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Trace gas fluxes from intensively managed rice and soybean fields across three growing seasons in the Brazilian Amazon

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The emission of gases that may potentially intensify the greenhouse effect has received special attention due to their ability to raise global temperatures and possibly modify conditions for life on earth. The objectives of this study were the quantification of trace gas flux (N_2O, CO_2 and CH_4) in soils of the lower Amazon basin that are planted with rice and soybean, and the relation of this flux to soil physical and chemical parameters and to precipitation. This study was conducted in agricultural fields planted with rice (*Oryza sativa*) and soybean (*Glycine max*), located near the cities of Belterra and Santarém in western Pará State, Brazil, during the production years of 2005 to 2007. Measurements were done using static chambers in the field, and samples were analyzed by gas chromatography in the laboratory. Statistical analysis was conducted to determine variation in gas flux in both crops, and the results show that CO_2 flux varied between 305 and 227 mg-C m^{-2} h^{-1} under rice, and 243 and 156 mg-C m^{-2} h^{-1} under soybean. Flux of N_2O under rice varied between 4.5 and 20.4 µg-N m^{-2} h^{-1}, and under soybean flux variation was between 4.0 and 9.4 µg-N m^{-2} h^{-1}. Variation in flux of CH_4 under rice was between 5.1 and 14.0 µg-C m^{-2} h^{-1}, and under soybean it was 0.4 and 1.2 µg-C m^{-2} h^{-1}. These results demonstrate that, during the study period, the rice crop had higher flux for all trace gases than the soybean crop.

Key words: Amazon region, trace gas, crops.

INTRODUCTION

Land use change, the anthropogenic clearing of forest for agriculture, and agricultural practices are three of the main contributors to the increase in atmospheric greenhouse gas (GHG) concentrations (Houghton, 1991; Fearnside, 2005; IPCC, 2007) and, thus; climate changes. The main gases that contribute to the

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greenhouse effect (GHG) are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and water vapor (H_2O) (Ostermayer, 2004). Without these gases, which act as a natural blanket around the earth, thermal infrared radiation absorbed by the earth´s surface would dissipate into space and the temperature of the planet would be approximately 20°C colder than the current global average of 15°C (Houghton, 2004). However, increased concentrations of GHG lead to retention of heat in the atmosphere, provoking disequilibrium in terrestrial ecosystems due to the increase in temperature. According to estimates of the Intergovernmental Panel on Climate Change (IPCC), the average global temperature will increase by 1.8ºC by the end of this century (IPCC, 2007). The consequences of this increase are affecting the quality of life currently experienced around the world and also for long-term agricultural sustainability.

The increase in the concentration of these gases in the atmosphere is principally due to anthropogenic actions manifested directly through fossil fuel burning, industrial production, and fires, and indirectly through the irrational use of natural resources (Cardoso et al., 2001).

Combined CO_2, CH_4, and N_2O contribute to more than 90% of anthropogenic climate warming gasses (Hansen et al., 2000). The fluxes of CO_2, CH_4, and N_2O are influenced by multiple factors, such as climate, nitrogen deposition, and land management practices. Agriculture releases to the atmosphere significant amounts of CO_2, CH_4, and N_2O (Smith et al., 2007; Metay et al., 2007). As a proportion of global anthropogenic emissions in 2005, agriculture contributed approximately 20% of CO_2 (Smith et al., 2007; Johnson et al., 2007) 58% of N_2O (Smith et al., 2007; Syakila and Kroeze, 2011), and 47% of CH_4, (Smith et al., 2007). Agricultural emissions of CH_4 and N_2O have increased globally by nearly 17% from 1990 to 2005 (IPCC, 2007), and agricultural N_2O emissions are projected to increase by 35 to 60% by 2030 due to increased nitrogen fertilizer use and increased animal manure production (FAO, 2003). Assuming that CH_4 emissions will grow in direct proportion to increases in livestock numbers, then global emissions from livestock is expected to increase by 60% by 2030 (FAO, 2003).

Land use change releases greenhouse gases when the forest is burned to clear the land (Houghton, 1991; Crutzen and Andreae, 1990; Goreau and Mello, 1988). Deforestation rates in the tropics have reached 2% of the total area, annually (Williams, 1990; Meyers, 1991). These deforested areas in the tropics are converted principally to plantations and pastures (Hecht, 1992; Fearnside, 2005). After land use change, agricultural practices such as soil tillage and application of mineral fertilizer affect soil gas emissions. Soil tillage accelerates decomposition of soil organic matter (SOM), whereas application of nitrogen-based fertilizer to the soil increases emissions of N_2O and NO (Davidson et al., 1996; Matson et al., 1996; Veldkamp et al., 1998; Crill et al., 2000; Mosier, 2001; Yan et al., 2001; Steudler et al., 2002).

Due to recent agricultural expansion in the Amazon evaluation of impacts by this land use on greenhouse, gas emissions have become a research priority. Many studies have documented the emissions from pastures (Verchot et al., 1999; Cerri and Cerri, 2007; Neil et al., 2005; Wick et al., 2005; Garcia-Montiel et al., 2001), and forests (Luizão et al., 1989; Melillo et al., 2001, Keller et al., 2005), but few studies have investigated emissions from croplands in the Amazon region. The variability in edaphic and climatic conditions in the Amazon basin is enormous, which makes research on this topic even more important. Within the region, there are many different scenarios of agricultural expansion occurring simultaneously, and these diverse situations will have different impacts on the way in which they alter natural processes and the rates at which these impacts occur. Within the region of western Pará State, for example, there has been a large front of expansion of mechanized agriculture during recent years, and few if any studies have been conducted in an attempt to evaluate the impacts caused by these activities and their effects on areas adjacent to these new centers of production. The area dedicated to soybean production in the region of Santarém, Pará State tripled between 1999 and 2002 (Lameira and Alencar, 2002), and was 28,150 ha in 2009, and was projected to reach 86,900 ha in 2010 (CONAB, 2012). The majority of this expansion has been in areas of secondary forest and pasture, with just 10% resulting from deforestation of primary forest (Venturieri et al., 2007). The area under soybean in the State of Pará, which was 86,900 ha in 2010 (CONAB, 2012), could triple by 2014 as a function of current market tendencies (FBOMS, 2004).

In light of this situation, this work had as its principal objectives the quantification of trace gas fluxes of N_2O, CO_2 and CH_4 in soils of the lower Amazon basin planted with soybean and rice, and the relation of this flux with soil chemical and physical parameters and also with precipitation. It was expected to find that N_2O emissions under soybean would be higher than those from soils under rice–because soybean is a legume with N-fixing ability and therefore increasing the nitrogen abundance in the soil. It was also expected that methane emissions would be higher in soils under rice cultivation, because of the lower oxygen content of these soils due to expected higher water content.

MATERIALS AND METHODS

This study was conducted in agricultural fields planted rice (*Oryza sativa*) and soybean (*Glycine max*), located near the cities of Belterra and Santarém in western Pará State, Brazil, during the production years of 2005 to 2007. The areas were initially planted with rice, then with soybean, both crops using a conventional management system, in the same area. During dry season this area was in fallow.

The region's climate is type Am in the Köppen classification

Table 1. Some physical and chemicals characteristics of clayey Yellow Latossols in Belterra municipality, Pará State (Two experimental sites).

