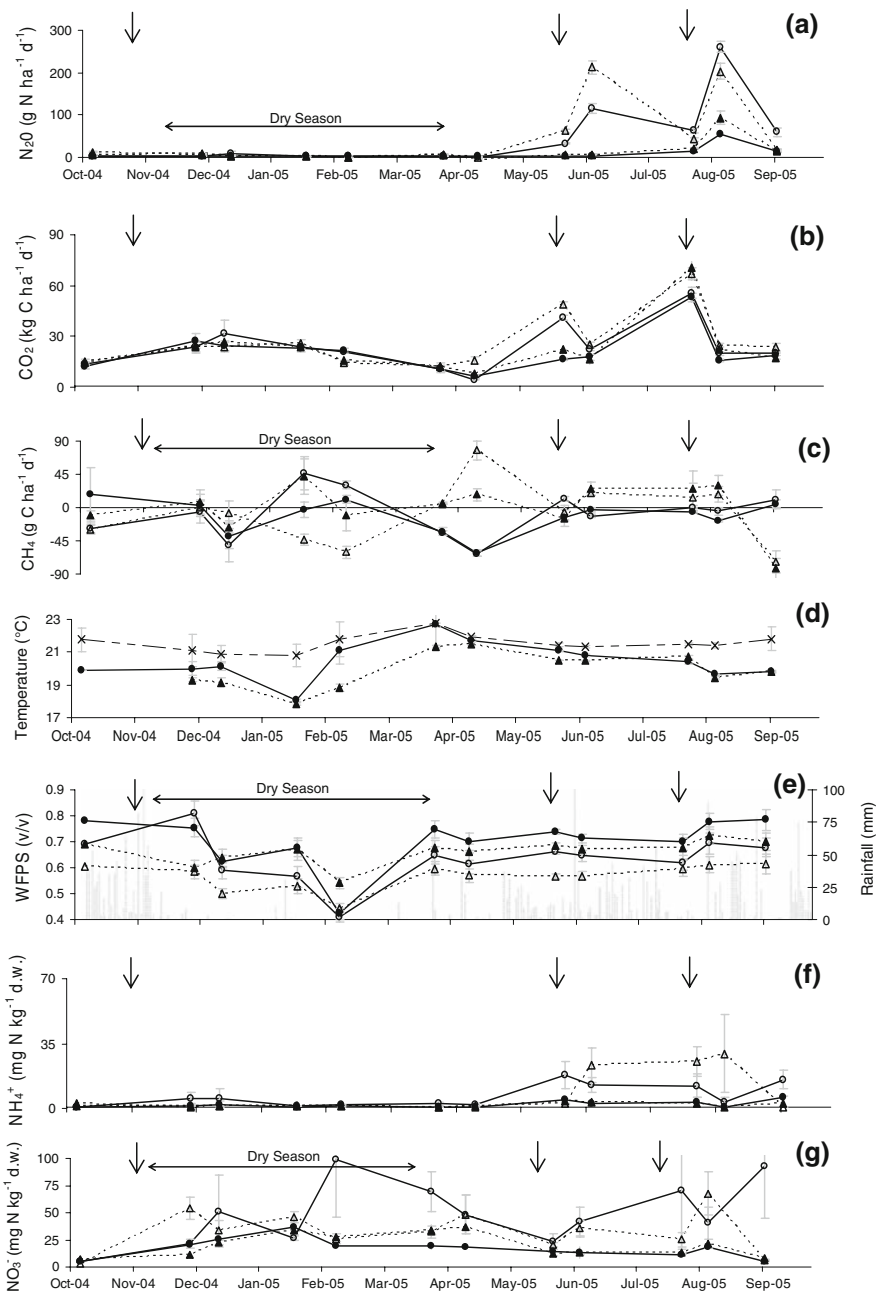

Fig. 1 Mean and standard error of monthly soil fluxes of (**a**) N_2O, (**b**) CO_2, (**c**) CH_4, (**d**) air and soil temperature, (**e**) water-filled pore space (WFPS), (**f**) soil NH_4^+ and (**g**) NO_3^- contents for the fertilized (FZ) and the non fertilized (NFZ) zones of the soil in two coffee plantations. Symbols used are as follows: open and solid circles, FZ and NFZ, respectively, in the monoculture; open and solid triangles, FZ and NFZ, respectively, in the shaded plantation. Solid lines are for the monoculture and dashed lines for the shaded plantation. Soil temperature was measured independently to the zone of fertilizer application then symbols used for Fig. 1d are solid circles, soil temperature in the monoculture; solid triangles, soil temperature in the shaded plantation; crosses, air temperature. In Fig. 1e daily rainfall is symbolized by the grey bars. The arrows indicate the fertilization events

and coffee associated with a small number of *Eucalyptus* tree species in the case of CM. In the CIn plantation *Coffea arabica* var. Catuaí was planted at 2 × 1 m (4,722 plants ha^{-1}) and *Inga densiflora* at 6 × 6 m within the coffee rows (278 trees ha^{-1}, height 7 m in 2004). In the CM plantation, coffee was planted at 2 × 1 m (5,000 plants ha^{-1}). Both plantations were fertilized with an annual average of 250 kg N ha^{-1}, 30 kg P ha^{-1} (triple super phosphate), 100 kg K ha^{-1} (KCl) and 80 kg Mg ha^{-1} (MgO). During the experimental period (6/10/04 to 8/09/05), fertilizer N was applied as NH_4NO_3 at 70 kg N ha^{-1} on 29/10/04 and urea (NPKMg: 18-3-10-8) at 90 kg N ha^{-1} on both 24/05/05 and 26/07/05.

From 6/10/04 until 8/09/05, we measured the soil temperature; water-filled pore space (WFPS), N mineral content and fluxes of greenhouse gases. Two complementary sampling regimes were carried out.

The first regime comprised measurements taken at regular intervals (monthly) over the year. The second regime involved intensive sampling during the period immediately following N fertilization, a time which was expected to include greater greenhouse gases fluxes. In May 2005, soil and gas measurements were made daily from one day prior to fertilizer application (23/05) until 7 days after application (31/05) and thereafter 10 (03/06), 13 (06/06) and 21 days (14/06) after fertilization. Again in July 2005, soil and gas samples were taken at 3 (29/07), 16 (11/08) and 44 days (08/09) following fertilizer application. With regards to the climate and fertilization events (Table 2) we have divided the experimental measurements into four periods: measurements made (1) during the dry season (DS) (4/11/04 to 27/03/05), (2) during the wet season before fertilization (WS Pre Fert) (01 to 28/10/05 and 28/03/05 to 23/05/05), (3) during the wet season following the May fertilization (WS Post Fert May, named the post fertilization period of May–July) (24/05/05 to 25/07/05) and (4) during the wet season following the July fertilization (WS Post Fert July, named the post fertilization period of July–September) (26/07 to 26/09/05).

The granular fertilizer was spread by hand to the base of the coffee plants. Therefore, a distinction was made between the fertilized zone (FZ); a 0.26 m^2 square centred 0.25 m uphill from the coffee plant and the non fertilized zone (NFZ); the rest of the plot. The FZ and NFZ represented 13 and 87% of the total area, respectively. The soil WFPS, N mineral content and fluxes of greenhouse gases were extrapolated at the plantation scale using the proportion occupied by each zone of the total plantation area: $var = 87\% var_{NFZ} + 13\% var_{FZ}$, with var_{FZ} and var_{NFZ} the mean values of the variable in the fertilized and non fertilized zones, respectively.

