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Soil emissions of NO, N_2O and CO_2 from croplands in the savanna region of central Brazil

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ABSTRACT

In the last 40 years, a large area of savanna vegetation in Central Brazil (Cerrado) has been converted to agriculture, with intensive use of fertilizers, irrigation and management practices. Currently, the Cerrado is the main region for beef and grain production in Brazil. However, the consequences of these agricultural practices on NO, N_2O and CO_2 emissions from soil to atmosphere are still poorly investigated. The objectives of this study were to quantify soil emissions of NO-N, N_2O-N and CO_2-C in different no-till cultivation systems in comparison with native savanna vegetation. The agricultural areas included: (a) the maize and *Brachiaria ruzizienses* intercropping system followed by irrigated bean in rotation; (b) soybean followed by natural fallow; and (c) cotton planting over *B. ruzizienses* straw. The study was performed from August 2003 to October 2005 and fluxes were measured before and after planting, after fertilizations, during the growing season, before and after harvesting. NO-N fluxes in the soybean field were similar to those measured in the native vegetation. In the cornfield, higher NO-N fluxes were measured before planting than after planting and pulses were observed after broadcast fertilizations. During *Brachiaria* cultivation NO-N fluxes were lower than in native vegetation. In the irrigated area (bean cultivation), NO-N fluxes were also significantly higher after broadcast fertilizations. Most of the soil N_2O-N fluxes measured under cultivated and native vegetation were very low (<0.6 ng N_2O-N cm^{-2} h^{-1}) except during bean cultivation when N_2O-N fluxes increased after the first and second broadcast fertilization with irrigation and during nodule senescence in the soybean field. Soil respiration values from the soybean field were similar to those in native vegetation. The CO_2-C fluxes during cultivation of maize and irrigated bean were twice as high as in the native vegetation. During bean cultivation with irrigation, an increase in CO_2-C fluxes was observed after broadcast fertilization followed by a decrease after the harvest. Significantly lower soil C stocks (0–30 cm depth) were determined under no-tillage agricultural systems in comparison with the stocks under savanna vegetation. Fertilizer-induced emission factors of N oxides calculated from the data were lower than those indicated by the IPCC as default.

1. Introduction

The savannas of central Brazil, locally known as Cerrado, have been the focus of intense agricultural expansion since the 1970s. By 2002, approximately 80 million hectares, corresponding to about 39.5% of the total Cerrado area, had already been converted into different land uses. Cultivated pastures and agriculture fields occupy 26.5 and 10.5% of the Cerrado, respectively (Sano et al., 2008). If cattle ranching over natural grasslands (about 23 million ha) and secondary forests are accounted for, the overall agro-pastoral land-use in the Cerrado biome increases to about 47% (Bustamante and Ferreira, 2011). Although pasture is still the main land use in the region, croplands are continuously expanding, especially for the cultivation of soybean and maize. The gentle relief of the Cerrado region that has favored mechanized agriculture and the development of cultivars adapted to soils and seasonal climate were particularly important factors in cropland expansion. In the case of soybean (*Glycine max*), nitrogen is derived from biological N_2 fixation (BNF) reducing costs of nitrogen fertilization and making production economically more feasible in Brazil (Alves et al., 2003). Brazil is the third largest world producer of maize. Maize productivity has been growing systematically (from 1.9 in 1990 to 3.3 t ha^{-1}

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in 2004) with the use of improved varieties, good cultivation conditions and high inputs of N fertilizers. The area cultivated with cotton in the Cerrado region doubled in the last decade coming currently only after soybean, maize and bean (from 3,395,000 ha in 1996–1997 to 6,939,000 ha in 2006–2007). Meanwhile, productivity increased from 1230 in 1996–1997 to 3147 kg ha^{-1} in 2004–2005 (MAPA, 2008) due to the use of modern technology, mechanization and high inputs of fertilizer and biocides (on average ten applications of biocides during the crop cycle). Although common bean is not an important export product, it is the main source of protein for less privileged segments of the Brazilian population. In contrast to soybeans, N fixing symbiosis is not very effective in beans and productivity gains are related to the use of N fertilization (Vargas et al., 1994).

The rapid expansion of agriculture in the Cerrado region was accompanied by deforestation, intensive use of fertilizers, irrigation and other management practices that are related to substantial changes in biogeochemical cycles. Agricultural practices have been known to affect emission rates of trace gases from soil to the atmosphere (Jambert et al., 1997; Sitaula et al., 2000; Akiyama et al., 2000; Giacomini et al., 2006) and some of these gases have important effects on atmosphere chemistry. The production and emission of NO, N_2O and CO_2 from soil are the result of the mineralization of organic matter and depend on environmental factors, such as inorganic N availability, temperature, soil moisture and land use (Hall et al., 1996).

In spite of the changes in intense land use in the region, little information exists on trace gas emissions from cropland soils in the Cerrado. Carvalho et al. (2006) found higher NO fluxes immediately and three days after N fertilization and irrigation in maize fields under conventional and no-tillage systems, but N_2O fluxes were under the detection limit. Low N_2O soil fluxes after N fertilization were measured from a rotation rice-*Brachiaria*-soybean-*Crotalaria* under conventional and no-till management practices in the Cerrado region (Metay et al., 2007).

In this context, the objectives of this study were: (1) to quantify the soil emissions of NO-N, N_2O-N and CO_2-C during the cultivation cycle of different crops in no-till systems in the Cerrado region in comparison to native vegetation, and (2) to determine the relationships between soil trace gas fluxes and soil N and C, temperature and moisture.

2. Methods

2.1. Study sites

The study was carried out at two commercial farms: Dom Bosco Farm and Pamplona Farm, both located in the municipality of Cristalina (Federal State of Goiás, Brazil). Study areas characteristics, soil classification and soil characteristics of the study sites are presented in Table 1. The climate is tropical (Köppen Aw) with two well-defined seasons: dry season (May to September) and wet season (October to April), during which 90% of the annual precipitation occurs. Rainfall was measured daily in the Dom Bosco and Pamplona Farms. Total precipitation is presented in Table 1 while Fig. 1 presents monthly distribution of rainfall. At the Dom Bosco Farm two cultivation systems under no-till and with mechanical harvest were studied: (a) Maize (*Zea maiz* cv. 30k75) and *Brachiaria ruzizienses* intercropping system followed by irrigated bean (*Phaseolus vulgaris*, type "Preto"), hereafter maize-*Brachiaria*-bean rotation. This cultivation system was introduced in 1998 after ten years of *Brachiaria* sp. cultivation following conversion from native vegetation using slash-and-burn. (b) Soybean (*G. max* cv. P98C81 Pioneer) followed by natural fallow (no winter cover crop). The crop was introduced in 1977 after removal of native vegetation using slash-and-burn and soybean seeds are inoculated with *Bradyrizobium japonicum*. A native cerrado area with the same soil type was selected as reference site. This area has been protected from fire since 1974 but it burned accidentally in October 2004 before the last measurement of soil emissions.

Table 1
Study areas characteristics, soil classification and soil characteristics of the study areas (Dom Bosco Farm and Pamplona Farm).

	Study areas	
	Dom Bosco Farm	Pamplona Farm
Study areas characteristics		
Coordinates	16°18′S and 47°30′W	16°15′S and 47°37′W
Altitude	826 m	826 m
Total precipitation (study period)	2078.5 mm (Aug 2003 to Oct 2004)	1555 mm (Nov 2004 to Aug 2005)
Soil classification		
Brazilian Soil Taxonomy (Embrapa, 1999)	Latossolo Vermelho	Latossolo Vermelho
US Soil Taxonomy	Oxisols	Oxisols
Soil characteristics (0–20 cm depth)		
pH		
Native soil	4.2–4.4	4.2–4.4
Cultivated soils	5.1–5.9	5.1–5.9
Cation exchange capacity-ECEC		
Native soil	9.0 cmol C kg^{-1}	9.0 cmolc kg^{-1}
Cultivated soils	8.5 cmol C kg^{-1}	10.4 cmolc kg^{-1}
Base saturation		
Native soil	11.0%	11.0%
Cultivated soils	74.3%	57.7%
Clay content (0–5 cm depth)		
Native soil	67.8 ± 4.2%	75.9 ± 1.9%
Cultivated soils	48.8 ± 6.5% (maize-*Brachiaria*-bean rotation) 72.2 ± 5% (soybean field)	67.6 ± 4.7% (cotton field)
Drainage	Well-drained	Well-drained