HOR	Depth	Sand	ADA	Clay	C	Fe_2O_3	H_2O	ΔpH	Ca	Mg	K	S	Al	T	Silt/	Ki	V	m	P
	cm	(g/kg of soil)				pH					(cmol$_c$ kg^{-1} soil)				clay		%		(mg/kg)
Typic Hapludox – coordinates: 02º54'S e 54º56'W																			
A1	0 - 11	30	640	890	19.8	61	3.7	-0.1	0.40		0.05	0.50	2.70	10.5	0.09	1.91	5	84	4
AB	23	20	510	920	13.6	63	4.1	-0.3	0.30		0.03	0.45	2.10	7.8	0.07	1.86	5	84	2
BA	45	20	0	930	9.6	66	4.3	-0.4	0.40		0.02	0.44	1.80	5.9	0.05	1.86	7	82	1
Bw1	91	20	0	930	6.4	67	4.4	-0.4	0.30		0.01	0.32	1.70	4.4	0.05	1.88	7	85	1
Bw2	160	10	0	930	4.2	67	4.7	-0.6	0.40		0.01	0.44	1.00	3.6	0.06	1.92	11	71	1
Typic Hapludox – coordinates: 02º 45'S e 54º54'W																			
O	3 - 0	160	50	680	55.9	41	4.8	-0.8	6.8	3.2	0.23	10.3	0.3	22.9	0.24	2.03	13	89	1
A1	0 - 15	100	50	820	18.1	49	4.5	-0.5	0.5	0.5	0.04	1.1	1.6	8.4	0.10	1.99	5	92	<1
AB	29	70	68	840	11.3	52	4.5	-0.5	0.4		0.02	0.44	1.7	6.4	0.11	1.98	1	90	<1
BA	44	60	0	870	7.9	52	4.7	-0.6	0.50		0.02	0.53	1.5	4.6	0.08	1.94	1	88	<1
Bw1	79	70	0	870	5.1	52	4.9	-0.9	0.40		0.01	0.42	1.3	4.0	0.07	1.94	1	91	<1
Bw2	122	60	0	890	5.0	55	5.0	-1.0	0.40		0.01	0.42	1.3	3.5	0.06	1.92	1		
Bw3	200	50	0	880	4.0	54	5.0	-1.0	0.40		0.01	0.43	1.1	3.5	0.08	1.95	1		

ADA, Clay dispersed in water.

system (IBAMA, 2004), and the soils are predominately clayey Oxisols on slightly undulating terrain, classified by the Brazilian Soil Classification System (Embrapa, 1999) as Typic Hapludox, with an average clay content above 850 g kg^{-1} (Table 1) (Moraes et al., 1995; Rodrigues et al., 2001).

In the city of Santarém, annual average air temperature varies between 25.4 and 27.1°C, and relative humidity is high year-round with an average of 86.7%. Precipitation indices present large annual variation with an average of 1920 mm (INMET, 2010), and there are two distinct seasons: a rainy season from December to May, and a dry season from July through November. In the city of Belterra, annual average temperature varies between 25 and 28°C with an average annual relative humidity of 86%. Precipitation also occurs in two distinct periods, with a dry season from July to January presenting a monthly average of 62.5 mm, and a rainy season from February to June with an average of 770 mm (INMET, 2010).

Experimental design

Sampling was done in two 1 ha monoculture fields of soybean and of rice. In each of the 4 fields, 10 static chambers were randomly distributed for each sampling event. During the crop cycle (and concurrent with sampling), mineral fertilizer was applied to both crops at a rate of 400 kg ha^{-1} (2% N, 45% P, and 60% K), and nitrogen fertilizer was applied at a rate of 60 kg ha^{-1} of urea (60% N) 60 days after plant emergence. Soybean productivity was 3,180 kg ha^{-1} (± 400 kg) per year; rice productivity was 3,000 kg ha^{-1}.

Sampling was divided into 3 stages: Period 1: From initial seedling planting (day zero) to day 7, with daily sampling to verify the effects of fertilizer application; Period 2: Day 8 up to harvest day, with sampling conducted once a week; Period 3: Harvest day to day 5 after harvest, with sampling done each day.

Gas sample collection protocol

The static chamber method was used to sample N_2O and CH_4, following the protocol described in Keller et al. (2005). Chambers were randomly installed in the field and inserted into the soil to a maximum depth of 3 cm. For each sampling event, 10 chambers were sampled and at each chamber 4 samples were taken. Sampling began by placing a lid on top of the base 5 min after the chamber base was put in the soil. Samples were taken using a nylon syringe at 1, 10, 20, and 30 min after the lid was put in place. Air temperature at the height of the chamber and at 2 cm in the soil were measured a digital thermometer and the chamber height was measured at 3 internal points to calculate gas concentration.

Collected samples were transported to the gas chromatography laboratory at Embrapa Amazônia Oriental in Santarém and analyzed using a Shimadzu (GC 8A) gas chromatograph within 24 h. N_2O and CO_2 were determined using an electron capture detector (ECD), with injector,

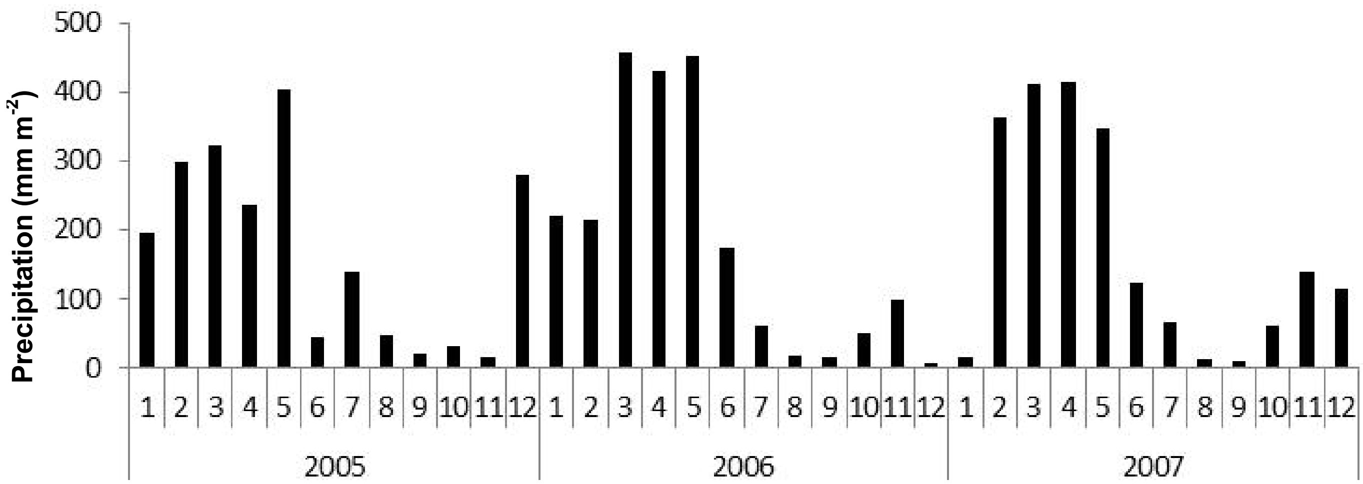

Figure 1. Total precipitation during entire study period.

detector, and column temperatures of 330, 330 and 80°C, respectively. Peaks of gas concentration were compared to primary standards (calibrated to National Institute of Standards and Technology) containing known concentrations of N_2O (308.1 and 753 ppb) and CO_2 (969 and 30000 ppm). Concentrations of CH_4 were determined using a flame ionization detector (FID), injector, detector, and column temperatures of 125, 125 and 40ºC, respectively. Peaks of CH_4 concentration were compared to primary standards (calibrated to National Institute of Standards and Technology) containing known concentrations of 1.75 and 0.884 ppm.