Soil properties

In May 2003, soil was sampled at 10 cm depth intervals in the top 40 cm layer, 40–50 cm from the coffee plant. Samples were collected from five locations in the CM plantation. Due to the presence of the *Inga* trees in the CIn plantation, four soil samples each were collected 2 and 4 m away from the shade tree. Samples were air-dried, sieved (2 mm) and analysed for total C and N by dry combustion using an automatic CHN analyser. Soil pH in water was measured using a standard pH electrode and particle size distribution by following the hydrometer (Bouyucos) procedure (Henríquez and Cabalceta 1999). Cation exchange capacity (CEC) was determined by extraction with 1 M ammonium acetate at pH 7.0 (Sumner and Miller 1996) and particle density (method of kerosene) was determined as described by Henríquez and Cabalceta (1999). The soil bulk density was determined with the core method (Grimaldi et al. 2003), using 100 cm^3 volumetric cylinders in two soil pits. In each zone (FZ: 50 cm away from the coffee rows and NFZ: midway between the rows) of each plantation, three cylinders were collected for every 10 cm depth down to 40 cm.

The soil was acidic, with the pH in the CIn treatment tending to be lower than in the CM treatment (Table 1). As with most Andosols, the soil total C content was large. It was similar between the treatments, except in the 20–30 cm layer ($P < 0.05$) which had a greater total C content in the CM than in the CIn plantation. Total soil N for the 0–10 cm layer was higher ($P < 0.05$) in the CIn than in the CM treatment. The C:N ratio was smaller ($P < 0.05$) in the CIn than in the CM treatment, with respective means for the 0–10 cm layer of 10.4 ± 0.0 and 11.4 ± 0.0. At all measured depths the CM treatment had a greater clay content ($P < 0.05$), less silt ($P < 0.05$) and less sand in the top 10 cm ($P < 0.05$), when compared to the CIn treatment. The soil bulk densities were higher ($P < 0.05$) in the CM than in the CIn treatment at all depths midway between the coffee rows (NFZ) and in the top 10 cm near the base of the coffee plants (FZ). The C.E.C. and particle densities of both soils were similar.

Soil fluxes of greenhouse gases (N_2O, CO_2 and CH_4)

Gas samples were collected from static chambers which consisted of a round PVC base (0.1 m^2), hermetically sealed using a lid equipped with a small centre port for gas sampling. In both plantations, and for each position (FZ and NFZ), six chambers were deployed into the soil to 5 cm depth, two weeks prior to initial measurements. In the CIn plantation, chambers were installed 2 m from the *Inga* trees. Eight samples of surrounding ambient air close to chamber were taken immediately prior to chamber closure, four for N_2O and four for both CO_2 and CH_4

Table 1 Properties of the soils of the coffee monoculture (CM) and the *Inga* shaded plantation (CIn) in the Central Valley of Costa Rica

	CM		CIn	
pH				
0–10	4.92^{α} (0.24)		4.67^{α} (0.06)	
10–20	5.45^{α} (0.22)		5.18^{α} (0.11)	
20–30	5.53^{α} (0.11)		5.44^{α} (0.07)	
30–40	5.65^{α} (0.11)		5.53^{α} (0.03)	
Total C (%)				
0–10	3.60^{α} (0.14)		3.70^{α} (0.16)	
10–20	3.18^{α} (0.11)		2.87^{α} (0.13)	
20–30	2.88^{β} (0.1)		2.50^{α} (0.11)	
30–40	2.50^{α} (0.16)		2.33^{α} (0.16)	
Total N %				
0–10	0.32^{α} (0.01)		0.36^{β} (0.01)	
10–20	0.28^{α} (0.01)		0.28^{α} (0.01)	
20–30	0.26^{α} (0.01)		0.24^{α} (0.01)	
30–40	0.22^{α} (0.02)		0.23^{α} (0.01)	
C.E.C [a] (cmol kg^{-1})				
0–30	42.47		44.12	
30–90	41.18		41.17	
Sand/Silt/Clay (%)				
0–10	$37.3^{\alpha}/35^{\alpha}/27.8^{\beta}$ (0.9/0.9/0.9)		$40.6^{\beta}/37.1^{\beta}/22.3^{\alpha}$ (0.7/0.4/0.7)	
10–20	$35^{\alpha}/34.7^{\alpha}/30.3^{\beta}$ (0.8/0.8/0.9)		$37.4^{\alpha}/38.6^{\beta}/24.1^{\alpha}$ (1.3/0.8/0.9)	
20–30	$35.3^{\alpha}/34.4^{\alpha}/30.3^{\beta}$ (0.6/0.9/0.9)		$35.1^{\alpha}/39.7^{\beta}/25.2^{\alpha}$ (0.9/0.8/0.7)	
30–40	$38.5^{\alpha}/31.9^{\alpha}/29.6^{\beta}$ (0.7/0.8/1.3)		$37.4^{\alpha}/40.2^{\beta}/22.5^{\alpha}$ (0.8/1.1/1.0)	
Particle density (g cm^{-3})				
0–10	2.53^{α} (0.00)		2.53^{α} (0.01)	
10–20	2.55^{α} (0.01)		2.56^{α} (0.00)	
20–30	2.58^{α} (0.02)		2.58^{α} (0.01)	
30–40	2.58^{α} (0.01)		2.59^{α} (0.02)	
Bulk density (g cm^{-3})	FZ	NFZ	FZ	NFZ
0–10	0.98^{β} (0.02)	1.04^{β} (0.02)	0.86^{α} (0.01)	0.93^{α} (0.02)
10–20	0.98^{α} (0.03)	1.02^{β} (0.02)	0.92^{α} (0.03)	0.91^{α} (0.02)
20–30	0.91^{α} (0.02)	0.95^{β} (0.01)	0.92^{α} (0.01)	0.89^{α} (0.02)
30–40	0.88^{α} (0.01)	0.93^{β} (0.01)	0.90^{α} (0.00)	0.89^{α} (0.01)

FZ, Fertilized Zone; NFZ, Non Fertilized Zone; Mean (standard error)

[a] Cation Exchange Capacity, no repetition of the measurement

Means for the two coffee systems followed by different letters (α, β) are significantly different from each other ($P < 0.05$)

analyses. Chambers were closed and after 1 h, a 60 ml gas sample was taken by syringe from the enclosed chamber head space and transferred to four 10 ml pre-evacuated glass vials (Exetainers); two for N_2O analysis and two for both CO_2 and CH_4 analyses. The increase in N_2O, CO_2 and CH_4 concentrations had previously been verified to be linear during this 1-h closure period. Filled Exetainer vials were sealed with lacquer, normally used to seal wine bottles, to avoid leakage during storage and transportation for subsequent analysis. All samples were analyzed within 1 month. The conservation of gas concentrations over one month was periodically tested with sets of standards; some of which remained at the laboratory in Scotland with others being sent from CEH, UK to CATIE, Costa Rica by air and back. Gas samples were analyzed using a Hewlett Packard 5890 chromatograph, fitted with an electron capture detector for N_2O analysis and with a flame ionisation detector and a methanizer for analysis of

CH_4 and CO_2. The gases were separated on Poropak Q columns. Soil fluxes of greenhouse gases were calculated from the product of the volume of air enclosed (25 l) and the difference between N_2O concentration of ambient air and chambers divided by the chamber area and time of enclosure. The fertilizer rates applied to the chambers placed in the FZ was calculated as the surface ratio between the chamber and FZ multiplied by the rates applied to the FZ. Annual fluxes of greenhouse gases were estimated by linear interpolation between the measurement dates.