At the Pamplona Farm an area cultivated with cotton (yield of 4.5 t ha^{-1}) under no-till and mechanically harvested was used in this study. Herbaceous cotton (*Gossypium hirsutum* cv. ITA 90-Pioneer) was cultivated over *B. ruzizienses* straw. *B. ruzizienses* was planted by airplane and dried with herbicide (2,4D – U46DFluid 868/720 CS) 20 days before cotton planting. Previously, the area was cultivated with soybean followed by natural fallow during winter. This rotation system was established in 1980 after removal of native vegetation using slash-and-burn. This study includes only the period cultivated with cotton. A native cerrado *stricto sensu*

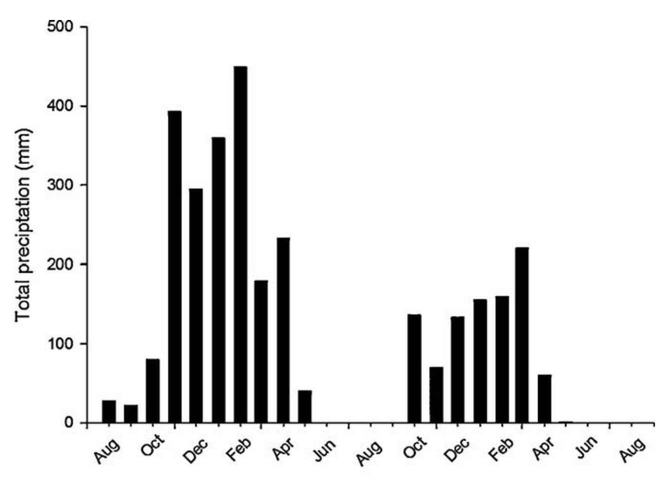

Fig. 1. Monthly precipitation during study period in the Dom Bosco Farm (from August 2003 to October 2004) and Pamplona Farm (from November 2004 to August 2005).

area with the same soil type was chosen as reference site. This area has been protected from fire since 1994 but it burned accidentally in November 2004 before the first gas flux measurement. Table 2 presents details on the areas under cultivation including period of measurements, cropping cycles and management practices.

The management of fertilizers was representative of the agricultural practices in central Brazil region. In general, for soybean only one N-application is performed together with P-addition during planting. For the other crops, besides the N-fertilization during planting, one (bean) or two (maize and cotton) broadcast fertilizations are made during crop growth. In the present study, two broadcast N-fertilizations were made during bean cultivation. The second broadcast fertilization was performed with a relative low amount of urea because of the low temperatures just after the first fertilization.

2.2. Physical and chemical characterization of soils

Soil samples (0–20 cm depth) for chemical characterization were collected before the beginning of trace gas measurements (July 2003) in each cultivation system and in native areas. Soil samples (0–5 cm depth) were collected in 20 points distributed randomly for texture determination per system.

2.3. Trace gas flux measurements

In each area one plot of 10 m × 15 m was selected for trace gas sampling. In the Dom Bosco Farm (soybean, maize-irrigated bean and native vegetation) six replicates for soil NO-N and CO_2-C and four replicates for N_2O-N measurements were made. In the native area N_2O-N fluxes were collected only from August 2003 to February 2004 because fluxes were mostly under the detection limits in accordance with previous results from Pinto et al. (2002) and Varella et al. (2004). In the cotton field (Pamplona Farm) the fluxes of NO-N and CO_2-C were measured in three replicates in planted rows and in three replicates between rows while in the native area six replicates were measured for NO-N and CO_2-C fluxes. N_2O-N fluxes were measured at four points both in the cotton field (whether in row or between rows) and in the area under cerrado vegetation.

In the cultivated areas NO-N, N_2O-N and CO_2-C fluxes were measured before and after planting, after nitrogen fertilizations, along the growing season and shortly before and after harvest. In the soybean field, one measurement was also taken during the fallow period (dry season). In the native vegetation, measurements were taken monthly, except in November 2003 and July 2004 because of technical problems. Technical problems also prevented the measurements of N_2O-N fluxes in October 2004 (irrigated bean and native vegetation – Dom Bosco Farm) and November 2004 (cotton and native vegetation – Pamplona Farm).

Soil surface fluxes of NO-N, N_2O-N and CO_2-C were measured using polyvinyl chloride (PVC) cylindrical chambers with 24 cm diameter and 8.7 L. Chamber bases were installed into the upper 2 cm of the soil 30 min before of the measurement. Air was circulated in a closed loop between the chamber and the analyzers.

NO-N and CO_2-C fluxes were measured using the dynamic chamber technique. NO was analyzed using an NOx Box (Scintrex LMA-3), after first converting NO to NO_2 by passing the gas sample through CrO_3. NO_2 reacts with Luminol® solution to produce a luminescent reaction that is functionally related to the mixing ratio of NO_2. NO concentration was recorded over a 5-min period. Fluxes were calculated from the rate of increase of NO concentration using the linear portion of the accumulation curve. The instrument was calibrated twice daily, before and after sampling, using mixtures of a NO standard (0.4 ppm) with NO- and NO_2-free air. CO_2 was analyzed over a 3-min period using a photosynthesis system with integrated infrared gas analyzer and data system (LiCor 6200). CO_2 concentrations were logged every 2 s, yielding a continuous monitoring of increasing CO_2 concentrations that were used to fit the most appropriate regression function.

N_2O fluxes were measured with a static chamber technique (Matson et al., 1990). The samples were collected from the headspace of the chamber using 60 mL polypropylene syringes with siliconized polypropylene plungers at 10-min intervals. In the laboratory, the samples were analyzed within 24 h after sample collection with a gas chromatograph (Shimadzu GC-14A) fitted with a ^{63}Ni electron capture detector. N_2O fluxes were calculated from the rate of concentration increase, determined by linear regression based on samples. The detection limit (0.6 ng N_2O-N cm^{-2} h^{-1}) defined by Verchot et al. (1999) was adapted in this study since a similar system and methods were used.

Soil temperatures (2.5 and 5.0 cm depth) were determined during the gas flux measurements.

2.4. Soil sampling

After gas flux measurements soil samples (0–5 cm depth) were collected from within the chambers to determine soil moisture, inorganic-N availability and microbial biomass C. Six soil samples were collected in the soybean and maize-irrigated bean plots as well as in the native area (Dom Bosco Farm) while in the cotton field (Pamplona Farm) three soil samples in rows and three between rows and six samples in the native area were collected.

2.5. Water-filled pore space (%WFPS)

Soil samples were dried to constant weight at 105 °C for gravimetric soil moisture determination. Bulk density was determined (0–5 cm depth) using volumetric cylinders (Embrapa, 1999). For particle density, a value of 2.65 g cm^{-3} was used. Values of the gravimetric soil moisture were converted to WFPS values (Linn and Doran, 1984): WFPS % = $(\theta_g \times \text{sbd} \times 100\%)/[1 - (\text{sbd}/\text{spd})]$, where θ_g = gravimetric soil moisture; sbd = soil bulk density; spd = soil particle density.

2.6. Inorganic-N availability and soil microbial biomass C

Field-moist soil samples (0–5 cm) were extracted with KCl (2 M) for 1 h and the inorganic-N concentrations were determined by colorimetry. NO_3-N was determined by UV-absorption according to Meier (1991) and NH_4-N was determined through reaction with Nessler reagent. The results are expressed on a dry weight basis (DW).

Microbial biomass C (0–5 cm) was determined by the chloroform fumigation-incubation method proposed by Jenkinson and Powlson (1976). In the Dom Bosco Farm, composite soil samples (compose of six subsamples) were collected from August 2003 to June 2004 for determination of microbial biomass, therefore statistical analyses were not possible for this period. After this period, six soil samples were collected at every sampling date.

2.7. C and N stocks (0–30 cm depth)

Sampling for determination of organic C and total N concentrations and bulk density was done in February 2005, in three trenches per area. In each trench one sample was collected from 0–5, 5–10, 10–20 and 20–30 cm depths. Samples for bulk density were collected with volumetric rings and dried at 105 °C. Soil C and N stocks were calculated from soil C and N concentration and bulk density. As bulk density may change after conversion to cropland,

Table 2
Dates of gas sampling and fertilization and amount and form of N applied during crop cycles at the Dom Bosco Farm and Pamplona Farm (from August 2003 to August 2005).