Gas fluxes emitted from the soil surface (F) were calculated from the linear correlation of gas concentration over the sampling time using Equation 1:

$$F = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \frac{m}{Vm} \tag{1}$$

Where: ΔC = change in gas concentration within the chamber; (Δt) = time that the chamber remained closed; *V* and A are, the volume and the area of the soil covered by the chamber, respectively, and m = molecular mass of each gas (N_2O, CH_4 and CO_2)

Soil sampling

Soil was sampled at 10 cm depth from inside the area covered by the chamber immediately after gas collection was finished. Samples were placed in labeled plastic bags and transported to the laboratory for weighing on a precision balance to obtain wet mass. Soils were dried at 105ºC for 48 h in an oven and then weighed again to obtain dry mass.

Water filled pore space (WFPS; Linn and Doran, 1984) was calculated using soil bulk density (dg), soil particle density (dp) and the concentration of water in the soil (u), according to Equations 2 to 4.

(2)

(3)

(4)

Where: θ = soil moisture (%); α = soil pore space (%); dg =soil bulk density (g cm^{-3}); dp = soil particle density (g cm^{-3}), and u= concentration of water in the soil (%).

Statistical analysis

Data analysis was done using the program Statistica 8.0 (Statsoft Inc.). Normality was tested, and when necessary data were log transformed (CO_2= log (CO_2); N_2O = log (N_2O + 60), CH_4= log (CH_4 + 650), in mg m^{-2} h^{-1} (CO_2), µg m^{-2} h^{-1} (N_2O and CH_4), respectively. Differences were tested using one-way analysis of variance (ANOVA) and the Tukey post-hoc test. A probability level of α = 0.05 was used for all tests. Linear regression was used to investigate possible relationships between soil moisture content and gas flux.

RESULTS

Precipitation and soil moisture

Rainfall is highly seasonal in the research area and the monthly totals during the study period (January 2005 to December 2007) are shown in Figure 1. Most agricultural activities took place in the rainy season with 70% of annual precipitation occurring during this season.

In the rice fields, WFPS displayed an increasing trend throughout the study, with the second period often being the wettest. During the 2005 rice crop cycle, WFPS values averaged 39% and the highest value (43%) during the second period. Year 2006 was a wetter, with annual soil moisture above 58%, and with the highest value (69%) again during the second sampling period. Year 2007 was the wettest of the three years, with annual WFPS values above 55% and period 3 being the wettest this year (61%; Table 2).

In the soybean fields WFPS decreased over time with no period being consistently wetter. In 2005, WFPS was 61, 64 and 63% for periods 1-3, respectively, while in 2006, it was 47, 33 and 28% for periods 1-3, respectively.

Table 2. Average flux of N_2O, CO_2 and CH_4 and the standard error of the mean (±SEM) for the years 2005-2007 in mechanized soybean and rice fields. The periods (1, 2, and 3) represent cultivation phases.

Year	Treatment	N_2O ± SEM (µg-N m^{-2} h^{-1})	CO_2 ± SEM (mg-C m^{-2} h^{-1})	CH_4 ± SEM (µg-C m^{-2} h^{-1})	WFPS (%)
Soybean					
	Period 1	1.9 ± 0.5	500± 57	-0.2 ± 0.3	60.6±0.9
2005	Period 2	1.6 ± 0.4	131 ± 15	-0.8 ± 0.4	64.0±1.0
	Period 3	2.6 ± 2.8	120 ± 34	-0.2 ± 0.7	62.8±1.3
	Period 1	7.4 ± 2.3	178 ± 22	-0.1 ± 0.4	47.1±1.9
2006	Period 2	7.9 ± 1.0	155 ± 24	-1.3 ± 0.7	32.8±1.8
	Period 3	6.2 ± 1.6	143 ± 24	-0.5 ± 0.1	28.3±5.6
	Period 1	3.6 ± 0.9	104 ± 13	0.5 ± 2.9	22.6±2.0
2007	Period 2	2.6 ± 0.7	407 ± 36	0.1 ± 2.5	31.1±1.3
	Period 3	21.5 ± 3.3	122 ± 18	0.6 ± 5.6	34.2±3.7
Rice					
	Period 1	77.8±18.8	350 ± 32	-1,0 ± 0.4	35.0±2.1
2005	Period 2	5.3 ± 2.0	607 ± 54	-0.8 ± 0.9	43.0±2.7
	Period 3	1.8 ± 0.8	205 ± 17	6.6 ± 4.7	41.8±5.3
	Period 1	8.2 ± 1.6	135 ± 12	-1.2 ± 1.4	46.4±2.1
2006	Period 2	6.7 ± 1.4	245 ± 44	0.4 ± 0.3	69.3±2.1
	Period 3	5.8 ± 2.1	181 ± 41	-1.9 ± 2.9	60.2±1.3
	Period 1	3.3 ± 1.1	180 ± 22	-8.6 ± 12.3	51.2±1.4
2007	Period 2	3.4 ± 0.8	350 ± 45.3	0.1 ± 2.6	55.2±2.0
	Period 3	2.9 ± 0.6	427 ± 48.8	0.04 ± 2.0	61.6±1.1

In 2007, the WFPS values were lowest, with periods 1-3 showing 22.6, 31.1 and 34.2%, respectively (Table 2).

In the rice fields, N_2O had an average cycle flux of 28.3 µg m^{-2} in 2005, with a steep decrease from period 1 (seedling planting to 7 days afterward) to the other periods (Table 2). In 2006, the cycle average decreased to 6.9 µg m^{-2}, followed by a slight decrease through the end of the cultivation cycle. In 2007, the average of the three periods was even lower (3.2 µg m^{-2}) remaining stable during the three periods.

In the soybean plantation, in 2005, N_2O had little variation during periods 1-3 (Table 2). In 2006, N_2O fluxes were 4 times greater. While in 2007, N_2O fluxes decreased in the first two periods followed by a large increase in period 3.

In the rice plantation, CH_4 had the largest variation of the trace gas fluxes during the 3 years of the study with a 3-year average of -0.006 µg m^{-2}, and the values increased from period 1 to 3 with period 3 (harvest) showing the largest value (6.6 µg m^{-2}). In 2006, the fluxes for periods 1-3 were -1.1, 0.4 and -1.9 µg m^{-2}, respectively. In period 1 of 2007 the values for CH_4 flux was highly negative (-8.62 µg m^{-2}), with periods 2 and 3 having a flux of 0.1 and 0.04 µg m^{-2}, respectively.

In the soybean plantation CH_4 flux displayed similar trends. Period 1 for years 2005 and 2006 had a flux of -0.17 and -0.09 µg m^{-2}, respectively; decreasing in period 2 to -0.85 and -1.33 µg m^{-2}, for years 2005 and 2006, respectively. During period 3, the flux was -0.21 µg m^{-2} (2005) and -0.49 µg m^{-2} (2006). In 2007, the fluxes were 0.47, 0.11 and 0.63 µg m^{-2} for periods 1-3, respectively.

During the cultivation cycle of rice in 2005, CO_2 had an average annual flux of 387.1 mg m^{-2}, with periods 1-3 having fluxes of 349.8, 607.0 and 205.4 mg m^{-2}, respectively. Flux values for 2007 were lower with an annual average of 318.6 mg m^{-2}, while period 1 had a flux of 179.7 mg m^{-2} and period 2 had 349.5 mg m^{-2}. In the soybean plantation CO_2 in 2005 had an annual average flux of 500.36 mg m^{-2}, diminishing to 130.87 and 119.52 mg m^{-2} for periods 2 and 3, respectively. The same pattern between periods was evident in 2006, with a flux of 177.6, 155.3 and 142.7 mg m^{-2}, for periods 1-3, respectively. In 2007, period 2 had a very high flux of 406.7 mg m^{-2}, while period 1 had 103.7 and period 3 had 122.3 mg m^{-2}.