Additional measurements

Between 6/10/04 and 8/09/05, and concomitant with gas flux measurements, soil temperature was measured with a thermometer in the shade at 5 cm depth and soil was sampled from the top 10 cm to analyze for gravimetric moisture and mineral nitrogen content (NH_4^+, NO_3^-). In both plantations, soil was sampled from six random locations in each position (FZ and NFZ), stored in plastic bags at 4°C for 14 h and analyzed. Gravimetric soil moisture was measured by oven-drying a sub-sample at 105°C for 24 h. The WFPS was calculated by the formula proposed by Linn and Doran (1984) and the porosity was calculated from the bulk density (γ_d) and the particle density (γ_s) as $(1 - \gamma_d/\gamma_s)$ (Table 1). Both NO_3^- and NH_4^+ were extracted by shaking a subsample of 10 g soil with 100 ml KCl for 1 h. Suspensions were centrifuged for 5 min at 1,260*g* and the supernatants were filtered through Whatman 42 filters. Extracts were stored at 4°C and analyzed within 10 days by colorimetry (Alliance® Integral Futura equipment) (Mulvaney 1996).

The soil N mineralization potential was determined on seven soil samples from CM and five from CIn, by measuring the difference between final and initial ammonium content (analysis as described above) of fresh soil, incubated under anaerobic conditions at 40°C for 7 days (Anderson and Ingram 1993).

In each coffee plantation, litterfall was collected monthly from October 2003 until September 2004 in six wooden litter traps (0.5 m^2; two quadrats of 0.5 × 0.5). One quadrate was placed beside a coffee plant and the other on the central line midway between coffee rows. Litter was separated by vegetative part (leaves, branches, fruits and flowers) and by species (coffee and *Inga* trees), oven-dried (65°C) to constant weight, weighed and analyzed for N (dry combustion).

Statistics analysis

Statistical analysis was performed using the software InfoStat (2004), with a probability level of 5% to test the significance of the treatments effects. The distribution of each variable was tested using the test of Shapiro–Wilks with the entire data set for each variable. The *t*-test or the non parametric test of Mann–Whitney, were used to compare two means for normally and not normally distributed variables, respectively. For multicomparison ANOVA and the non parametric test of Kruskal Wallis were performed, respectively, on normally and not normally distributed variables. Comparisons were made between periods within a coffee system and between coffee systems within given periods. For the variables extrapolated at the plantation scale using weights of 0.13 and 0.87, respectively for the FZ and the NFZ, the statistical tests were performed on the weighted data. Stepwise linear multiple regression was performed to identify the independent variables that were significantly related to soil fluxes of N_2O, CO_2 and CH_4. The analysis considered the continuous variables only (i.e., rainfall, soil and air temperature, WFPS, soil mineral N concentrations, soil fluxes of N_2O, CO_2 and CH_4). The annual litterfall was not included in the analysis since the measurements were not carried out on the same year as soil fluxes of GHG measurements. The linear models were established with the complete data set or with the data set of each plantation. The coefficient of determination r^2 of the regression model describes the degree of linear association. The reliability of a parameter is given as its significance ($*P < 0.05$; $**P < 0.01$; $***P < 0.001$).

Results

Soil fluxes of greenhouse gases

Soil N_2O fluxes and their natural log transformation values were not normally distributed. Before the May fertilization soil N_2O emissions from both treatments were low (<12 g N ha^{-1} day^{-1}) and showed similar temporal dynamics in the FZ and NFZ in both systems (Fig. 1a). After the May and July fertilizations, N_2O

fluxes clearly increased, especially in the FZ (Fig. 1a). N_2O fluxes in the FZ increased linearly to maxima of 167.4 ± 29.3 and 241.5 ± 27.0 g N ha^{-1} day^{-1}, 21 days (14/06) after the May fertilization in the CM and CIn treatments, respectively (Fig. 2a). Sixteen days after the July fertilization (11/08), N_2O fluxes increased to similar values of 261.1 ± 12.6 and 202.9 ± 18.7 g N ha^{-1} day^{-1}, in the FZ of the CM and the CIn plantations, respectively (Fig. 1a). Emissions of N_2O in the NFZ, on 11/08/05, also increased to