Farm	Cultivation systems and native areas	Vegetation covers	Planting and harvest or planting and spraying dates	Gas sampling period/dates	Fertilization dates	Amount of N applied (kg ha^{-1})	N source	Crop period (N applied)
Dom Bosco (2999.4 ha)	Maize and *Brachiaria ruzizienses* intercropping system followed by irrigated bean in rotation (75 ha)	Maize (*Zea maiz* cv. 30k75)	Planting 05-Sep-03 Harvest 17-Feb-04	28-Aug-03 to 19-Feb-04 (5 sampling dates)	05-Sep-03 29-Sep-03 13-Oct-03	33.7 103.2 18.4	MAP[b] (in the crop rows) Urea (broadcasting) Urea (broadcasting)	Planting 16 DAE[d] 30 DAE[d]
		Brachiaria ruzizienses	Planting 05-Sep-03 Spraying of glyphosate 06-May-04	28-Apr-04	No fertilization			
		Irrigated bean (*Phaseolus vulgaris*, type "Preto") irrigation interval 30 h and 6 mm of water in each event	Planting 06-Jun-04 Harvest 19-Oct-04	11-Jun-04 to 19-Oct-04 (9 sampling dates)	08-Jun-04 21-Jul-04 04-Aug-04	19.3 81.0 2.4[a]	MAP[b] (in the crop rows) Urea (broadcasting) Urea (broadcasting)	Planting 33 DAE[d] 47 DAE[d]
	Soybean followed by natural fallow (207 ha)	Soybean (*Glycine max* cv. P98C81 Pioneer)	Planting 05-Dec-03 Harvest 24-Apr-04	28-Aug-03 to 28-Apr-04 (7 sampling dates)	05-Dec-03	21.2	MAP[b] (in the crop rows)	Planting
	Native area (620 ha)	Cerrado vegetation (cerrado *stricto sensu*) (Ribeiro & Walter, 1998)		28-Aug-03 to 19-Oct-04 (13 sampling dates)				
Pamplona (14,085.2 ha)	Cotton planting over *Brachiaria ruzizienses* straw (721 ha)	*Brachiaria ruzizienses*	Planting 06-Oct-04 Spraying of 2,4D 07-Nov-04	No sampling	No fertilization			
		Herbaceous cotton (*Gossypium hirsutum* cv. ITA 90-Pioneer)	Planting 27-Nov-04 Harvest 30-Jul-05	23-Nov-04 to 01-Aug-05 (10 sampling dates)	27-Nov-04 23-Dec-04 25-Jan-05	24.0 36.0 90.0	DAP[c] (in the crop rows) Ammonium sulfate (broadcasting) Urea (broadcasting)	Planting 15 DAE[d] 45 DAE[d]
	Native area (2677.5 ha)	Cerrado vegetation (cerrado *stricto sensu*) (Ribeiro & Walter, 1998)		29-Nov-04 to 01-Aug-05 (8 sampling dates)				

[a] Unusual fertilization: N-applied because beans plants growth was affected by low temperature.
[b] MAP = Mono-ammonium phosphate.
[c] DAP = Di-ammonium phosphate.
[d] DAE = Days after emergence.

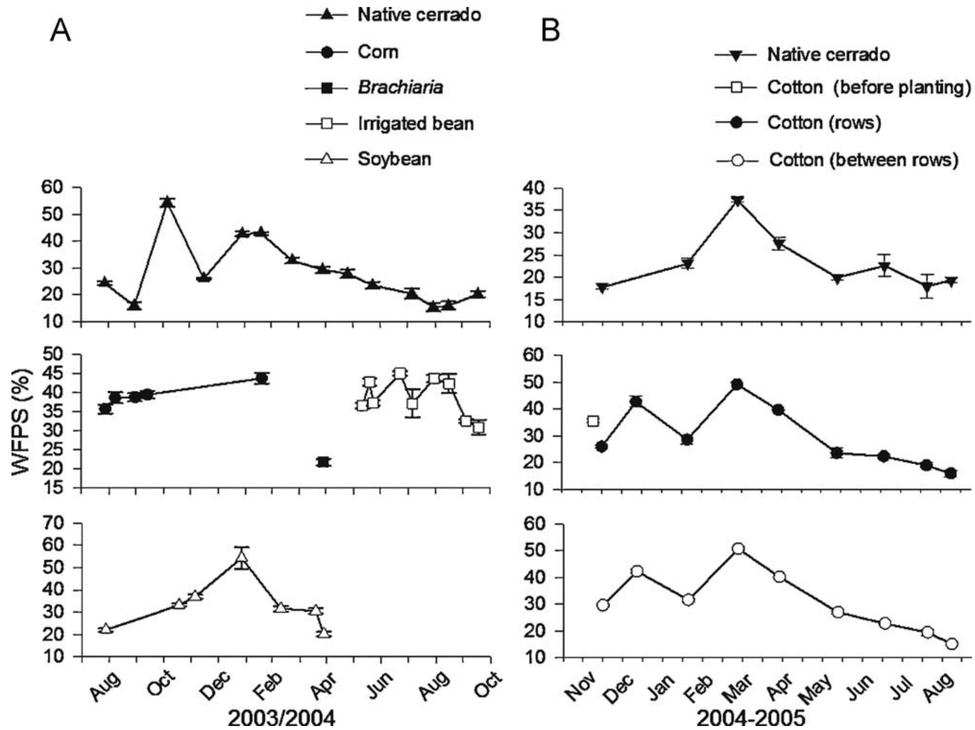

Fig. 2. Water filled pore space (% WFPS) at 0–5 cm soil depth in croplands and in native cerrado in the same period. (A) Dom Bosco Farm (from August 2003 to October 2004), (B) Pamplona Farm (from November 2004 to August 2005).

errors in estimated C and N stocks may occur when sampling is based on fixed depths (Davidson and Ackerman, 1993; Veldkamp, 1994; Neill et al., 1997). In this study, soil bulk density differed significantly from the reference area (under native vegetation) only under maize-bean-rotation. In this case soil C and N stocks were corrected for comparison of equivalent soil mass (Neill et al., 1997).

2.8. Fertilizer-induced emission factors (FIE)

Fertilizer-induced emission factors (FIE) for maize, bean and cotton were estimated. Fertilizer-induced emission factor (FIE) is defined by the IPCC (2007) as the emission of N, as N-N-NO and N_2O from fertilized areas by subtracting the emission from a reference area without fertilizer (assuming that all other conditions are similar to those of fertilized soil). The FIE is expressed as a percentage of total N applied.

Fluxes were integrated for the crop cycle considering the mean fluxes measured and the number of days in each crop phase. For practices that used mechanization (planting and harvesting) a response period of five days was considered while for N fertilization or watering, a period to three days was considered based on the duration of the N pulses recorded by Pinto et al. (2002, 2006) and Carvalho et al. (2006) in Oxisols of the region. Monthly means were considered during the growth season (without fertilization or watering). Fluxes from the native cerrado were calculated considering monthly means and the occurrence of rain events in the dry season generating pulses with three days of duration. In order to consider the influence of random errors, an error estimate was calculated for every crop and for native areas. The estimated error for the cropping period was calculated using the propagated error for every day of measurements. The propagated error was calculated using the square root of the sum of square of the standard errors for every date. The estimated error was then calculated dividing the propagated error by the total flux during the cropping period and expressed as percentage.

2.9. Statistical analysis

All statistical analyses were conducted using SPSS ver. 13.0 with a 0.05 probability level. The normal distribution of data was tested using Kolmogorov–Smirnov test statistics (Sokal and Rohlf, 1981). Data were ln-transformed when they did not follow a normal distribution. One-way analysis of variance (ANOVA) followed by the post hoc Tukey test was used to compare means. N_2O flux and NH_4^+-N data were not normally distributed even after transformation. In this case, non-parametric Kruskal–Wallis and Mann–Whitney tests were used.

Cultivation phases and management practices (before and after planting, after N fertilization, growing season, before and after harvesting) for every crop were compared. In the case of cotton cultivation, data collected from row and between rows were also compared. Cultivated areas were also compared with reference areas (native vegetation). Relationships between NO, N_2O and CO_2 fluxes and environmental variables were evaluated with linear regression using the stepwise process.