In the rice crop, there were no statistical differences between periods of cultivation, but significant differences were found between years of cultivation (F=25, 8; $p < 0.01$) for CO_2 flux (Table 3). N_2O on the contrary, showed significant differences between years and also between periods; with period 1 different than 2 and 3, and 2 equal to 3. There were no differences found for CH_4 flux

Table 3. Average trace gas (N_2O, CO_2 and CH_4) flux values and the respective WFPS values (%) with standard error of the mean (±SEM) for years 2005 to 2007 in an area of mechanized cultivation of soybean and rice.

Crop	Period (years)	CO_2 (mg-C m^{-2} d^{-1})	N_2O (µg.m^{-2})	CH_4 (µg.m^{-2})	WFPS (%)
	2005	443.9±30.6^{a}	38.0±9.2^{a}	-0.006±0.7^{a}	39.2±1.6^{a}
Rice	2006	197.5±23.2^{b}	7.0±0.9^{b}	-0.6±0.8^{a}	60.3±1.4^{b}
	2007	310.8±24.4^{c}	3.2±0.5^{b}	-3.0±4.3^{a}	55.5±1.0^{b}
	2005	305.1±32.2^{a}	1.8±0.4^{a}	-0.5±0.2^{a}	62.3±0.6^{a}
Soybean	2006	166.8±15.0^{b}	7.5±1.3^{a}	-0.6±0.3^{a}	40.4±1.4^{b}
	2007	254.1±22.5^{ab}	6.6±11.5^{a}	0.3±0.3^{a}	29.0±1.2^{c}

*Different letters in the same columns and crop represent statistically significant differences ($p < 0.05$).

between years or periods. There were significant differences for WFPS between years and periods (F=56, 4; $p < 0.01$); with period 1 different than 2 and 3, and 2 equal to 3 (Table 3).

In the soybean crop, CO_2 showed significant differences for years (F=10, 4; $p < 0.01$) and between periods (F=3.7; $p < 0.05$), with period 1 equal to 2 and different than 3, and 2 equal to 3. N_2O had significant differences between years (F=12, 4; $p < 0.01$) and between periods (F=14.4; $p < 0.01$), with period 1 equal to 2 and different than 3, and 2 equal to 3. Trends for CH_4 and WFPS followed those for the rice crop.

DISCUSSION

The high frequency of sample collection during the period of crop management was important to be able to evaluate the effects of rice and soybean crop systems on the emission of N_2O. Furthermore, the soil preparation management in the soybean crop, together with high temperatures and rainfall, represent a unique situation to measure N_2O emission in the soil-atmosphere continuum.

With respect to N_2O flux, there was a significant difference in the soybean plantation in relation to period (F=10.4; $p < 0.01$) and also for year (F=21.8; $p < 0.01$), which could be explained by the greater availability of N in period 1 compared to the other periods. This greater availability of N is probably associated with good conditions for nitrifying and denitrifying bacterial activity (Firestone and Davidson, 1989). This is related to soil tilling under conventional management prior to seedling emergence that stimulates organic matter cycling, O_2, temperature, and moisture conditions (Dobbie and Smith, 2001) that favor N availability, which is reflected in greater N_2O emission (Table 3). These results are similar to those for young pastures in the Amazon rich in available N (Davidson et al., 2001). Greater availability of N and conditions of WFPS > 60% (Table 2) favor denitrifying bacterial activity in this system which should result in greater emission of N_2O (Oenema et al., 1997, Davidson et al., 2001). This is one of the causes of the positive and significant relationship between N_2O and WFPS in the soybean crop. Anaerobic conditions associated with high concentrations of N, principally in the form of nitrate (N-NO_3^-) represent ideal conditions for high denitrifying bacterial activity (Smith et al., 2003), which could also explain the elevated flux found in period 1 in soybean in all the years studied.

The data for emission of N_2O in this study are lower than those related in studies done in primary and secondary forests in the Amazon. Palm et al. (2002) reported an annual N_2O flux of 9.1 µg m^{-2} in secondary forest in Peru. Keller et al. (2005) found average annual N_2O fluxes of about 75 µg m^{-2} on a clay soil and 16 µg m^{-2} on a sandy soil in primary forest in the Brazilian Amazon.

Various studies have reported elevated N_2O emissions in soybean crops during 20 days before and after harvest (Yang and Cai, 2005; Ciampitti et al., 2005, 2007). These high levels of emissions are apparently related to greater concentrations of labile C as a product of node senescence, which is used as a primary substrate by the microbial population, favor the growth of all microbes but in particularly the nitrifying and denitrifying bacteria (Ciampitti et al., 2005). Escobar et al. (2010) found that N_2O emissions after soybean harvest were three times greater in no-till compared to a conventional management system. In the Peruvian Amazon, Palm et al. (2002) found that N_2O fluxes in high and low input annual agricultural systems were 2 to 3 times higher than those in secondary forest and 3 to 10 times higher compared to perennial tree-based systems. Greater N_2O emission could be related to a greater proportion of soil pores being filled with water in this clayey soil, a product of the property of having many small pores and high levels of moisture (Skiba and Ball, 2002), which would reduce O_2 diffusion, thus, through microbial competition for O_2, creating anaerobic sites (Baggs et al., 2006), favoring N_2O emission through denitrification. Therefore, we can conclude that, in 2005 and 2006, the maximum emission of N_2O in these conventional agricultural management systems occurred in period 1, decreasing in period 2, and then increasing in period 3 (Table 2).

High levels of WFPS lead to an increase in anaerobic microsites causing an exponential increase in N_2O emissions (Smith et al., 2003). In the present study, N_2O emissions from the soil under conventional agriculture increased with increasing WFPS, which is in agreement with other studies that reported a greater denitrification rate in soils with higher water content (Bateman and Baggs, 2005; Liu et al., 2006). Interestingly, in the Amazon, Wick et al. (2005), found no relationship between soil N_2O emissions and WFPS in pastures. In the current study, when WFPS exceeded 50% in this system, N_2O emissions dramatically increased. This is consistent with the results of Keller et al. (2005) in primary forest in the Brazilian Amazon. Palm et al. (2002) found large increases in N_2O flux with a doubling or tripling of WFPS in soybean, rice, and corn cropping systems in the Peruvian Amazon. In this case denitrification would be the dominant process (Moreira and Siqueira, 2006; Aita et al., 2007). The transition point between the processes that operate aerobically (nitrification) and anaerobically (denitrification) is frequently cited as 60% WFPS (Sehy et al., 2003; Webb et al., 2010). During the 2005 and 2007 crop cycles, after period 2 the soy crop had an increase in N_2O emission, probably due to the increase in available N in the soil caused by the fall of senescent leaves and the senescence of roots and rhizome nodules, as shown by Yang and Cai (2005) in soybeans.

During the 3 years of soy cultivation, soil respiration, which is determined by root and microbial activity (Cattani et al., 2002), could have been influenced by soil preparation and addition of N fertilizer which may have provoked the high CO_2 flux in period 1 compared to the 3 years of flux (Table 2). However, other factors such as WFPS and soil temperature have been discussed as being possible controllers of CO_2 flux from the soil to the atmosphere (Carvalho, 2005; Kuzyakov, 2006).

