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CH_4 and N_2O Emissions in a Rice Field: First Measurements in the Uruguayan Productive System

Emisiones de CH_4 y N_2O en un arrozal: primeras medidas en el sistema productivo uruguayo

Irisarri, P.[1]; Pereyra, V.[2]; Fernández, A.[2]; Terra, J.[3]; Tarlera, S.[2]

[1]*Universidad de la República, Facultad de Agronomía, Departamento de Biología Vegetal, Montevideo, Uruguay*
[2]*Universidad de la República, Facultad de Química, Laboratorio de Ecología Microbiana y Ambiental, Montevideo, Uruguay*
[3]*Instituto Nacional de Investigación Agropecuaria (INIA), Treinta y Tres, Uruguay*

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Correspondence

Silvana Tarlera,
starlera@fq.edu.uy

Abstract

Irrigated rice fields are major sources of two important greenhouse gases (GHG), methane and nitrous oxide. As an initial step towards obtaining local information, emissions of CH_4 and N_2O from rice paddy soil were measured by the static chamber technique in greenhouse and field experiments conducted in eastern Uruguay. In the greenhouse experiment, the effect of two flooding moments (21 and 45 days after emergence) and nitrogen fertilization (0 and 50 kg N ha^{-1}) on gas emissions was studied. Early flooding and nitrogen fertilization tended to increase N_2O emissions. In the field experiment, effect of winter soil cover crop and nitrogen fertilization (0 and 82 kg N ha^{-1}) were tested. Higher CH_4 fluxes were observed mainly during the reproductive stage of the plant in the N-fertilized treatment with ryegrass winter crop. N_2O flux peaked at flushing. Results indicate that the use of cover crops might increase GHG emissions during the rice cycle. Despite differences in agronomic management practices employed in Uruguay, CH_4 and N_2O fluxes are within magnitudes previously reported for rice fields worldwide.

Keywords: rice paddy soil, greenhouse gases, N fertilization

Resumen

Los arrozales son fuente de dos importantes gases de efecto invernadero (GEI), metano y óxido nitroso. Como un paso inicial hacia la obtención de información local, se midieron las emisiones de CH_4 y N_2O del suelo y de las plantas de arroz mediante la técnica de la cámara estática en experimentos en invernáculo y a campo en el este de Uruguay. En el experimento en invernáculo, se estudió el efecto del momento de inundación (21 y 45 días después de la emergencia) y de la fertilización nitrogenada (0 y 50 kg N ha^{-1}) sobre las emisiones. La inundación temprana y la fertilización nitrogenada tendieron a aumentar las emisiones de N_2O. En el experimento a campo, se estudió el efecto de la cobertura invernal y de la fertilización nitrogenada (0 y 82 kg N ha^{-1}). Se detectaron mayores flujos de CH_4 durante la etapa reproductiva de la planta en el tratamiento fertilizado con cobertura invernal previa de raigrás. El flujo de N_2O fue máximo después de los baños. Los resultados indican que el uso del cultivo de cobertura podría incrementar las emisiones de GEI durante el ciclo del arroz. A pesar de las distintas prácticas de manejo del cultivo empleadas en Uruguay, los flujos de CH_4 y N_2O se encuentran dentro de los valores informados previamente para arrozales de otras partes del mundo.

Palabras clave: suelo inundado cultivado con arroz, gases de efecto invernadero, fertilización N

Introduction

Agricultural soils are important global sources of methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2007). In Uruguay, the CO_2 captured by forests almost doubles their emission, which is why CH_4 and N_2O are the main greenhouse gases (GHGs). It is estimated that agriculture is responsible for 92.6% of the emissions of CH_4 and almost all of those of N_2O (MVOTMA and others, 2010). Greenhouse gases (GHGs) have different heating capacities, based on their impact on radiant energy and their duration in the atmosphere compared to the reference gas, carbon dioxide (CO_2). CH4 and N_2O have a 25-fold and 298-fold higher heating potential than CO_2 respectively, for a 100-year time scale (IPCC, 2007).