3. Results

3.1. Soybean cultivation and maize-irrigated bean rotation (Dom Bosco Farm)

Soil moisture during bean cultivation was influenced by irrigation and ranged from 31% to 45% WFPS while values measured in soil under native vegetation ranged in the same period from 23.5% to 15.2%. In the other agricultural areas, soil moisture was affected by seasonal rainfall distribution. The highest values of WFPS in the 0–5 cm soil depth in each study area were about 43% in the maize field and the native cerrado and about 54% in the soybean field (Fig. 2).

Soil temperatures (5.0 cm depth) varied with different vegetation covers and were highest in the soybean area and in the native cerrado ranging from 22.7 to 31.0 °C and 22.0 to 34.2 °C,

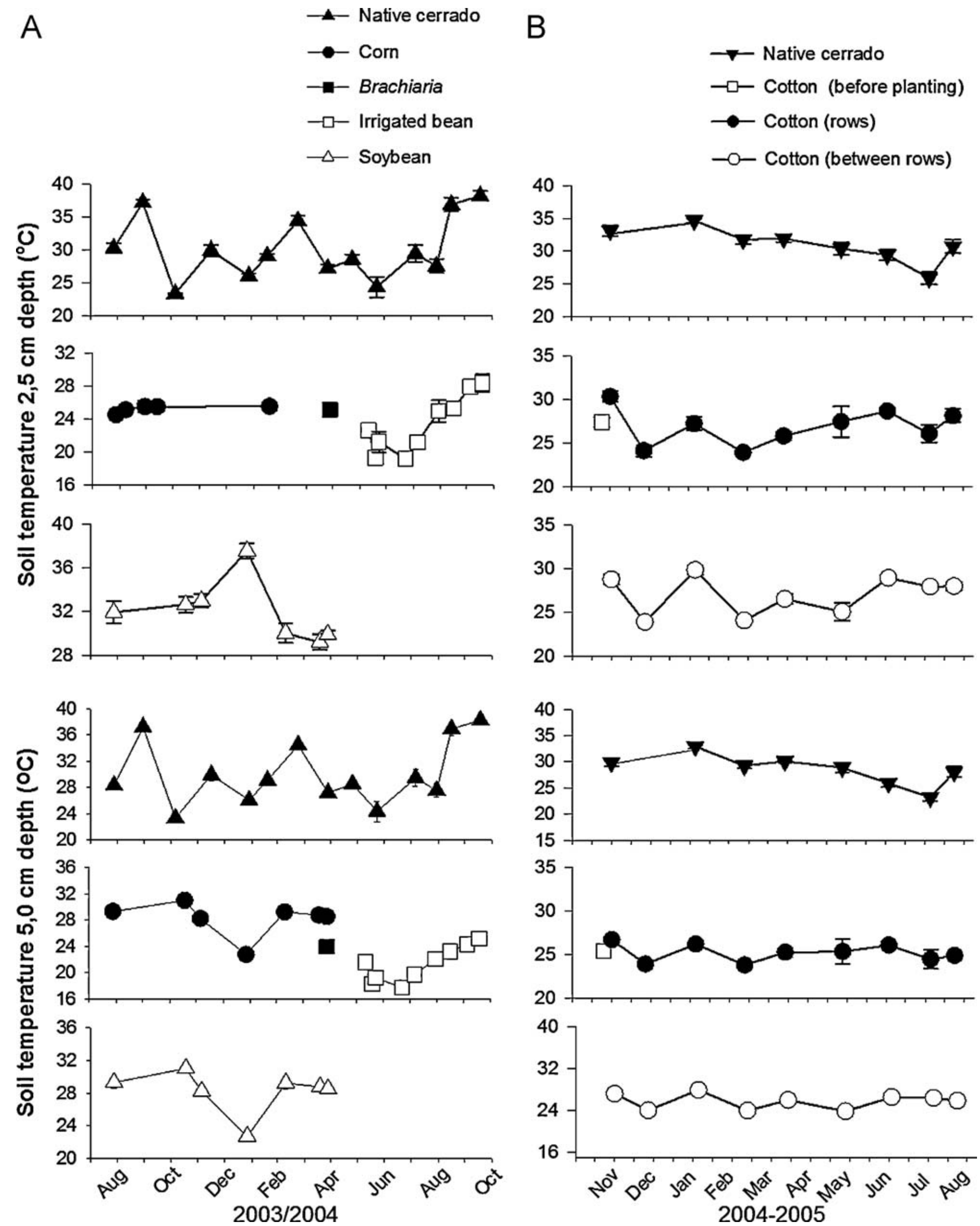

Fig. 3. Soil temperature (°C) at 0–2.5 and 2.5–5.0 cm depth in croplands and in native cerrado in the same period. (A) Dom Bosco Farm (from August 2003 to October 2004), (B) Pamplona Farm (from November 2004 to August 2005).

respectively (Fig. 3). Under maize-bean rotation soil temperatures were lower and varied from 17.7 to 25.0 °C.

In the native cerrado, NO_3^--N concentration varied from 0.8 (wet season) to 11.8 mg NO_3^--N kg^{-1} soil (dry season). Soil NH_4^+-N concentration peaked in November 2003 (151.1 mg NH_4^+-N kg^{-1} soil) and in June 2004 (106.1 mg NH_4^+-N kg^{-1} soil) while during the other months concentrations varied from 11.7 to 68.7 mg NH_4^+-N kg^{-1} soil (Fig. 4).

In the soybean field, during the fallow period and after the first rain events, the NO_3^--N concentration was around 52 mg NO_3^--N kg^{-1} soil but decreased (*ca.* 1–3 mg NO_3^--N kg^{-1} soil) during the period of intense plant growth. Shortly before and after the harvest, nitrate increased again (up to 21 mg NO_3^--N kg^{-1} soil). Availability of NH_4^+-N ranged from 21.3 to 50.7 mg NH_4^+-N kg^{-1} soil.

In the area under maize-bean rotation, the NH_4^+-N concentration was 152.1 mg NH_4^+-N kg^{-1} soil before maize planting and increased to 320.7 mg NH_4^+-N kg^{-1} soil after planting with N-fertilization. However, NH_4^+-N concentration decreased in the subsequent phases until the postharvest phase. During maize cultivation, NO_3^--N availability before planting and after planting and the first broadcast N-fertilization was about 27 mg NO_3^--N kg^{-1} soil but decreased significantly during the post-harvest phase (3.6 mg NO_3^--N kg^{-1} soil).

Afterwards, during the cultivation of *Brachiaria* (April 2004), while NO_3^--N concentration remained close to 2 mg NO_3^--N kg^{-1} soil, the concentration of NH_4^+-N was about 23 mg NH_4^+-N kg^{-1} soil increasing to 263.1 mg NH_4^+-N kg^{-1} soil one day after bean planting. In the irrigated bean field, the soil NH_4^+-N concentration remained high shortly after the first broadcast N-fertilization (July 2004, 218.6 mg N kg^{-1} soil) but was lower after the second broadcast N-fertilization (August 2004, 53.1 mg NH_4^+-N kg^{-1} soil) until the postharvest phase (October 2004, 84.5 mg NH_4^+-N kg^{-1} soil). Availability of NO_3^--N increased significantly (28.6 mg NO_3^--N kg^{-1} soil, $P = 0.000$, $F = 30.95$) before the planting of bean. During bean cultivation, the highest NO_3^--N concentrations were measured after the first (53.7 mg NO_3^--N kg^{-1} soil) and after the second