After seedling planting, the high availability of N could stimulate microbial activity leading to an increase in soil respiration. Furthermore, it is likely that soil preparation through tillage increased soil aeration and increasing the availability of labile organic matter that was previously protected by aggregates (Follett, 2001). High mineral N availability could have been responsible for the high CO_2 flux in period 1 during N fertilization activities, as compared to CO_2 flux for all years (Table 1). It is probable that fertilization had stimulated the absorption of N in the initial phase of soybean cultivation, and as a consequence, increased root and microbial respiratory activity. Carvalho (2005) demonstrated that N availability explained 66% of the flux of CO_2 in savannah soils cultivated with corn under different management systems.

In period 2, compared to all 3 years, there were high fluxes of CO_2, just as in period 1. This pattern could be due to the growth cycle of soybean, being accelerated just after N fertilizer application, thus stimulating the autotrophic component of the soil and increasing soil CO_2 flux (Table 2). The same pattern in flux is comparable to that obtained in an Oxisol in São Paulo State by La Scala et al. (2006). Additionally, the highest flux determined after soil preparation (Table 2) could be explained by the liberation of CO_2 previously produced through microbial action decomposing residual organic matter exposed by the physical fracturing of the soil or by root respiration (D'Andréa et al., 2006).

In 2007, CO_2 flux in period 1 was inferior compared to period 2, and although N fertilizer was applied in period 1; this difference could be in response to the limited addition of N associated with a smaller C: N of soluble material and also to the capacity of microbes to adapt to conditions of low availability of N (Marques et al., 2000). The high CO_2 flux values in period 2, when compared to the other periods could possibly be due to soil preparation during seedling planting. Various studies have attributed the increase in CO_2 flux during the initial phase of cultivation to the destruction of soil structure and the exposition of organic matter to microbial action (Reicosky and Lindstrom, 1993).

The two biggest peaks of CH_4 flux during the rice crop cycle could be related to the availability of C for methanogenesis from residues from the previous crop, from production of organic matter by the growing crop itself, from soil organic matter, and from root exudates. Additionally, morphogenic changes in rice plants that occur in the final growth phase wherein plants reach the maximum number of tillers and panicles in the reproductive phase (Lindau et al., 1991), phases in which these peaks occurred. These results for methane production are similar to those found by Palm et al. (2002) in the Peruvian Amazon (range = 5.2 - 33 μg $m^{-2}.h^{-1}$) who attributed the positive flux of methane to high-input agricultural practices in a rice/soybean/corn system. Furthermore, these authors showed an inverse relationship with WFPS wherein the high-input agriculture system continued to produce methane even at just 45% WFPS. Interestingly, in the study by Palm et al. (2002) all the other treatments (low-input agriculture, shifting cultivation, agroforestry, peach palm plantations, and forest fallow) had CH_4 consumption.

The pulse in the CH_4 flux in the rice crop in period 3 of 2005 (6.58 μg m^{-2}) is a significant result when compared to annual values reported for forests in the Amazon (-30 μg m^{-2}) (Palm et al., 2002); (-12.5 μg m^{-2}) (Keller et al., 2005), and this result could be due to the production of organic compounds from the anaerobic decomposition of organic matter such as leaves and dried panicules. This could also be due to catabolism of labile organic compounds by methanogenic microbes (Neue et al., 1996), as well as to the increase in the exudation of organic compounds by roots, a process that increases as the plant develops. These exudates serve as substrate for methanogenic bacteria metabolism, thus increasing the production of CH_4 (Aulakh et al., 2001). According to these authors, there is a positive correlation between the

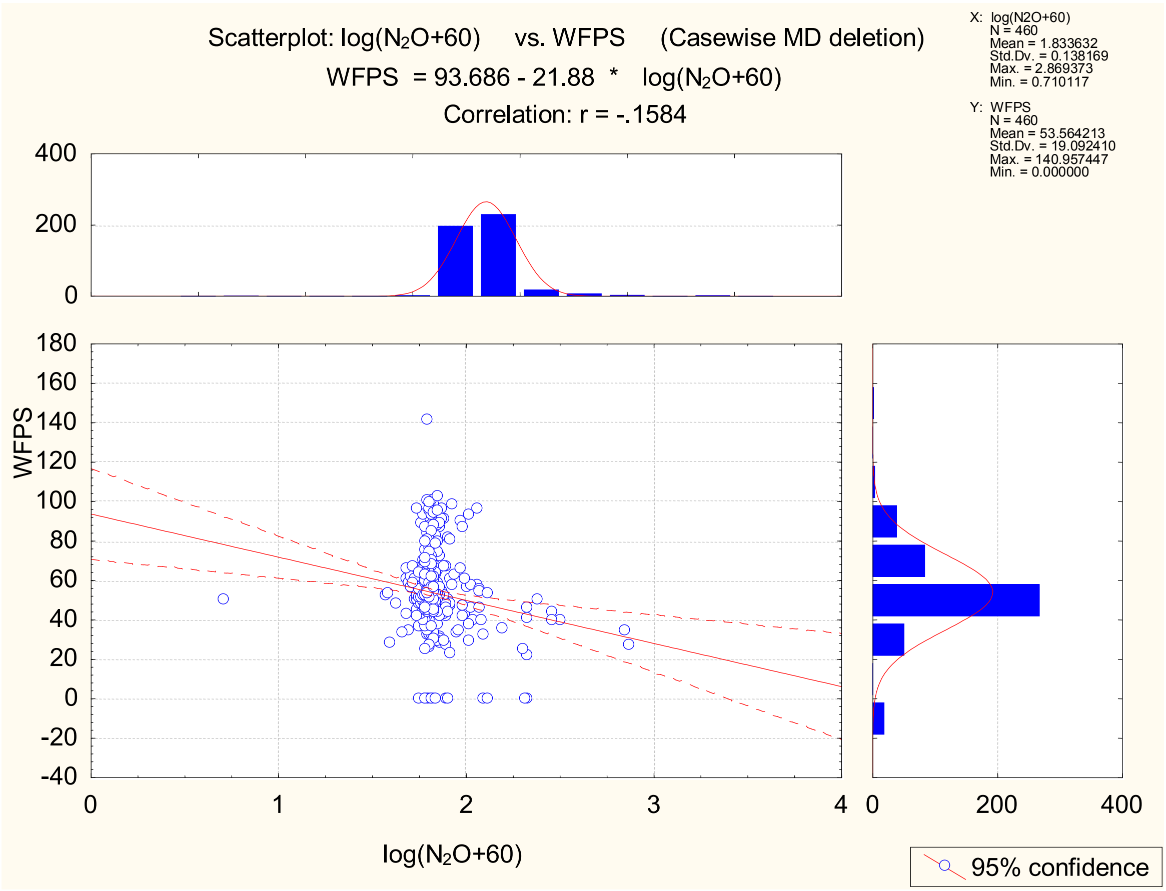

Figure 2. Correlation between WFPS x CO_2 (A), and WFPS x N_2O (B) in rice.

dry mass of roots and shoots in rice plants with the exudation of organic compounds by roots, so as the plant grows exudation increases, a process that is dependent on the photosynthetic rate of the plant, which in turn is dependent of available sunlight and the nutritional status of the plant (Taiz and Zeiger, 1991). However, in the initial phase of growth of rice cultivated in soil that has received residual plant matter, the largest contribution of C to methanogenesis is from the decomposition of these residuals and from the labile soil organic matter fractions, with less contribution from root exudates (Watanabe, 1999). In the present study, the conventional system of cultivation demonstrates the importance of the incorporation of crop residues and vegetation before the start of the next crop cycle, a practice that favors the accumulation of C, thus initially permitting greater fluxes of CH_4 and CO_2.