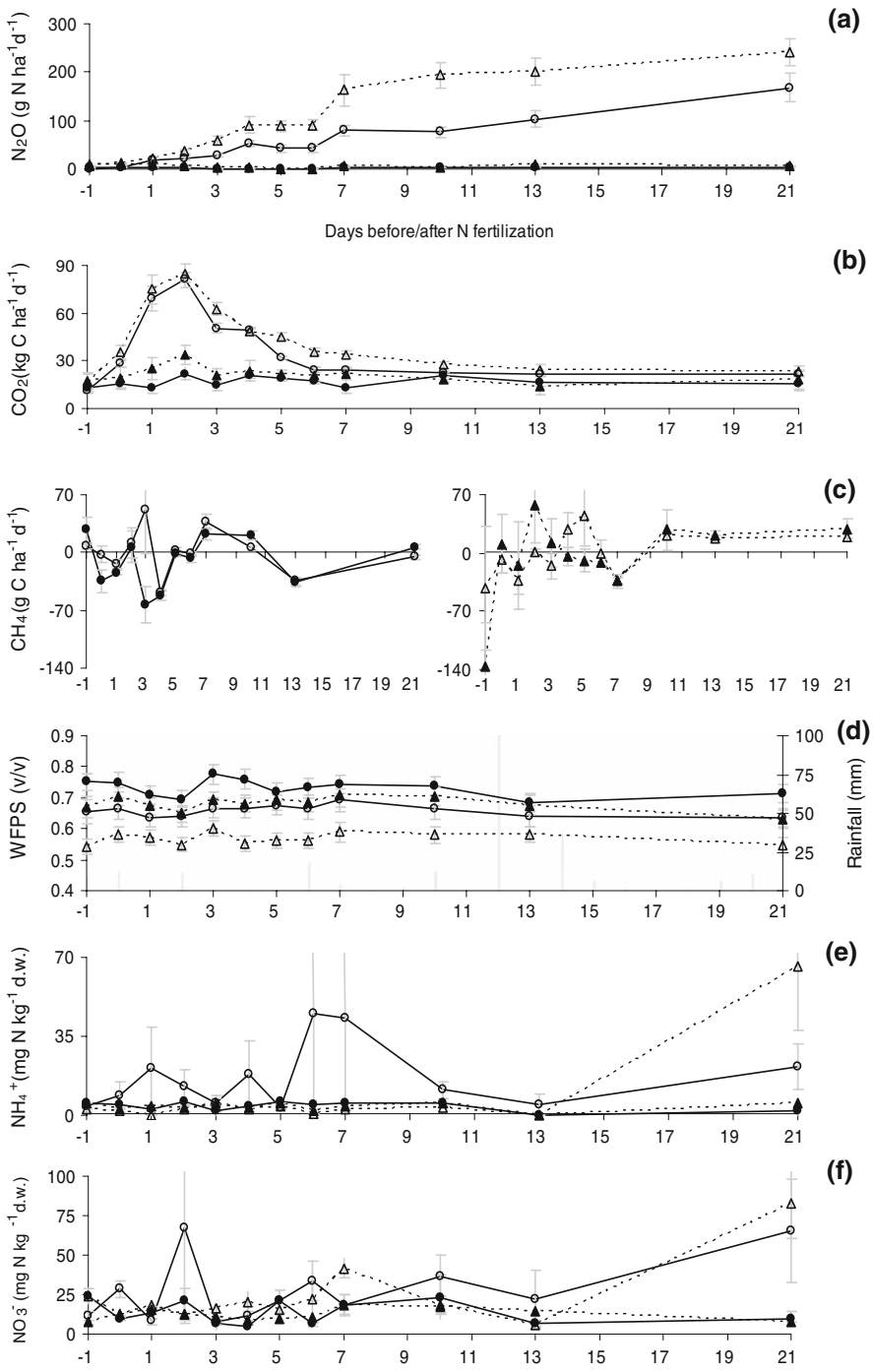

Fig. 2 Mean and standard error of daily soil fluxes of (**a**) N_2O, (**b**) CO_2, (**c**) CH_4 (in the monoculture on the left, in the shaded plantation on the right), (**d**) water-filled pore space (WFPS), (**e**) soil NH_4^+ and (**f**) NO_3^-contents for the fertilized (FZ) and the non fertilized (NFZ) zones of the soil in two coffee plantations after urea application (90 kg N ha^{-1}) in May 2005. Symbols used are as follows: open and solid circles, FZ and NFZ, respectively, in the monoculture; open and solid triangles, FZ and NFZ, respectively, in the shaded plantation. Solid lines are for the monoculture and dashed lines for the shaded plantation. In Fig. 1d daily rainfall is symbolized by the grey bars

values of 54.8 ± 4.7 and 93 ± 15.3 g N ha^{-1} day^{-1}, in the CM treatment and the CIn treatment, respectively (Fig. 1a). On 08/09, 44 days after the fertilizer application of July, N_2O fluxes were still higher than during the wet season period previous to fertilization, with values of 59.3 ± 10.8 and 17.9 ± 1.2 g N ha^{-1} day^{-1} in the FZ and 13.0 ± 2.4 and 13.5 ± 1.7 g N ha^{-1} day^{-1} in the NFZ of the CM and the CIn treatments, respectively.

In the CIn plantation, average N_2O fluxes were significantly lower during the dry season than during the wet season before fertilization however the opposite was observed in the CM plantation ($P = 10^{-4}$) (Table 2). During the wet season, mean emissions of N_2O were more than three times higher after the fertilization events than before and were more influenced by the July than May fertilization (Table 2), mainly due to high emissions from the NFZ in July (Fig. 1a). Mean soil N_2O emissions were higher in the CIn than in the CM treatment during the wet season ($P < 0.003$), although not significantly after the July fertilization (Table 2). Annual N_2O fluxes were more than four times greater in the FZ than in the NFZ and were calculated to be 1.3 times higher from the CIn plantation than from the CM plantation (Table 4).

Neither soil CO_2 fluxes nor their natural log transformations were normally distributed. Before the May and July fertilizations, soil respiration rates of both plantations were similar in the FZ and NFZ (Fig. 1b). In November, at the beginning of the dry season, soil respiration increased and remained high throughout this season (Fig. 1b). Two days after urea application in May, soil respiration in the FZ increased to maxima of 81.0 ± 4.6 and 87.5 ± 7.1 kg C ha^{-1} day^{-1}, respectively in the CM and CIn treatments (Fig. 2b). Subsequently, soil respiration decreased to levels similar to those prior to fertilization (Fig. 2b). Three days after the July fertilization (29/07), soil respiration was large, with values of 55.7 ± 3.0 and 53.1 ± 2.6 kg C ha^{-1} day^{-1}, respectively in the FZ and NFZ, of the CM plantation; and 66.9 ± 3.5 and 70.3 ± 4.2 kg C ha^{-1} day^{-1}, respectively in the FZ and NFZ, of the CIn plantation (Fig. 1b).

In both systems, mean soil respiration was about twice higher during the dry season than during the wet season before fertilization (Table 2). During the wet season, in both coffee plantations, average soil respiration was higher ($P < 10^{-4}$) during the two

Table 2 Means (SE) of soil temperature, WFPS, NH_4^+ and NO_3^- concentration, N_2O, CO_2 and CH_4 fluxes in the coffee monoculture (CM) and the *Inga* shaded coffee plantation (CIn), during the dry season (DS, 4/11/04 to 27/03/05) and the wet season (WS)

	CM				CIn			
	DS	WS			DS	WS		
		Pre Fert	Post Fert May	Post Fert July		Pre Fert	Post Fert May	Post Fert July
T (°C)	19.9 (0.3)$^{a\beta}$	22.1 (0.2)$^{c\beta}$	20.9 (0.1)$^{b\beta}$	20.0 (0.1)$^{a\alpha}$	18.7 (0.2)$^{a\alpha}$	21.2 (0.1)$^{d\alpha}$	20.5 (0.0)$^{c\alpha}$	20.0 (0.1)$^{b\alpha}$
WFPS (%)	61.5 (3.3)$^{a\alpha}$	72.6 (1.0)$^{a\beta}$	72.0 (0.5)$^{a\beta}$	74.2 (1.5)$^{a\alpha}$	60.1 (1.5)$^{a\alpha}$	65.8 (0.7)$^{ab\alpha}$	66.7 (0.5)$^{b\alpha}$	68.8 (1.2)$^{b\alpha}$
NH_4^+ (mg N kg^{-1})	1.8 (0.4)$^{a\alpha}$	2.1 (0.6)$^{a\alpha}$	5.7 (0.9)$^{b\alpha}$	4.2 (1.0)$^{b\alpha}$	1.3 (0.3)$^{a\alpha}$	2.3 (0.7)$^{a\alpha}$	4.1 (0.6)$^{a\alpha}$	4.0 (1.1)$^{a\alpha}$
NO_3^- (mg N kg^{-1})	29.3 (3.7)$^{b\alpha}$	21.6 (2.4)$^{ab\alpha}$	15.4 (1.8)$^{a\alpha}$	19.9 (3.5)$^{ab\alpha}$	27.9 (2.4)$^{b\alpha}$	25.2 (4.2)$^{ab\alpha}$	14.2 (1.1)$^{a\alpha}$	16.7 (2.5)$^{ab\alpha}$
N_2O (g N ha^{-1} d^{-1})	3.4 (0.3)$^{b\beta}$	2.1 (0.3)$^{a\alpha}$	9.4 (0.7)$^{c\alpha}$	40.1 (3.9)$^{d\alpha}$	2.5 (0.3)$^{a\alpha}$	5.2 (1.2)$^{b\beta}$	17.9 (1.1)$^{c\beta}$	48.4 (7.1)$^{d\alpha}$
CO_2 (kg C ha^{-1} d^{-1})	23.9 (1.1)$^{b\alpha}$	9.8 (0.8)$^{a\alpha}$	20.0 (0.9)$^{b\alpha}$	29.8 (2.7)$^{b\alpha}$	22.5 (1.2)$^{b\alpha}$	11.8 (1.1)$^{a\alpha}$	24.7 (1.4)$^{bc\alpha}$	36.8 (3.8)$^{c\alpha}$
CH_4 (g C ha^{-1} d^{-1})	−5.6 (6.1)$^{b\alpha}$	−26.4 (7.3)$^{a\alpha}$	−12.6 (4.0)$^{b\alpha}$	−6.1 (2.1)$^{b\alpha}$	−2.0 (8.0)$^{a\alpha}$	−7.0 (9.8)$^{a\beta}$	6.7 (6.9)$^{a\beta}$	−10.0 (11.8)$^{a\alpha}$