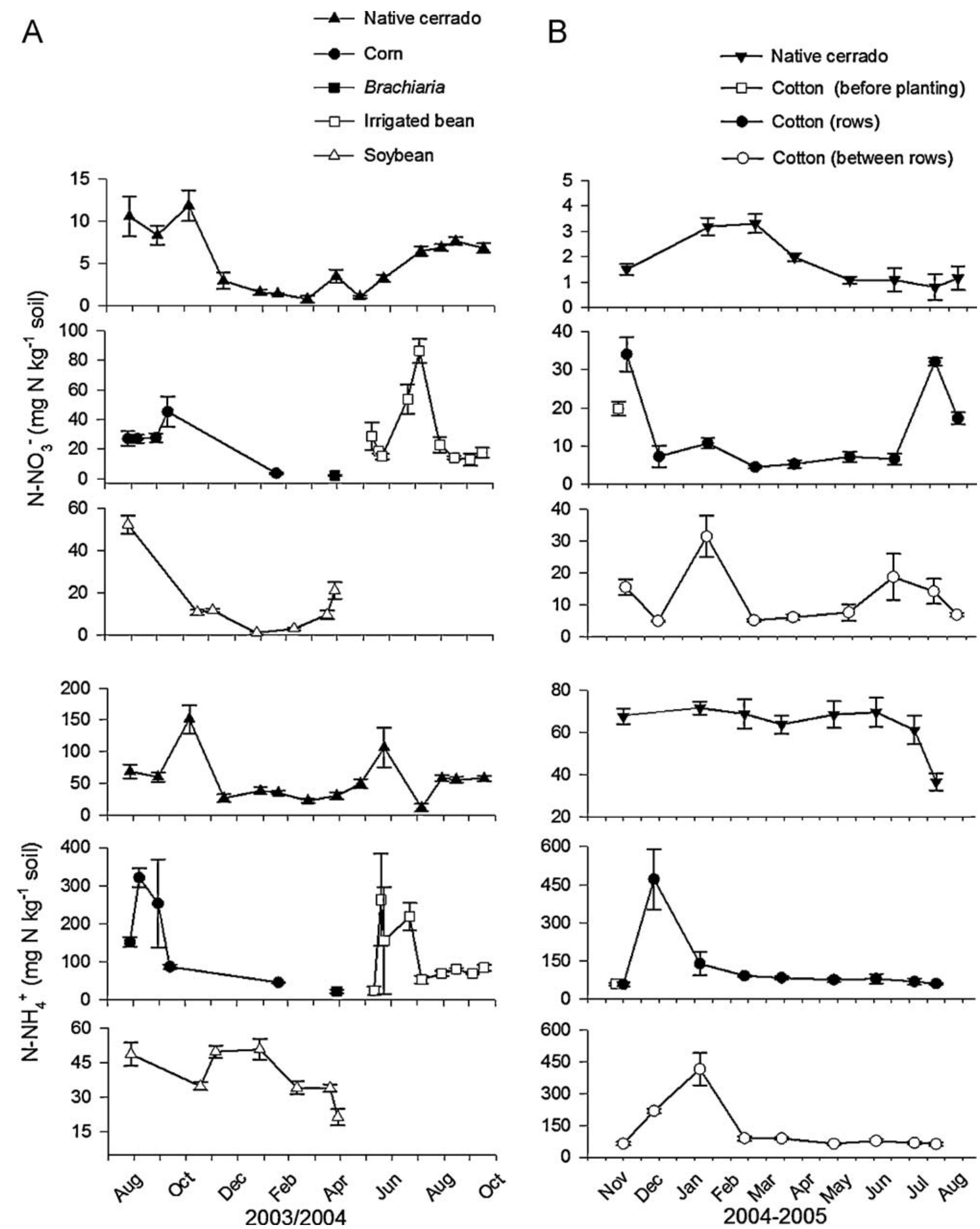

Fig. 4. Soil $NO_3{}^-$-N (mg $NO_3{}^-$-N kg^{-1} soil) and $NH_4{}^+$-N (mg $NH_4{}^+$-N kg^{-1} soil) at 0–5 cm in croplands and in native cerrado in the same period. (A) Dom Bosco Farm (from August 2003 to October 2004), (B) Pamplona Farm (from November 2004 to August 2005).

(83.5 mg $NO_3{}^-$-N kg^{-1} soil) N-fertilization. In the other cultivation phases, $NO_3{}^-$-N concentrations were lower (from 12.9 to 22.8 mg $NO_3{}^-$-N kg^{-1} soil).

Soil microbial biomass tended to be similar in the soybean field, during maize cultivation and in native cerrado soil (86.8–444.3 mg C kg^{-1} soil) but was higher during cultivation of irrigated bean (309.8–590.3 mg C kg^{-1} soil) (Fig. 5).

3.2. Soil NO-N and N_2O-N fluxes

In the native cerrado, a pulse of NO-N (8.4 ng NO-N cm^{-2} h^{-1}) was measured after the first rain events (28 mm) during the dry season. In the transition from dry to wet season higher and very variable NO-N fluxes (5.7 ± 10.9 ng NO-N cm^{-2} h^{-1}) were also measured after rain events (45 mm) (Fig. 6). Afterwards, NO-N fluxes ranged between 0.07 and 1.50 ng NO-N cm^{-2} h^{-1}. Soil moisture (% WFPS) accounted for 70% the NO-N fluxes measured in the native cerrado soil during the wet season (P = 0.000, F = 27.92).

In general, NO-N fluxes during the soybean cropping cycle were similar to those measured in the native cerrado but were not explained by the environmental variables tested. NO-N fluxes were slightly higher during the fallow period and shortly after the harvest (1.3 and 1.1 ng NO-N cm^{-2} h^{-1}, respectively). Lowest NO-N fluxes in the soybean field were measured prior to the harvest (0.3 ng NO-N cm^{-2} h^{-1}).

NO-N fluxes during maize cultivation were also not explained by the environmental variables tested. Higher NO-N fluxes were measured before planting (2.7 ng NO-N $cm^{-2\ -1}$) than after planting (0.4 ng NO-N cm^{-2} h^{-1}) with row fertilization. Pulses of NO-N emissions were observed two days after the first and second (3.9 and 8.8 ng NO-N cm^{-2} h^{-1}, respectively). During *Brachiaria* cultivation, NO-N fluxes (0.3 ng NO-N cm^{-2} h^{-1}) were lower than those in the native cerrado (1.5 ng NO-N cm^{-2} h^{-1}) but increased during cultivation of bean with irrigation, NO-N fluxes were significantly higher shortly the first and second broadcast fertilization with urea (5.0 ng NO-N cm^{-2} h^{-1} and 12.2 ng NO-N cm^{-2} h^{-1}, respectively).