The increase of tillers and leaves, and consequently, the number of canals of escape of CH_4 from the soil through the plant, also could have contributed to the intensity of the first peak of CH_4 (0.44 µg m^{-2}) in period 2 of 2006 (Huang et al., 1997; Nouchi et al., 1990). This peak could also be related to the intense liberation of root exudates during the phases of panicule differentiation, booting stage, panicule emission, and finally, florescence in the reproductive phase of rice (Aulakh et al., 2001). Furthermore, senescent leaves begin to fall at this stage forming a litter layer on the soil surface, and tillers that do not produce a panicule, senescent roots and their exfoliates, dead rice plants, and root exudates have a significant role in providing C to methanogenic organisms (Watanabe, 1999). Anaerobic decomposition of these materials reduced the redox potential and is a source of C for methanogenesis in inundated soils thus increasing the production of CH_4 (Lauren and Duxbury, 1993; Cai et al., 1997; Chidthaisong and Watanabe, 1997).

With respect to the flux of N_2O, the low values registered in rice soils in period 3 of 2005, and compared with the 3 periods of 2007, could be related to a low availability of N and to aerobic conditions since WFPS was <60% (Table 1). In general, Oxisols are characterized as being N-limited and present low nitrification rates (Nardoto and Bustamante, 2003), and only rarely the production of N-NO_3^- exceeds the demand of microorganisms and roots.

Eichner (1990) found N_2O emission rates in agricultural soils cultivated with leguminous plants to be between 0.34 and 4.6 kg N_2O-N ha.year^1. In the present study,

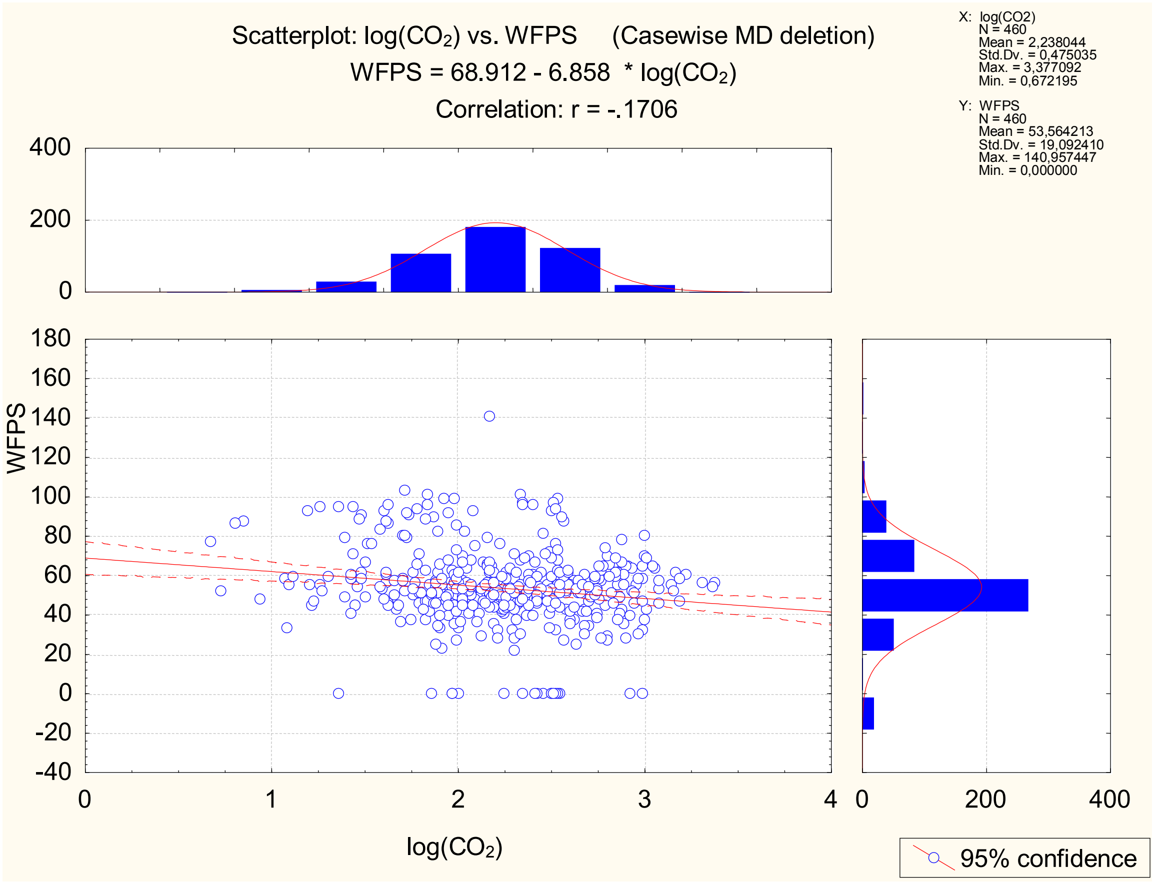

Figure 3. Correlation between WFPS x N_2O in soybean.

fluxes varied between 0.53 kg ha year[1] and 0.90 kg N_2O-N ha year[1]; values that are lower than 2.3 and 1.27 kg N_2O-N ha year[1] in high- and low-input annual soybean/rice/corn agricultural systems in the Peruvian Amazon (Palm et al., 2002).

In Table 2, the rice crop had larger fluxes than the soybean crop in all study years, corroborating previous studies (Motschenbacher et al., 2014) that described the role of greater organic matter production by rice as compared to soybean and its relation to the gases analyzed in the present study. Furthermore, in the rice crop there was a significant correlation between the flux of CO_2 and N_2O with WFPS ($p<0.05$), as reported by other authors (Keller et al., 2005; Weitz et al., 2001), which can also be visualized in Figure 2.

In the soybean crop, this correlation was significant only for WFPS × N_2O (Figure 3).

Conclusions

There was annual variation in the rice and soybean crops for carbon dioxide and nitrous oxide, but there was no variation for methane between crops. There was positive and significant correlation between N_2O nitrous oxide and WFPS in the soybean crop. During the period from initial seedling planting to day 7 (period 1), the rice crop emitted more nitrous oxide than in the period from day 8 up to harvest day or in the period from harvest day to 5 days after harvest the other two periods; in the soybean crop this happened more frequently in from harvest day to 5 days after harvest, (period 3). In general the gas fluxes (carbon dioxide, nitrous oxide, and methane) were greater in the rice than the soybean crop.

Conflict of Interest

The authors have not declared any conflict of interest.

REFERENCES

Aita C, Giacomini SJ, Hübner AP (2007). Nitrificação do nitrogênio amoniacal de dejetos líquidos de suínos em solo sob sistema de plantio direto. Pesq. Agropec. Bras. 42:95-102.

Aulakh MS, Wassmann R, Rennenberg H (2001). Methane emissions from rice fields – quantification, mechanisms, role of management and mitigations options. Adv. Agron. 70:193-260.