The wet season is divided into three periods: the pre-fertilization period (1 to 28/10/04 and 28/03/05 to 23/05/05), the post fertilization period of May–July (24/05/05 to 25/07/05) and the post fertilization period of July–September (26/07 to 26/09/05)

Means during the different periods within a coffee culture, followed by different letters (a, b, c, d) are significantly different from each other ($P < 0.05$)

Means for the two coffee systems within a period, followed by different letters (α, β) are significantly different from each other ($P < 0.05$)

post fertilization periods than before fertilization (Table 2). Annual soil respiration was similar in both zones of each treatment and in both treatments (Table 4).

Soil CH_4 fluxes and their natural log transformation values were not normally distributed. Methane fluxes were very variable in space and time throughout the measuring period (Fig. 1c). Soil CH_4 fluxes in both treatments showed roughly similar temporal dynamics in the FZ and NFZ (Figs. 1c and 2c). In the CM plantation, net CH_4 production occurred in January and February, during the dry season while CH_4 was consumed in March and April during the wet season before fertilization (Fig. 1c). In the same plantation, soil CH_4 net production occurred three, seven and ten days after the May fertilization (Fig. 2c, left). In the CIn treatment, net CH_4 production was dominant on CH_4 consumption after fertilizer application in May (Fig. 2c, right).

On average methane consumption was observed except in the CIn plantation during the post fertilization period of May–July (Table 2). In the CM treatment, mean CH_4 consumption was significantly lower during the dry season when compared to the wet season previous to fertilization ($P = 2\ 10^{-4}$) (Table 2). In the same treatment, during the wet season, average CH_4 consumption was significantly lower after the May and July fertilizations than before ($P = 2\ 10^{-4}$) (Table 2). Mean CH_4 consumption was lower in the CIn than in the CM treatment (Table 2) ($P = 10^{-4}$) during the wet season before fertilization. During the post fertilization period of May–July, CH_4 was consumed in the CM plantation but produced in the CIn plantation (Table 2). Annual CH_4 consumption was similar in both zones of each treatment and in both treatments (Table 4).

Soil temperature, WFPS, mineral N content and N mineralization potential

Soil temperature was not normally distributed. As expected in a wet tropical climate, soil temperatures did not vary much during the year (Fig. 1d). The lowest soil temperatures (18.1 ± 0.1°C and 17.9 ± 0.1°C for the CM and CIn plantations, respectively) were observed in January when the air temperature was the lowest (Fig. 1d). Overall air and soil temperatures were significantly lower during the dry season than during the wet season in both coffee plantations (Fig. 1d, Table 2). During the dry season and part of the rainy season (until June), soil temperatures were statistically lower in the shaded system (CIn) than in the monoculture (CM) (Table 2).

Soil WFPS was not normally distributed. The WFPS in the FZ (near the coffee plant) was significantly smaller than in the NFZ (midway between the rows) except in the CM plantation during the dry season (Fig. 1e). The lowest WFPS (0.42 ± 0.02 and 0.49 ± 0.02 v/v, respectively in the CM and CIn treatments) were observed in February (Fig. 1e) when the climate was driest. The large rainfall event on 10/08/05 caused the observed increase in soil WFPS between 29/07 and 11/08 (Fig. 1e). In the CIn plantation, mean soil WFPS was significantly lower during the dry than during the wet season (Table 2). During the wet season, mean WFPS of the top soil was higher in the CM than in the CIn plantation (Table 2), although not significantly after the July fertilization.

Soil NH_4^+ and NO_3^- concentrations and their natural log transformation values were not normally distributed. High standard errors were associated with soil NH_4^+ and NO_3^- concentrations, due to large spatial variability of soil mineral nitrogen distribution in the plantations. Before the May fertilization, soil NH_4^+ contents for all treatments were very low (<6 mg N kg^{-1} d.w.) (Fig. 1f). Both the May and July fertilizations increased the soil NH_4^+ contents in the FZ of both plantations: a rapid but transient increase occurred after the May fertilization in the CM plantation while a deferred but larger increase occurred in the CIn plantation (Fig. 2e). Nevertheless, since the FZ represented only 13% of the total area, we estimated only a small increase of soil NH_4^+ content at the plantation scale after fertilization (Table 2). In both plantations, inorganic N pools were dominated by NO_3^-. Throughout the year, soil NO_3^- concentrations were high in both systems (Fig. 1g), with larger values generally observed during the dry season than during the wet season, including the fertilization events (Table 2). During the dry season, high soil NO_3^- contents were observed in the FZ of the CM treatment (Fig. 1g). In the CIn treatment differences between FZ and NFZ were not significant, except on 29/11 (Fig. 1g). After the May and July fertilizations, high NO_3^- concentrations were measured in both treatments (Figs. 1g and 2f).

Soil N mineralization potential rates, measured in the laboratory, were almost twice as high for the CIn treatment (3.7 ± 0.2 mg N kg^{-1} d.w. day^{-1}) than for the CM treatment (2.2 ± 0.2 mg N kg^{-1} d.w. day^{-1}).

Litterfall

At the end of the wet season, in November 2003, the litterfall increased in both coffee plantations (Fig. 3), as the result of the fall of leaves and coffee beans, just before and during coffee harvest. In the CIn plantation, the litterfall remained high, during the dry season, until February, and decreased progressively. In August, large quantities of fruits and leaves of the *Inga* trees fell on the ground. In the CM plantation, the litterfall slightly decreased from December to February and increased again in March and April. From May until September, the litterfall was low in this plantation. In both plantations, the average litterfall was greater during the dry than during the wet season although not significantly (775 ± 68 and 550 ± 111 kg dry matter ha^{-1} in the CM plantation and 1214 ± 42 and 877 ± 148 kg dry matter ha^{-1} in the CIn plantation, during the dry and wet season, respectively). Annually litterfall was 7.5 ± 0.3 and 11.9 ± 0.6 Mg dry matter ha^{-1} in the CM and CIn plantations, respectively. The mean N content of the litterfall was similar in both plantations (2.04% ± 0.6 and 2.11% ± 0.6 in the CM and CIn plantations, respectively). In terms of N incorporation to the systems, the litterfall accounted for 153 ± 6.8 kg N ha^{-1} $year^{-1}$ in the CM treatment and 246 ± 16 kg N ha^{-1} $year^{-1}$ in the CIn treatment.