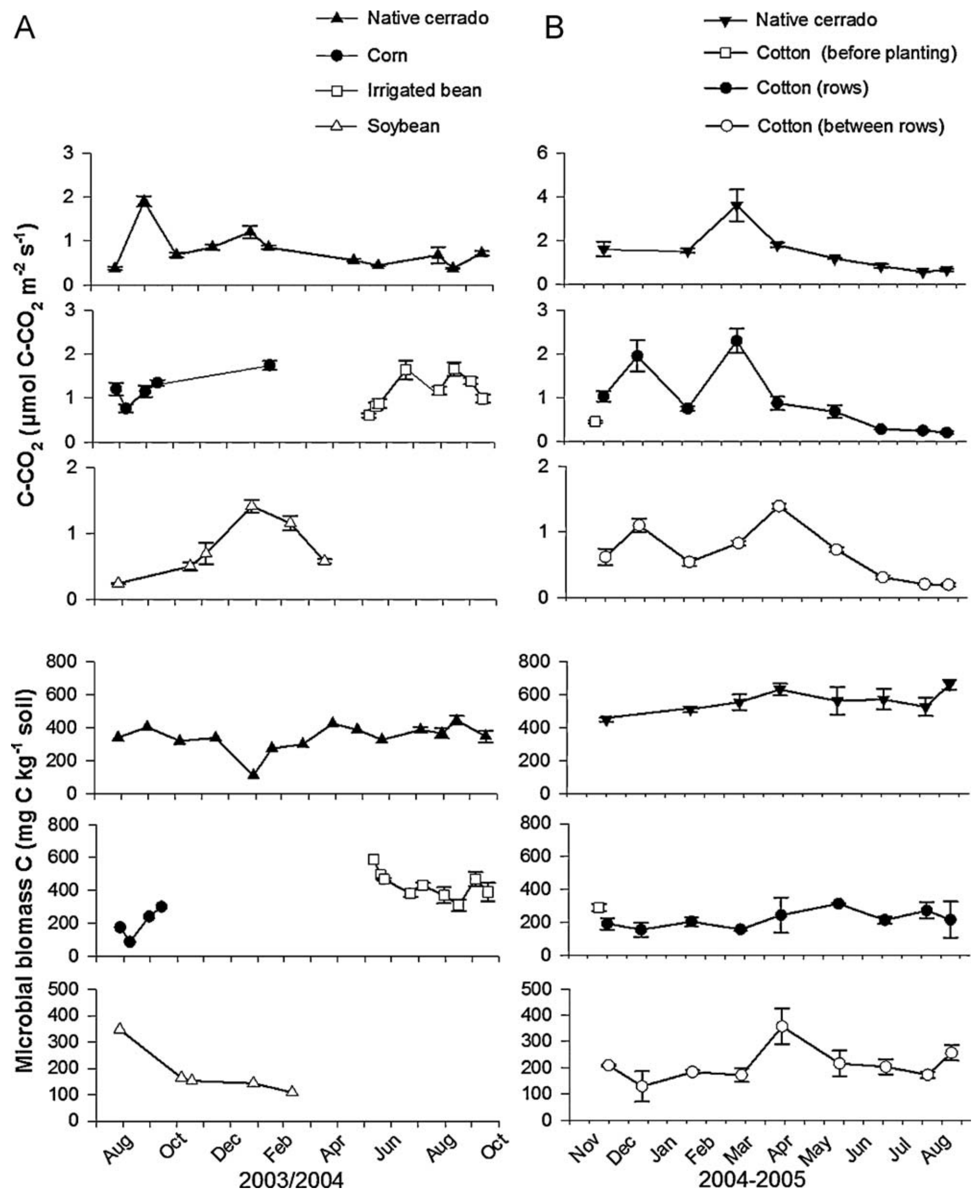

Fig. 5. Soil CO_2-C fluxes (μmol CO_2-C m^{-2} s^{-1}) and microbial biomass (mg C kg^{-1} soil) in croplands and in native cerrado in same period. (A) Dom Bosco Farm (from August 2003 to October 2004), (B) Pamplona Farm (from November 2004 to August 2005).

During the other cultivation phases, NO-N fluxes varied between 0.3 and 0.7 ng NO-N cm^{-2} h^{-1}. Availability of NO_3^+-N accounted for 82% (P = 0.000, F = 104.47) of the NO-N fluxes during the cultivation of bean with irrigation.

Most of the soil N_2O-N fluxes measured under cultivated and the native cerrado were very low and under the detection limit (0.6 ng N_2O-N cm^{-2} h^{-1}). Nevertheless, under bean cultivation with irrigation, N_2O-N fluxes increased significantly shortly after irrigation with broadcast fertilizations with urea (2.3 ng N_2O-N cm^{-2} h^{-1} and 10.6 ng N_2O-N cm^{-2} h^{-1}). Modest and variable increments in N_2O-N fluxes occurred during the senescence of the bean (1.7 ng N_2O-N cm^{-2} h^{-1}) as well during nodule senescence in the soybean field (3.8 ng N_2O-N cm^{-2} h^{-1}). Availability of NO_3^--N accounted for 85% (P = 0.000, F = 62.00) of N_2O fluxes during cultivation of bean with irrigation while fluxes from the soybean field, the native cerrado and during maize cultivation could not be explained by the environmental variables tested.

Integrated fluxes per crop cycle are presented in Table 3. Emission of NO-N per hectare under maize and bean cultivation were similar (0.3 kg NO-N ha^{-1}) while for soybean it was 0.2 kg NO-N ha^{-1}. Negative N_2O-N fluxes were recorded, indicating possible uptake, in 50% and 60% of observations during the fallow period in the dry season, before and shortly after planting of the maize and soybean plants, respectively. Negative N_2O-N fluxes were not observed during the irrigated bean cycle and emissions were around 0.2 kg N_2O-N ha^{-1}. Nitrogen losses as NO-N represented 0.1% of the N fertilizer added during maize cultivation (155.3 kg N), while losses as N_2O-N represented 0.3%. For irrigated bean, nitrogen losses as NO-N represented 0.2% of the N fertilizer added during cultivation (102.7 kg N), while losses as N_2O-N represented 0.2%.

3.3. Soil CO_2-C fluxes

Soil CO_2-C fluxes in the native cerrado ranged from 0.4 (dry season) to 1.2 μmol CO_2-C m^{-2} s^{-1} (wet season) and were similar to those in the soybean field (0.2 μmol to 1.2 μmol CO_2-C m^{-2} s^{-1}). Soil moisture (% WFPS) accounted for 63% (P = 0.000, F = 20.45) of soil CO_2-C fluxes in the soybean field.

In general, CO_2-C emissions during cultivation of maize and irrigated bean were twice as high as in the native cerrado.

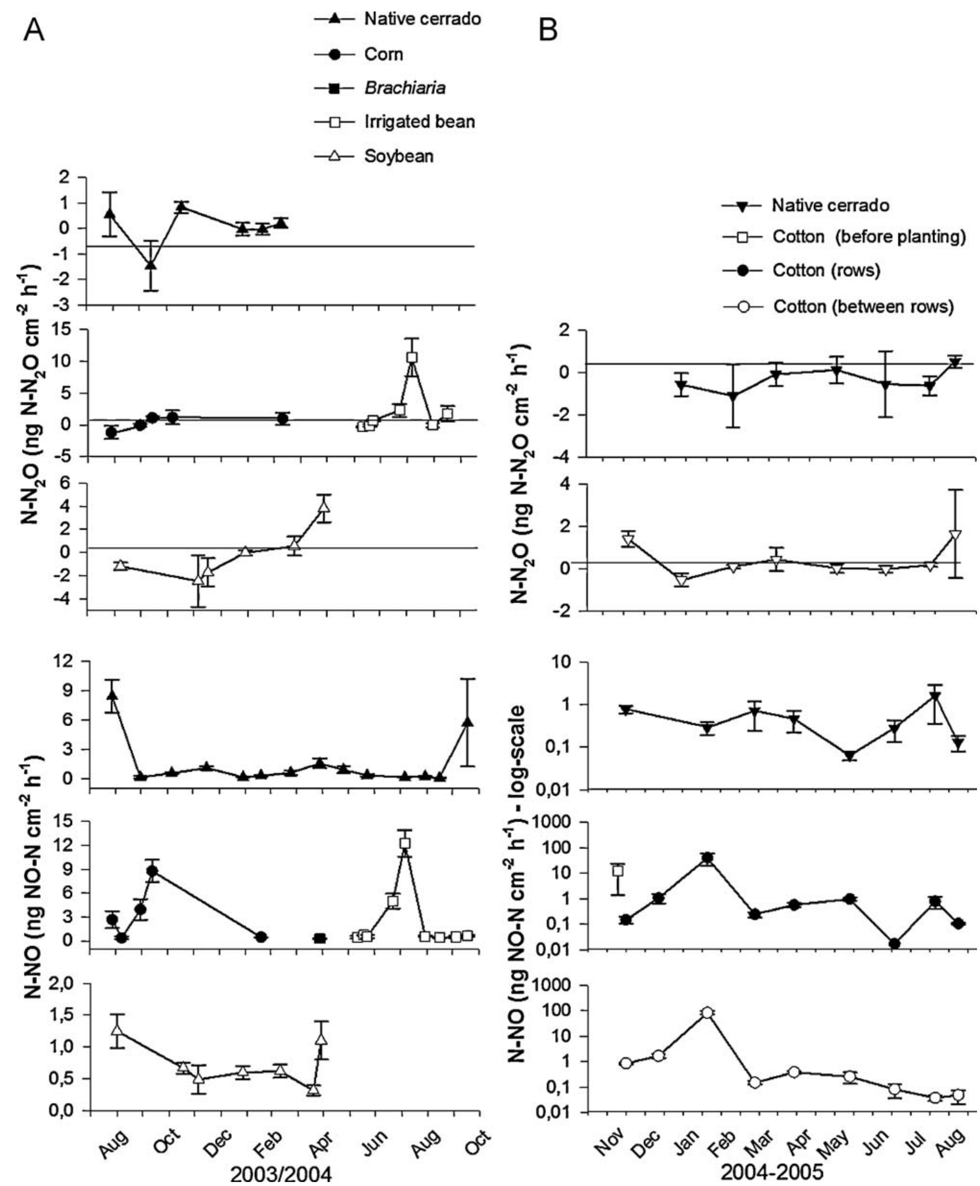

Fig. 6. Soil N_2O-N (ng N_2O-N cm^{-2} h^{-1}) and NO-N (ng NO-N cm^{-2} h^{-1}) fluxes in croplands and in native cerrado in the same period. (A) Dom Bosco Farm (from August 2003 to October 2004), (B) Pamplona Farm (from November 2004 to August 2005). Data points in Pamplona Farm represents log N-NO.