Baggs EM (2006). Partitioning the components of soil respiration: A

research challenge. Plant Soil 284:1-5.
Bateman EJ, Baggs EM (2005). Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. Biol. Fert. Soils 41:379-388.
Cai Z, Xing G, Yan X, Xu H, Tsuruta H, Yagi K, Minami K (1997). Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilizers and water management. Plant Soil 196:7-14.
Cardoso AN, Saminez TC, Vargas MA (2001). Fluxo de gases traço de efeito estufa na interface solo-atmosfera em solos do Cerrado. Planaltina, DF: Embrapa Cerrados. P. 23.
Carvalho AM (2005). Uso de plantas condicionadoras com incorporação e sem incorporação no solo: composição química e decomposição de resíduos vegetais; disponibilidade de fosforo e emissão de gases. Brasilia, Universidade de Brasilia. (Tese Doutorado) P. 167.
Cattani JH (2002). Unexpected results of a pilot throughfall exclusion experiment on soil emissions of CO_2, CH_4, N_2O, and NO in eastern Amazonia. Biol. Fert. Soils 36:102-108.
Cerri CC, Cerri CEP (2007). Agricultura e aquecimento global. Bol. Inf. Soc. Bras. Ci. Solo 32(1):40-44.
Chidthaisong A, Watanabe I (1997). Methane formation and emission from flooded rice soil incorporated with 13C-labeled rice straw. Soil Biol. Biochem. 29(8):1173-1181.
Ciampitti IA, Ciarlo EA, Conti ME (2005) Nitrous oxide emission during soybean culture: inoculation and nitrogen fertilization effects. Ci. Suelo 23:123-131.
Ciampitti IA, Ciarlo EA, Conti ME (2008). Nitrous oxide emission from soil during soybean [(*Glycine max* (L) Merrill] crop phonological stages and stubbles decomposition period. Biol. Fert. Soils 44(4):581-588. http://dx.doi.org/10.1007/s00374-007-0241-7.
Companhia Nacional de Abastecimento – CONAB (2012). Disponivel em www2.conab.gov.br/download/sureg/PA/SOJA.xls. Acessado em 31/10/2012
Crill PM, Keller MM, Weitz A, Grauel B, Veldkamp E (2000). Intensive field measurements of nitrous oxide emissions from a tropical agricultural soil. Glob. Biogeochem. Cycles 14:85-95.
Crutzen PJ, Andreae MO (1990). Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. Science 250:1669-1678.
D'Andréa AF, Silva MLN, Silva CA (2006). Emissões de CO_2 do solo: Métodos de avaliação e influência do uso da terra. In: Roscoe, R.; Mercante, F. M.; Salton, J. C., eds. Dinâmica da matéria orgânica do solo em sistemas conservacionistas: Modelagem matemática e métodos auxiliares. Dourados: Embrapa Agropecuária Oeste. Cap. 8:199-242.
Davidson EA, Matson PA, Brooks PD (1996). Nitrous oxide emission controls and inorganic nitrogen dynamics in fertilized tropical agricultural soils. Soil Sci. Soc. Am. J. 60:1145-1152.
Davidson EA, Bustamente MMC, Siqueira Pinto A (2001). Emissions of nitrous oxide from soils of native and exotic ecosystems of the Amazon and Cerrado regions of Brazil. Sci. World 1(S2):312-319.
Dobbie KE, Smith KA (2001). The effects of temperature, water-filled pore space and land use on N_2O emissions from an imperfectly drained gleysol. Eur. J. Soil Sci. 52(4):667-673.
Empresa Brasielira de Pesquisa Agropecuária-EMBRAPA (1999). Inventário de Emissões de Gases de Efeito Estufa provenientes de atividades agrícolas no Brasil: emissões de metano provenientes da pecuária (relatório revisado), Jaguariúna.
Eichner MJ (1990). Nitrous oxide emission from fertilized soils: summary of available data. J. Environ. Qual. 19:272-280.
Escobar LF, Amado TJC, Bayer C, Chavez LF, Zanatta AJ, Fiorin JE (2010). Postharvest nitrous oxide emissions from a subtropical Oxisol as influenced by summer crop residues and their management. Rev. Bras. Ciênc. Solo 34:435-442.
FBOMS (2004). Available at http://www.socioambiental.org/inst/docs/inst/docs/download/soja.pdf . Accessed 21 may 2013
Fearnside PM (2005). Deforestation in Brazilian Amazonia: History, Rates, and Consequences. Conserv. Biol. 19(4):680-688.
Firestone MK, Davidson EA (1989). Microbilogical basis of NO and N_2O production and consumption in soil. In: ANDREAE, M. O.; SCHIMEL, D.S., Eds.) Exchange of trace gases between terrestrial ecosystems and the atmosphere. John Wiley & Sons. pp. 7-21.
Follett RF (2001). Soil management concepts and carbon sequestration in crops and soils. Soil Till. Res. 61(1-2):77-92.
Goreau TJ, Mello WZ (1988). Tropical deforestation: Some effects on atmospheric chemistry. Ambio. 17:275-281.
Hansen J, Sato M, Ruedy R, Lacis A, Oinas V (2000). Global warming in the twenty-first century: an alternative scenario. Proc. Natl. Acad. Sci. USA, 97:9875-9880.
Hecht SB (1992). Logics of livestock and deforestation: The case of Amazonia, in Development or Destruction: The conversion of tropical forests in Latin America. Edited by T. E. Downing, S. B. Hecht, H. A. Pearson, and C. Garcia-Downing, pp. 7-25.
Houghton RA (1991). Tropical deforestation and atmospheric carbon dioxide. Clim. Chang. 19:99-118.
Houghton JT (2004). Global warming: the complete briefing. 3rd ed. Cambridge Press. P. 341.
Huang Y, Sass RL, Fisher Jr FM (1997). Methane emission from Texas rice paddy soils. 2. Seasonal contribution of rice biomass production to CH_4 emission. Glob. Chang. Biol. 3(6):491-500.
Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis-IBAMA. Floresta Nacional do Tapajós - Plano de Manejo. IBAMA, Belterra, Pará. 2004. P. 373.
INMET (Instituto Nacional de Meteorologia. Normas Climatológicas) (2010). Disponível em: <http://www..inmet.gov.br>. Acesso em: 20 fev. 2011.
IPCC (Intergovernmental Panel on Climate Change) (2007). Climate change 2001: The scientific basis. United Kingdom: Cambridge University, 2001. P. 881.
IPCC (2007). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
IPCC (Intergovernmental Panel on Climate Change) (2007). The physical Science basis: Contribution on working group I to the fourth assessment report of the intergovernmental Panel on Climate Change.
Johnson JMF, Franzluebbers AJ, Weyers SL, Reicosky DC (2007). Agricultural opportunities to mitigate greenhouse gas emissions. Environ. Poll. 150:107-124.
Keller M, Varner R, Dias JD, Silva H, Crill P, Oliveira Jr RC, Asner GP (2005). Soil-atmosphere exchange of nitrous oxide, nitric oxide, methane, and carbon dioxide in logged and undisturbed forest in the Tapajos National Forest, Brazil. Earth Interact. 9:1-28.
Kuzyakov Y (2006). Sources of CO_2 efflux from soil and review of partitioning methods. Soil Biol. Biochem. 38:425-448.
La Scala JRN, Bolonhezi D, Pereira GT (2006). Short-term soil CO_2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. Soil Till. Res. 91:244-248.
Lameira WJ, Alencar A (2002). Multitemporal analysis of soybean expansion in the Santarém region. Poster presented at the Second LBA Science Conference, Fortaleza, CE, Brazil.
Lauren JG, Duxbury JM (1993). Methane emissions from flooded rice amended with a green manure. In: Harper, LA; Mosier, AR; Duxbury, JM (Eds.). Agricultural ecosystem effects on trace gases and global climate change. Wisconsin: Am. Soc. Agron. (ASA Special Publication 55:183-192.
Lindau CW, Bollich PK (1991). Effects of urea fertilizer and environmental factors on CH4 emissions from Louisiana, USA rice field. Plant Soil 136(2):195-203.
Linn DM, Doran JW (1984). Effects of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and no tilled soil. Soil Sci. Soc. Am. J. 48:1267-1272.
Liu XJ, Mosier AR, Halvorson AD, Zhang FS (2006). The impact of nitrogen placement and tillage on NO, N_2O, CH_4 and CO_2 fluxes from a clay loam soil. Plant Soil 280:177-188.
Luizão F, Matson P, Livingston G, Luizão R, Vitousek P (1989). Nitrous oxide flux following tropical land clearing, Global Biogeochem. Cycles 3(3):281-285.
Márquez TCLLSM, Vasconcellos CA, Pereira Filho I, França GE, Cruz JC (2000). Evolvimento de dióxido de carbono e mineralização do nitrogênio em Latossolo Vermelho-escuro com diferentes manejos.