Determinants of soil fluxes of GHG

The multiple linear regression performed with the complete data set indicates that soil fluxes of N_2O were mainly related to soil respiration and NH_4^+ contents (Table 3 (1)). When the regression was performed with the data set of each plantation, soil fluxes of N_2O appeared to be also related to changes in soil temperature, in the CIn plantation (Table 3 (2)). The relationship between N_2O fluxes and WFPS was not linear (Fig. 4). When WFPS was under 50%, N_2O losses were low in spite of non limiting NO_3^- contents. High losses of N_2O occurred between 50 and 75% WFPS after the May and July fertilizations. Above 75% WFPS, soil fluxes of N_2O decreased when soil NH_4^+ contents were very low and NO_3^- contents below 25 mg N kg^{-1} soil (Fig. 4).

According to the analysis performed with the complete data set as well as with the data sets for each plantation, soil respiration was primarily related to soil WFPS, NH_4^+ and NO_3^- contents (Table 3 (3)). The fluxes of CH_4 were only associated with changes in soil respiration when the multiple linear regression was performed with the complete data set (Table 3 (4)). For the CIn plantation, changes in CH_4 fluxes were also related to soil NO_3^- content and temperature (Table 3 (5)).

Discussion

Seasonal changes of soil variables and fluxes of GHG

The total annual rainfall, of almost 2,900 mm, between 01/10/04 and 30/09/05 was larger than the 25 year annual average of 2,300 mm for Cicafé (Mata and Ramírez 1999). During the experimental period (October 2004–September 2005), the dry season started and ended 1 month earlier than previously observed.

Most of the measured soil environmental properties varied seasonally: WFPS and soil temperatures decreased during the dry season, whereas soil NO_3^- contents tended to be larger during the dry than during the wet season even after fertilization. During

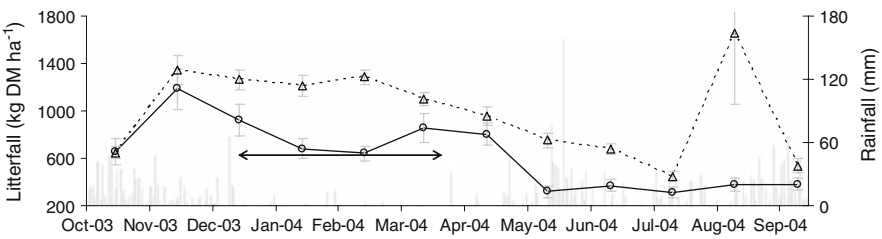

Fig. 3 Mean and standard error of monthly litterfall in two coffee plantations in Costa Rica. Symbols used are as follows: open circle and solid line, monoculture; open triangle and dashed line shaded plantation

Table 3 Regression models of soil N_2O, CO_2 and CH_4 fluxes established with the data set of the coffee monoculture (CM), of the *Inga* shaded coffee plantation (CIn) or with the complete data set

	r^2	Model	
N_2O	Complete data set	0.25	Ln N_2O = 0.87*** (±0.09) Ln CO_2 + 0.35*** (±0.05) Ln NH_4^+ − 0.77** (±0.27) (1)
	CIn	0.32	Ln N_2O = 0.84*** (±0.12) Ln CO_2 + 0.42*** (±0.07) Ln NH_4^+ + 0.41*** (±0.09) Soil T − 8.67*** (±1.78) (2)
CO_2	Complete data set	0.17	CO_2 = 5.03*** (±0.55) Ln NH_4^+ − 6.06*** (±0.88) Ln NO_3^- − 0.51*** (±0.08) WFPS + 73.42*** (±6.59) (3)
CH_4	CM	0.11	CH_4 = 18.61*** (±3.08) Ln CO_2 − 62.3*** (±9.36) (4)
	CIn	0.09	CH_4 = 13.86** (±5.08) Ln CO_2 + 21.16*** (±5.17) Ln NO_3^- + 12.61*** (±3.62) Soil T − 362.87*** (±78.98) (5)

N_2O (g N ha^{-1} day^{-1}), CO_2 (kg C ha^{-1} day^{-1}), CH_4 (g C ha^{-1} day^{-1}), NH_4^+ (mg N kg^{-1} d.w.), NO_3^- (mg N kg^{-1} d.w.), Soil T (°C), WFPS (%)

* $P < 0.05$, ** $P = <0.01$ and *** $P < 0.001$ and (±x) = standard error of predictor variables

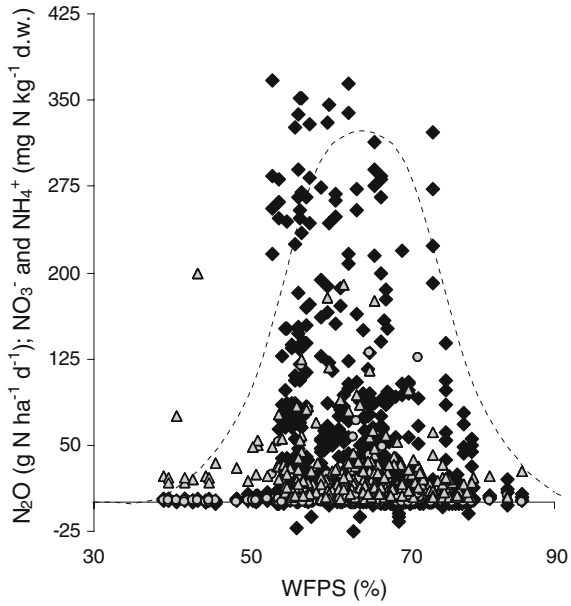

Fig. 4 Relationship between soil fluxes of N_2O (black diamond), NH_4^+ (grey circle) and NO_3^- (grey triangle) contents and WFPS for two coffee plantations in Costa Rica. Dashed line is a Gaussian curve indicating the shape of N_2O fluxes distribution according to WFPS

the dry season, NO_3^- was still being produced as observed by Reynolds-Vargas et al. (1994) during field incubations of soil cores in the same experimental station. It is likely that NO_3^- removal through leaching would be low, as well as plant uptake due to reduced photosynthetic rates at low air humidity (Vaast et al. (2008). However, NH_4^+ did not accumulate during the dry season, probably because NH_4^+ quickly nitrified to NO_3^- as shown by Babbar and Zak (1994) on nearby soils and due to immobilization by soil microorganisms as reported by Dioniso (2007) for the same coffee plantations. Laboratory incubations using soil from the CM plantation demonstrated that N mineralized at relatively large rates (2.2 mg N kg^{-1} d.w. day^{-1}). This rate was comparable to the 2.8 mg N kg^1 d.w. day^{-1} reported by Reynolds-Vargas et al. (1994) for nearby soils.