Soil respiration during maize cultivation varied from 0.8 to 1.8 μmol CO_2-C m^{-2} s^{-1}. Soil respiration measured in the dry season in the maize field was three times higher than in native cerrado soil. NH_4^+-N availability accounted for 55% (P = 0.001, F = 12.40) of CO_2-C fluxes during maize cultivation. During cultivation of bean with irrigation, a significant increase (P = 0.000) in CO_2-C fluxes (from 0.9 to 1.6 μmol CO_2-C m^{-2} s^{-1}) was observed two days after broadcast fertilization. Soil respiration remained higher until harvest and decreased after harvest to values similar to those measured shortly before and after planting. Soil respiration under cultivation of bean with irrigation was also not explained by the environmental variables tested.

Table 3
Estimative of soil NO-N and N_2O-N emissions per hectare from croplands (maize, irrigated bean, soybean and cotton) and native savanna.

Study area	Period (days)	NO-N emitted (kg ha^{-1})	Error estimate (%)	N_2O-N emitted (kg ha^{-1})	Error estimate (%)
Dom Bosco Farm					
Native cerrado	173	0.1	11.2	0.01	1528.0
Maize	173	0.3	21.1	0.2	35.7
Native cerrado	135	0.1	37.1	0.03	167.4
Irrigated bean	135	0.3	9.3	0.2	129.7
Native cerrado	153	0.2	17.6	−0.03	0.0
Soybean	153	0.2	13.4	0.1	28.1
Pamplona Farm					
Native cerrado	258	0.3	2.4	−0.2	13.1
Cotton	258	0.8	21.9	0.1	6.0

3.4. Cotton cultivation – Pamplona Farm

In the cotton field at the Pamplona Farm WFPS values and soil temperatures did not differ significantly in rows and between rows with the highest values of WFPS around 50% while in native cerrado soil it was 37%. Soil temperature (5.0 cm depth) ranged from 23.2 to 32.9 °C and from 23.8 to 27.9 °C in the native cerrado and in the cotton field, respectively. During the wet season, soil temperatures in the native cerrado soil were significantly higher (P = 0.042, F = 4.38) than in the cultivated area, while during the dry season (May to August 2005), soil temperatures were similar in the two areas.

In the native cerrado, soil NO_3^--N concentrations ranged from 0.8 to 3.3 mg N kg^{-1} during the period of the study. The availability of NO_3^--N increased by up to 1.5 times after planting in comparison to the pre-planting phase with the application N fertilizer but only in rows. A second peak of NO_3^--N concentration was measured 15 days in rows before the harvest. The highest NO_3^--N concentration (31.4 mg N kg^{-1} soil) between rows was measured shortly after second broadcast N-fertilization. Throughout the other sampling dates, availability of NO_3^--N in rows and between rows varied from 4.4 to 18.6 mg N kg^{-1} soil. The highest concentrations of NH_4^+-N were measured after the first broadcast N fertilization. A large pulse of NH_4^+-N was measured after the second broadcast fertilization. In the other sampling dates, availability of NH_4^+-N varied from 60.8 to 91.5 mg N kg^{-1} soil and was similar to that observed in the native cerrado soil. The concentration of NH_4^+-N under the native cerrado soil significantly (P = 0.037) decreased at the end of dry season (36.6 mg N kg^{-1} soil).

Throughout all sampling dates, microbial biomass was higher under the native cerrado than under cultivation of cotton (rows and between rows). Soil microbial biomass values measured varied from 129.3 to 356.9 mg C kg^{-1} soil, while under native vegetation values varied from 448.5 to 662.4 mg C kg^{-1} soil.

3.4.1. Soil NO-N and N_2O-N fluxes

Soil NO-N fluxes under native vegetation varied from 0.06 to 1.6 NO-N ng cm^{-2} h^{-1}. Higher but very variable NO-N fluxes (12.6 ± 27.4 NO-N ng cm^{-2} h^{-1}) were measured under *Brachiaria* straw (before cotton planting). After the planting of cotton with N-fertilization in rows, the NO-N fluxes in rows (0.2 ± 0.08 NO-N ng cm^{-2} h^{-1}) were lower than fluxes between rows (0.9 ± 0.08 NO-N ng cm^{-2} h^{-1}) (P = 0.035). Slightly higher NO-N fluxes were measured in rows (1.1 NO-N ng cm^{-2} h^{-1}) and between rows (1.7 NO-N ng cm^{-2} h^{-1}) after the first broadcast fertilization. A large pulse of NO-N was measured after the second broadcasting of N-fertilizer in rows (39.3 ± 20.1 NO-N ng cm^{-2} h^{-1}) and between rows (83.3 ± 11.9 NO-N ng cm^{-2} h^{-1}). The fluxes measured in January 2005 were almost 1000 times higher than NO-N soil fluxes under the native cerrado. NO-N fluxes measured 15 days before the harvest were higher (P = 0.033, F = 10.19) in rows (0.78 NO-N ng cm^{-2} h^{-1}) than between rows (0.04 NO-N ng cm^{-2} h^{-1}). Availability of NH_4^+-N (0–5 cm depth) accounted for 85% (P = 0.000, F = 65.45) of NO-N fluxes between rows while NO-N fluxes in rows were not explained by the variables tested. In the native cerrado, 40% of the NO-N fluxes were explained by microbial biomass (P = 0.008, F = 7.89).

In general, the N_2O-N fluxes from the cotton field were similar to those from the native cerrado (−0.6 to 0.5 ng N_2O-N cm^{-2} h^{-1}). The N_2O-N values ranged from 0.5 to 1.6 ng N_2O-N cm^{-2} h^{-1} (shortly after harvest) and could not be explained by the variables tested.

Compared with the other cropping systems, cotton cultivation resulted in the highest emission of NO-N per hectare (0.8 kg NO-N ha^{-1}). Most N_2O-N fluxes (62%) were close to the detection limit and the emission per crop cycle was around 0.1 kg N_2O-N ha^{-1}, the same value calculated for maize cultivation. Nitrogen losses as NO-N represented 0.5% of the N fertilizer added during cotton cultivation (150 kg N), while losses as N_2O-N represented 0.1%.

3.4.2. CO_2-C fluxes

Soil CO_2-C fluxes under the native cerrado varied from 2.1 μmol CO_2-C m^{-2} s^{-1} (July 2005) to 13.2 μmol CO_2-C m^{-2} s^{-1} (March 2005) and were higher than in the cultivated area (0.7–7.1 μmol CO_2-C m^{-2} s^{-1}) throughout all sampling dates. Two days after cotton planting with the addition of N fertilizer a slight but significant increase (P = 0.012, F = 11.34) in CO_2-C fluxes was measured but only in rows (1.0 μmol CO_2-C m^{-2} s^{-1}).

Soil moisture (% WFPS, 0–5 cm depth) accounted for 88% (P = 0.000, F = 82.27) of CO_2-C fluxes measured in rows, 78% (P = 0.000, F = 39.44) between rows and 59% (P = 0.000, F = 24.59) in the native cerrado.

3.5. Soil C and N stocks

In comparison with the remnant of the native cerrado (62.3 Mg C ha^{-1}), significantly lower soil C stocks (0–30 cm depth) were determined under the maize-*Brachiaria*-bean rotation (56.4 Mg C ha^{-1}) adopted for 10 years after land conversion (P = 0.088) and in soybean followed by the natural fallow system (51.7 Mg C ha^{-1}) adopted for 31 years after land conversion (P = 0.007) Soil N stock (0–30 cm depth) was lower under soybean cultivation (2.7 Mg N ha^{-1}) than under the native cerrado and maize-bean rotation (3.3 Mg N ha^{-1}).

In the Pamplona Farm, C and N stocks after 27 years of cotton-soybean rotation were similar to those under native vegetation (53.2 Mg C ha^{-1} and 3.1 Mg N ha^{-1}).

4. Discussion

The low soil N_2O-N fluxes recorded under cultivation and native vegetation are in accordance with results from other studies in the Cerrado region under maize cultivation (Carvalho et al., 2006), pasture (Varella et al., 2004; Pinto et al., 2006) and cerrado vegetation (Pinto et al., 2002). Low soil N_2O fluxes are related to low NO_3-availability and aerobic conditions with WFPS lower than 60% (Davidson et al., 2000). In general, Oxisols in the Cerrado region are well-drained, relatively N-limited and exhibit low nitrification rates (Nardoto and Bustamante, 2003). Moreover, surface soils under no-till systems preserve a structure similar to those under native vegetation favoring good soil aeration.