Pesq. Agrop. Bras. 30:581-589.
Matson PA, Billow C, Hall SJ, Zachariassen J (1996). Fertilization practices and soil variations control nitrogen oxide emissions from tropical sugar cane. J. Geophy. Res. 101(D13):18533-18545.
Melillo JM, Steudler PA, Feigl BJ, Neill C, Garcia D, Piccolo MC, Cerri CC, Tian H (2001). Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon, J. Geophys. Res. 106(D24):34179-34188.
Metay A, Oliver R, Scopel E, Douzet JM, Moreira JAA, Maraux F, Feigl BJ, Feller C (2007). N_2O and CH_4 emissions from soils under conventional and no-till management practices in Goiânia (Cerrados, Brazil). Geoderma 141:78-88.
Meyers N (1991). Tropical forests: Present Status and future outlook. Clim. Chang. 19:3-32.
Moraes JL, Cerri CC, Melillo JM, Kicklighter D, Neill C, Skole DL, Stueudler PA (1995). Soil carbon stocks of de Brazilian Amazon basin. Soil Sci. Soc. Am. J. 59(1):244-247.
Moreira FMS, Siqueira JO (2006). Microbiologia e Bioquímica do solo. 2. Ed. Lavras: Editora UFLA. P. 729.
Motschenbacher JM, Brye KR, Anders MM, Gbur EE, Slaton NA, White MAE (2014). Long-Term Crop Rotation, Tillage, and Fertility Effects on Soil Carbon and Nitrogen in Dry-Seeded, Delayed-Flood Rice Production Systems. P. 28.
Mosier AR (2001). Exchange of gaseous nitrogen compounds between agricultural systems and the atmosphere. Plant Soil. 228:17-27.
Nardoto GB, Bustamante MMC (2003). Effects of fire on soil nitrogen dynamics and microbial biomass in savannas of Central Brazil. Pesq. Agrop. Bras. 38(8):955-962.
Neue HU, Wassmann R, Lantin RS, Alberto MaCR, Aduna JB, Javellana AM (1996). Factors affecting methane emission from rice fields. Atmos. Environ. 30(10-11):1751-1754.
Nouchi I, Mariko S, Aoki K (1990). Mechanisms of methane transport from the rhizosphere to the atmosphere through rice plants. Plant Physiol. 94(1):59-66.
Oenema O, Velthof GL, Yamulki S, Jarvis SC (1997). Nitrous oxide emissions from grazed grassland. Soil Use Manag. 13:288-295.
Ostermayer F (2004). Estudo das emissões de gases formadores do efeito estufa e balanço resultante da conversão de motores á gasolina de uma frota de veículos leves para gás natural e álcool hidratado. Porto Alegre. Programa de Pós graduação em Engenharia, Universidade Federal do Rio Grande do Sul. P. 164. (Tese Mestrado)
Palm CA, Alegre JC, Arevalo L, Mutuo PK, Mosier AR, Coe R (2002). Nitrous oxide and methane fluxes in six different land use systems in the Peruvian Amazon. Glob. Biogeochem. Cycles 16(4):1073.
Reicosky DC, Lindstrom NJ (1993). Fall tillage method: effect on short-term carbon dioxide flux from soil. Agron. J. 85:1237-1245.
Rodrigues TE, Santos PL, Oliveira Jr Rc, Valente MA, Silva J, Cardoso Jr EQ (2001). Caracterização dos Solos da Área do Planalto de Belterra, Município de Santarém, Estado do Pará. Documentos. Embrapa Amazônia Oriental, Belém, Pará, 115:01-55.
Sehy U, Ruser R, Munch JC (2003). Nitrous oxide fluxes from maize fields: relationship to yield, site-specific fertilization, and soil conditions. Agric. Ecosyst. Environ. 99:97-111.
Skiba U, Ball B (2002). The effect of soil texture and soil drainage on emissions of nitric oxide and nitrous oxide. Soil Use Manage. 18:56-60.
Smith KA, Ball T, Conen F, Dobbie KE, Massheder J, Rey R (2003). Exchange of greenhouse gases between soil and atmosphere: interaction between soil physical factors and biological process. Eur. J. Soil Sci. 54:791.
Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, Mccarl B, Ogle S, O'mara F, Rice C, Scholes B, Sirotenko O (2007). Agriculture. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Steudler PA, Garcia-Montiel DC, Piccolo MC, Neill C, Melillo JM, Feigl BJ, Cerri CC (2002). Trace gas responses of tropical forest and pasture soils to N and P fertilization. Glob. Biogeochem. Cycles 16(7):1-12.
Syakila A, Kroeze C (2011). The global nitrous oxide budget revisited. Greenhouse Gas Meas. Manage 1(1):17-26.
Taiz L, Zeiger E (1991). Photosynthesis: physiological and ecological considerations. In: Taiz, L. & Zeiger, E., eds. Plant physiology. New York: The Benjamim/Cummings. P. 31.
Veldkamp E, Keller MM, Nunez M (1998). Effects of pasture management on N2O and NO emissions from soils in the humid tropics of Costa Rica. Glob. Biogeochem. Cycles 12:71-79.
Venturieri A, Coelho AS, Thales MC, Bacelar MDR (2007). Análise da expansão da agricultura de grãos na região de Santarém e Belterra, oeste do estado do Pará. Anais do XIII Simpósio Brasileiro de Sensoriamento Remoto, Florianopolis, Brasil. P. 8.
Watanabe A (1999). Evaluations of origins of CH_4 carbon emitted from rice paddies. J. Geophys. Res. 104(D19):23623-23629.
Webb J, Pain B, Bittman S, Morgan J (2010). The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response - A review. Agric. Ecosyst. Environ. 137:39-46.
Weitz AM, Linder E, Frolking S, Crill PM, Keller M (2001). N_2O emissions from humid tropical agricultural soils: effects of soil moisture, texture and nitrogen availability. Soil Biol. Biochem. 33:1077-1093.
Wick B, Veldkamp E, Mello WZ, Keller M, Crill P (2005). Nitrous oxide fluxes and nitrogen cycling along a pasture chronosequence in Central Amazonia, Brazil. Biogeosci. Discuss. 2:499-535.
Williams M (1990). Forests, in the Earth as Transformed by Human Action, edited by R. W. Clark, J. F. Richards, J. T. Mathews, and W. R. Meyer, Cambridge University Press, Cambridge, New York. pp. 179-201.
Yan X, Hosen Y, Yagi K (2001). Nitrous and nitric oxide emissions from maize field plots as affected by N fertilizer type and application method. Biol. Fertil. Soils 34:297-303.
Yang L, Cai Z (2005). The effect of growing soybean (*Glycine max* L.) on N_2O emission from soil. Soil Biol. Biochem. 37:1205-1209.