N_2O fluxes varied mainly as a result of fertilizer application but also with seasonal changes (Table 2). In the CIn plantation, mean soil emissions of N_2O during the wet season previous to fertilization were twice higher than during the dry season (Table 2). Higher N_2O emissions in the wet season before fertilization may be due to higher soil temperature,

NH_4^+ content and WFPS (Table 2). In the CIn plantation the exponential increase in N_2O emission rate with increasing soil temperature (Table 3 (2)) was shown elsewhere (e.g. Smith et al. 2003). Ammonium appeared to be an important variable of soil N_2O fluxes (Table 3 (1) and (2)), suggesting that nitrification was a significant source of N_2O from these soils. This hypothesis agrees with laboratory experiments on the same soil showing that nitrification was the main source of N_2O in a range of WFPS [39–87%] (Hergoualc'h et al. 2007). The distribution of N_2O fluxes as a function of the WFPS followed a Gaussian curve, similar to that modelled by Davidson (1991). Below 50% WFPS, soil fluxes of N_2O were low despite high NO_3^- concentrations in the soil. At these low soil moistures, N_2O was most likely a product of nitrification. The highest N_2O emission rates occurred between 50 and 75% WFPS as a result of favourable conditions for N_2O production from both nitrification and denitrification and the coinciding high N availability due to fertilization. Above 75% WFPS, soil emissions of N_2O decreased, most likely due to decreased N availability rather than decreased rates of N_2O production. This assumption was deduced from a laboratory experiment using the same soil (Hergoualc'h et al. 2007) showing that both nitrification and denitrification contributed to the N_2O flux at WFPS ranging from 76 to 87%.

Soil respiration was higher during the dry season than during the wet season prior to fertilization. This was also reported from Australian tropical forest soils (Kiese and Butterbach-Bahl 2002). In contrast most studies on tropical soils report a decrease in soil respiration during the dry season, likely caused by reduced rates of root respiration and/or soil microbial respiration (e.g. Davidson et al. 2000; Verchot et al. 2000; Cattânio et al. 2002; Ishizuka et al. 2002). In the coffee plantations, the dry season coincided with a large litterfall (Fig. 3). As some rainfall events occurred during the dry season, litter was a source of easily decomposable carbon for microbial respiration and responsible for the negative relationship between soil respiration and WFPS (Table 3 (3)).

Soil CH_4 consumption is limited by diffusivity of CH_4 into the soil (Keller and Reiners 1994). Many studies on tropical soils have reported an increase in CH_4 consumption with decreased WFPS during the dry season (e.g. Steudler et al. 1996; Mosier and Delgado 1997; Verchot et al. 2008). In the coffee monoculture (CM), however, the opposite was observed with decreased CH_4 consumption during the dry season when compared to the wet season previous to fertilization (Table 2). The presence of a large litter layer on the ground and increased soil respiration rates during the dry season may favour the formation of anaerobic microsites suitable for CH_4 production, leading to lower mean CH_4 consumption and thereby reducing the overall CH_4 consumption rate. Many studies have shown that organic matter incorporation markedly increased CH_4 emission and reduced methanotrophy (Le Mer and Roger 2001). Decreased CH_4 consumption or increased CH_4 emission associated with increased soil respiration was observed from forest and pasture soils in the Amazon (Verchot et al. 2000). In the CM plantation the CH_4 flux was only related to variation in soil respiration (Table 3 (4)) whereas in the CIn plantation, it was related to soil respiration and soil temperature changes. In well-drained soils, CH_4 consumption is rather limited by gas-phase transport than by soil temperature (Verchot et al. 2000) but, at the same time, methanogenesis increases with increased soil temperature and seems to be more sensitive to soil temperature than methanotrophy (Le Mer and Roger 2001)

Fertilization consequences on GHG emissions

As expected, the response of N_2O emissions to fertilization was larger in the FZ than in the NFZ, as also reported for a banana plantation in Costa Rica (Veldkamp et al. 1998). Higher soil emissions of N_2O after the July fertilization, when compared to the May fertilization (Table 2) may be caused by (a) increased WFPS on 11/08 (Fig. 1e) due to the first heavy rainfall after fertilizer application and (b) a higher N availability in the soil after the July than May fertilization. Application of ^{15}N labelled urea to small areas in the CIn plantation demonstrated that only 32% of the fertilizer applied in May was taken up by coffee plants and that 52% of the N applied was still in the top 50 cm of the soil 15 days before the July fertilization (Harmand et al. unpublished data). The July fertilization of 90 kg N ha^{-1} leads to an excess of N in the soil, which may have increased N_2O emissions. Additionally, in the CIn plantation, high litterfall from the *Inga* in August and presumably high litter decomposition

may also have contributed to increase soil mineral N content.

Eighty-four percent of the annual N_2O was emitted during the post fertilization periods of May–July and July–August, representing about 1/3 (107 days) of the experimental period (337 days). Mean soil emissions of N_2O during these two periods were higher than the 5.6 and 7.2 g N ha^{-1} day^{-1} mean emissions of N_2O measured by Harmand et al. (2007a) after NH_4NO_3 fertilization (90 kg N ha^{-1}) in a coffee monoculture and a coffee plantation shaded by *Eucalyptus deglupta*, respectively, on an Acrisol (Ultisol) in Southern Costa Rica. Mean soil emissions of N_2O after the May fertilization were comparable with the 6.1 and 17.3 g N ha^{-1} day^{-1} measured by Montenegro and Abarca (2001) after urea fertilization (83 kg N ha^{-1}) in a coffee monoculture on an Andosol and a coffee plantation shaded by the N_2 fixing legume tree *Erythrina poeppigiana* on an Inceptisol, respectively, in Central Costa Rica. The impact of fertilizer application on N_2O emissions was large not only in terms of quantity of N_2O emitted but also in terms of duration of increased emissions. Nitrous oxide fluxes remained elevated for at least 44 days after the July fertilization while several studies in Costa Rica (Harmand et al. 2007a; Montenegro and Abarca 2001; Veldkamp and Keller 1997) indicate that the influence of fertilizer N application on fluxes of N_2O only lasted for approximately 3 weeks.

Fertilizer addition stimulated soil respiration rates in both systems. This supports previous observations by Montenegro and Abarca (2001) in unshaded and shaded coffee plantations in Central Costa Rica. The increase in soil CO_2 fluxes is probably caused by increased microbial respiration following N addition (Montenegro and Abarca 2001; Mutuo et al. 2005). It could also have resulted from urea hydrolysation.

Above the threshold of 40 mg NH_4^+–N kg^{-1} d.w. soil CH_4 oxidation can be temporary inhibited due to a preferential oxidation of NH_3 over CH_4 by methane monooxygenase enzymes (Khalil and Baggs 2005) and the toxicity of NO_2^- produced (Le Mer and Roger 2001); leading to net CH_4 production instead of consumption. Such a phenomenon may have happened in the CM plantation 7 days after the May fertilization when net CH_4 production was observed simultaneously with high soil NH_4^+ concentrations (43 mg N kg^{-1} d.w.) (Fig. 2c, left and e).

Comparison of coffee plantations

The soils of the two coffee plantations have different texture, bulk density and C:N ratio, due to inherent spatial variability of the soil physical properties and previous and current management practices. The smaller bulk density in the CIn than in the CM plantation can be explained by several factors. The presence of trees in the CIn plantation produced a more developed root system, as measured by Crouzet (2004) in the same systems. Before establishing the CM plantation, trees were removed mechanically which may have contributed to greater soil compaction. The smaller soil C:N ratio in the CIn than in the CM plantation can be partly explained by a larger N incorporation to the soil through litterfall and root turnover in the CIn system.