Although low fluxes of N oxides were observed in most of the study areas, agricultural practices could induce pulses of NO-N and N_2O-N. Availability of NO_3-N explained the N_2O-N fluxes under irrigated bean cultivation. The largest NO-N and N_2O-N peaks were measured after N-fertilizations associated with irrigation that resulted in an increase of N availability and favorable WFPS conditions (i.e. less aerobic soil environment). Also, slightly higher NO_3-N availability and N_2O-N fluxes were recorded during the senescence of bean and soybean and the post-harvest phase of cotton, especially in rows, which could be related to root mortality (Varner et al., 2003; Silver et al., 2005) and N release from roots and nodules. Jantalia et al. (2006) also observed higher N_2O-N fluxes in the last phase of soybean cycle in long term studies in the Southern region of Brazil.

Negative fluxes of N_2O were observed in the post-harvest phase. Although soils are usually considered a net source of atmospheric N_2O-N, they can also act as sinks, at least temporarily, depending on management practices and environmental conditions (Minami, 1997). In general, N_2O-N production and consumption processes occur in soil microsites and are, thereafter, very variable. Chapuis-Lardy et al. (2007), in a review of the role of soils as sinks for N_2O-N, pointed out that there are considerable uncertainties when trace gas sources or sinks are not uniformly distributed in the soil or located too close to the surface for gradients to be measured, or when non-diffusive transport is involved.

Large additions of organic matter as observed after the cultivation with *Brachiaria* and before cotton planting resulted in higher variability of NO-N fluxes with some peak values. This variability might be associated with the transition between the dry and wet season and the decomposition of *Brachiaria* straw after the application of herbicide (Passianoto et al., 2003). NO-N fluxes in rows under cotton cultivation were explained by NH_4^+-N availability. The slight increase in NO-N fluxes observed after first broadcast N-fertilization was possibly underestimated because time (4 h after application) may not have been sufficient for total reaction and production of higher pulses of NO-N. The second broadcast N-fertilization increased NO_3^--N and NH_4^+-N availability three days after N-application with consequent increases in NO-N fluxes in rows and between rows. Availability of inorganic-N and NO-N fluxes tended to be higher between rows. This could be a consequence of competition between roots and microbes for N in rows during this phase of the cropping cycle. Differences in the fluxes between the first and second broadcast fertilizations could be also related to the amount and the form of N added (ammonium sulfate or urea). Shortly before and after the cotton harvest, NO-N fluxes and NO_3^--N availability were higher in rows, probably due to root mortality and decomposition, especially fine roots (<2 mm diameter) as discussed before for N_2O-N fluxes.

Under native vegetation, NO-N fluxes were explained by soil moisture (Dom Bosco Farm) and microbial biomass (Pamplona Farm). Although both cerrado areas burned during the period of the study, there was no detectable effect of fire on soil NO-N fluxes. Pinto et al. (2002) also only observed soil NO-N pulses in burned native areas after the occurrence of rain events.

Seasonal distribution of rainfall affecting soil moisture was the main factor explaining soil CO_2-C fluxes under native vegetation, cotton (in rows and between rows) and soybean cultivation. None of the variables tested explained soil respiration under the cultivation of bean with irrigation. Although only under maize cultivation CO_2-C fluxes have been explained by NH_4^+-N concentration, effects of N-availability on soil CO_2-C fluxes were observed also under cotton and bean cultivation.

Microbial activity is controlled by availability of N and C, soil moisture and temperature. Although WFPS was higher in the cotton field during the wet season than in the native cerrado soil, soil respiration was lower under cotton cultivation than under the native cerrado. This could be explained by lower values of soil microbial biomass under cotton cultivation (about 2.5 times lower than in the native cerrado). Cotton cultivation demands a very intense management with several applications of biocides throughout the crop cycle and the study area is under this system (rotation of soybean-natural fallow-*Brachiaria*-cotton) since 1980. Higher soil respiration under native vegetation could be also associated with the burning that occurred before the first measurements. An increase in autotrophic respiration could be related to the resprouting of cerrado vegetation (grasses and woody layer).

Cotton cultivation in the Cerrado region has a longer cycle, extending from the wet to the dry season differently from soybean and maize cultivation. At the beginning of the wet season, soil under cotton cultivation was still covered with *Brachiaria* straw and this cover probably also led to lower soil temperatures and higher WFPS compared with the native cerrado. At the end of the wet season growth inhibitor and defoliant were applied over cotton plants leading to lower soil cover and probably increasing evaporation. *Brachiaria* straw was largely decomposed by the beginning of the dry season. As a result of these practices, soil under cotton cultivation during the dry season exhibited temperatures and WFPS similar to those under the native cerrado soil. Nevertheless, soil CO_2-C fluxes were still higher under native vegetation than under cotton during the dry season.

Soil respiration was higher in the system rotation maize-*Brachiaria*-irrigated bean (Dom Bosco farm) than under native vegetation. This could be related to the soil cover during the entire period of the study and to the diversity of covers (cereal (maize), grass (*Brachiaria*) and legume (bean)) and nutrient additions in association with irrigation. On the other hand, soybean cultivation followed by natural fallow during the dry season produced soil CO_2-C fluxes that were similar to those of the native cerrado.

Soil stocks of C and N are a function of C and N inputs and decomposition, management practices, soil and climate factors. A high N input through Biological Nitrogen Fixation (*ca.* 185 kg N ha^{-1} $year^{-1}$) is estimated for soybean (Alves et al., 2006), but grain production and pod filling are strong sinks for N. In addition, soybeans are still widely cultivated in the Cerrado region as a monoculture without a second crop. The high harvest index (*ca.* 86%) for aboveground biomass (Alves et al., 2006) and the little remaining necromass under natural fallow might contribute to soil C and N losses over time. On the other hand, maize-*Brachiaria*-bean rotation in the Dom Bosco Farm, which is a system that maintains soil cover through the year, also resulted in a lower soil C stock but maintained soil N probably due to irrigation during the dry season and the input of N fertilizer. On the other hand, soil under the crop rotation system without irrigation (soybean-*Brachiaria*-cotton) in the Pamplona Farm featured similar stocks of C and N to those under the native cerrado even after 27 years of cultivation. Model simulations showed that the potential soil C storage in Cerrado Oxisols was highest under cropping systems with two crops per year (for example, soybean-maize cropping under no-till) and also indicated that gains in soil C were related to gains in soil N under cropping systems with two crops per year (Bustamante et al., 2006). The long-term accumulation of soil C can be expected only when the net N balance of the cropping systems is positive (Sisti et al., 2004).

The fertilizer induced emission factor (FIE) established by the IPCC (2007) is 0.7% and 1% of the N applied via fertilizer for N-NO and N_2O-N, respectively. Our results indicated that FIE for N oxides under the environmental conditions and cultivation systems in the Cerrado are lower, which could affect the estimates of emissions made by inventories of anthropogenic greenhouse gas emissions in Brazil and in other tropical regions with similar soils.

The wide variation in estimated errors in the integration of the fluxes of NO and N_2O during the cropping period was probably due to the spatial variability, both horizontally and vertically, of cultivated and native soils. The spatial variability is caused by alterations in the processes and factors that drive the dynamics of C and N in the soil such as soil characteristics, agricultural practices (fertilization, irrigation and mechanization), rhizodeposition and variations in temperature and humidity. Such processes and factors influence the production, consumption and emission of nitrogen oxides, especially N_2O that is produced in anaerobic microsites (Skiba et al., 1993; Davidson et al., 1993; Hall et al., 1996; Russow et al., 2000).

5. Conclusions

Losses of N in the form of NOx are higher than in the form of N_2O-N from Oxisols of the Cerrado region under different crop systems. Agricultural practices (N-fertilization and irrigation) induced higher NO-N emissions in comparison to soils under native vegetation. Soil processes related to N_2O-N production and consumption in these soils, especially under changes in plant N allocation as during plant senescence and fine root mortality, need to be better understood.

Fertilizer-induced emission values (N_2O-N and NO-N), however, were lower than those established by the IPCC with possible impacts on inventories of greenhouse gas emissions. However, low fluxes might have an important regional impact when the total area of the Cerrado under agriculture is considered.

Soil C and N stocks (0–30 cm) are significantly lower under no-till soybean-natural fallow after 31 years of cultivation in comparison to native vegetation. However the effect of crop rotation on the maintenance of C and N stocks is not conclusive. In the case of the Cerrado, more studies are necessary to indicate practices that minimize soil C losses and simultaneously avoid increasing N oxide emissions.

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