Throughout this study, WFPS and soil temperatures in the top 10 cm were higher in the CM than in the CIn plantation. In the CIn treatment, shading provided by the tree canopy protected the soil from direct solar radiation and resulted in a lower soil temperature and higher moisture content in the top soil (data not shown). The lower bulk density in the shaded system when compared to the monoculture caused its lower WFPS.

During the post fertilization periods the patterns of soil mineral N contents were different between plantations. Following the May fertilization, urea hydrolyzed progressively but not spatially uniformly (large standard errors of the mineral N contents) in the CM plantation, as a combined result of fertilizer spreading heterogeneity and small rainfall rate. In the CIn plantation, urea hydrolysis was delayed, possibly because of greater rainfall interception by the tree canopy. Between 24 and 31 May 2005, trees in the CIn plantation intercepted 18% of the 47 mm of cumulative rainfall, as compared to 9% intercepted in the CM plantation (Siles 2007). The different patterns of soil nitrogen dynamics in the two systems were also likely related to their different soil mineralization potentials. The soil N mineralization potential of the CIn system was approximately twice that of the CM system, however no significant differences in mean soil mineral N content during the post fertilization periods were measured between the two systems, as nitrate could be leached or uptaken by coffee plants during the rainy season (Table 2). In the CM and CIn plantations, Harmand et al. (2007b)

measured high losses of NO_3^- in leaching water, of about 50% of the annual fertilizer input.

During the dry season both coffee systems showed similar patterns of N_2O emissions (Fig. 1a), however, during the wet season prior to fertilization and during the post fertilization period of May–July, mean N_2O emissions were twice as large in the CIn than in the CM plantation, resulting in a 1.3 times larger annual N_2O emission in the CIn treatment. Montenegro and Abarca (2001) measured annual N_2O emissions 1.6 times larger in a coffee plantation shaded by N_2 fixing trees than in a coffee monoculture. Differences in N_2O emissions between the CM and the CIn plantations were likely a result of different quantities of N added to the soil; leading to different soil mineralization potentials. The annual N input to the soil through fertilization and litterfall amounted 403 and 496 kg N ha^{-1} $year^{-1}$ in the CM and CIn plantations, respectively. The 1.2 times greater N input in the coffee plantation shaded by the leguminous tree (CIn) than in the monoculture (CM) likely helps explain the 1.3 times greater annual N_2O emission. According to Rochette and Janzen (2005), there is little doubt that legumes can increase N_2O emissions and measurements indicate that much of this increase may be attributable to the N release from root exudates and from decomposition of plant residues. Annual N_2O emission of the coffee plantations calculated with the IPCC (2006), as 1% of annual N added to the soil (from synthetic fertilizer and crop residue), is 4 and 5 kg N ha^{-1} $year^{-1}$, respectively for the CM and CIn plantation. This estimation is fairly close to the annual N_2O emission we obtained (Table 4) and would be improved by the knowledge of the annual N from crop residues belowground as specified in the IPCC methodology. The annual N_2O flux in the CM plantation was similar to the 4.5 kg N_2O–N ha^{-1} $year^{-1}$ measured by Verchot et al. (2006) from a 10 year old coffee monoculture on an Andosol in Indonesia, and the 3 kg N_2O–N ha^{-1} $year^{-1}$ for upland cropfields fertilized with 250 kg urea–N ha^{-1} $year^{-1}$ as estimated by Bouwman et al. (2002). Annual N_2O emission in the CIn plantation was similar to the 6.1 kg N ha^{-1} $year^{-1}$ measured by Veldkamp and Keller (1997) in a banana plantation in Costa Rica fertilized with 360 kg N ha^{-1} $year^{-1}$, but smaller than the 15.5 kg N ha^{-1} $year^{-1}$, measured by Verchot et al. (2006), in a 18 years old multistrata coffee garden with significant overstory of N_2 fixing trees in Sumatra, Indonesia.

Table 4 Annual fluxes of greenhouse gases from soil and (standard error) in the fertilized zone (FZ), non fertilized zone (NFZ) and extrapolated at the plantation scale (System) in the coffee monoculture (CM) and the *Inga* shaded coffee plantation (CIn), in the Central Valley of Costa Rica

	N_2O (kg N ha^{-1} $year^{-1}$)	CO_2 (Mg C ha^{-1} $year^{-1}$)	CH_4 (kg C ha^{-1} $year^{-1}$)
CM			
FZ	15.5 (0.8)	7.9 (2.5)	−4.0 (0.9)
NFZ	2.6 (0.1)	7.5 (2.6)	−3.2 (1.3)
System	4.3 (0.1)	7.5 (2.3)	−3.3 (1.1)
CIn			
FZ	16.7 (0.8)	9.0 (3.1)	−2.6 (1.8)
NFZ	4.1 (0.3)	8.3 (3.0)	−0.9 (1.7)
System	5.8 (0.3)	8.4 (2.6)	−1.1 (1.5)

We expected that soil respiration would be greater in the CIn than in the CM plantation as a result of greater carbon inputs to the soil (Fig. 3). However we did not observe significant treatment effect overall or in any of the individual measurement. Estimated annual CO_2 fluxes were close to the 6.7 Mg C ha^{-1} $year^{-1}$ measured by Campos (2006) in a corn-potato-corn rotation, in Mexico.

Soil flux of CH_4 in the two coffee plantations did not show exactly the same pattern during the wet season however annual CH_4 uptakes were similar to each other and in agreement with previous measurements of 2.1 kg C ha^{-1} $year^{-1}$ by Palm et al. (2002) in a non fertilized multistrata coffee agroforestry plantation in Peru.

Conclusions

The addition of inorganic nitrogen fertilizer markedly stimulated N_2O emissions from the soil in the coffee monoculture and the coffee plantation shaded by the N_2 fixing *Inga densiflora* species. Nitrogen fertilization also induced temporary increases in soil respiration and decreases in CH_4 consumption. Some other research studies (Dioniso 2007; Harmand et al. 2007b) have demonstrated a low efficiency of N fertilization in these plantations with low N uptakes by coffee plants and high NO_3^- leaching. This clearly

demonstrates the need to adapt N fertilization to the demand of coffee plants in order to reduce soil emissions of greenhouse gases and environmental pollution in general.

The 1.3 times higher annual N_2O emissions from the legume tree-shaded system (5.8 ± 0.5 kg N ha^{-1} $year^{-1}$) when compared to the monoculture (4.3 ± 0.3 kg N ha^{-1} $year^{-1}$) appeared closely related to the 1.2 times greater N input from both mineral fertilization and litterfall in this system (496 kg N ha^{-1} $year^{-1}$) when compared to the monoculture (403 kg N ha^{-1} $year^{-1}$). Yet, the difference of soil emissions of N_2O between the two treatments do not seem to be only justified by a difference of N input. For the two treatments, we obtained different regression models explaining soil fluxes of N_2O and CH_4 as a function of soil environmental variables. Thus, the mechanisms implied in soil fluxes of N_2O and CH_4 in the two coffee plantations appear to be governed differently by soil parameters. For a better understanding of the presence of N_2 fixing leguminous species on soil fluxes of GHG it appears necessary to further investigate the determinism of these fluxes in terms of microbial activities and communities.

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