Rice is the main irrigated crop in Uruguay, 55% of the cultivated area is in the east of the country and approximately 90% of production is exported (ACA, 2011). The national inventory of emitted GHGs estimates that rice cultivation is responsible for 4% of the CH_4 emitted in Uruguay (MVOTMA and others, 2010). One of the environmental challenges of systems that include flood rice cultivation is to reduce the emission of GHGs produced mainly by microbial activities. Emissions are strongly influenced by nitrogen fertilization, the management of soil and crop residues during fallowing and the management of irrigation water. Rice cultivation is considered the main global anthropogenic source of CH_4 (Jacobson, 2005). Emissions of CH_4 depend on rice cultivars (Kerdchoechuen, 2005), but are also increased by the incorporation of organic matter into the soil (Yagi and Minami, 1990; Bronson and others, 1997), and their mitigation is based on reducing the time the crop remains flooded (Yagi and others, 1996; Cai and others, 1997).

N_2O occurs mostly at the interface between dry and flooded soil (Cai and others, 2001; Xing and others, 2002). Its emission depends on soil drainage (Towprayoon and others, 2005) and is stimulated by nitrogen fertilization (Bronson and others, 1997; Crutzen and Lelieveld, 2001). The emission of CH_4 results from the balance between the activities of methanogenic archaea, strictly anaerobic, and methanotrophic, aerobic bacteria (Macalady and others, 2002). On the other hand, N_2O is the product of incomplete microbial transformations of nitrogen compounds incorporated into the soil as a fertilizer, in oxic (nitrification) or anoxic conditions (mainly denitrification and denitrifying nitrification) (Smith and others, 2003; Baggs and Philippot, 2011).

Rice cultivation in Uruguay is unique in the world as it shares the use of soils with pasture for livestock and other crops in rotation (ACA, 2011). Rice integrated into these systems produces high yields with the application of low doses of agrochemicals and preserves soil quality (Deambrosi, 2003; Méndez and others, 2003). Global trade presents increasing demands on the environmental impacts of production processes and their documentation, including the requirement of water use, environmental destination of agrochemicals, and GHG emissions among others (Itoh and others, 2011). This study aimed to obtain the first local emission data of CH_4 and N_2O in our country's particular rice production system. In addition, a first approximation was made of the impact of some management practices, nitrogen fertilization, water management, and winter covers, on the fluxes of these GHGs.

Material and methods

Greenhouse experiment

The greenhouse experiment was carried out at the National Institute of Agricultural Research (INIA) of the department of Treinta y Tres. Rice (*Oryza sativa* L., cultivar "El Paso 144") was planted in plastic crates with soil taken from the upper 0.30 m in the Experimental Unit "Paso de la Laguna" of INIA Treinta y Tres, with the following characteristics: silty loam texture, pH (H_2O) 5.2; N-NH_4^+ 0.3 mmol L^{-1}; organic C 30-35 g kg^{-1} and organic matter 50-55 g kg^{-1}. The apparent density of the soil was 1.36 g cm^{-3}. This experiment was carried out to assess the effects of the moment of flooding and nitrogen fertilization on emissions. A random plot design was used, with four replications and two chambers in each crate.

Each crate was filled with 52 kg of soil and basal fertilization of 120 kg ha^{-1} of ammonium phosphate (18-46-0) was applied. Rice was seeded at a density of 180 kg ha^{-1} and seedlings were irrigated weekly to field capacity. Nitrogen treatment consisted of the application of urea 50 kg ha^{-1} to the seedlings and at 21 days after the emergence (DAE). Rice plants emerged nine days after sowing. The water management treatment consisted of two dates of flood establishment, 21 DAE (early flood) and 45 DAE (late flood). The water level during the flood was kept at 5-6 cm above the ground until harvest, which was performed at 134 DAE.

Field experiment

The experiment was carried out at INIA's Paso de la Laguna Experimental Unit (33º16´S, 54º16´W) during the 2008-09 rice harvest to learn about the effect of the inclusion of winter cover crops on CH_4 and N_2O emissions during rice cultivation. The soil was Albic Natraqualf (USDA, 1998) with three previous years of rest without rice. The physicochemical characteristics of the soil are shown in Table 1.

Table 1. Soil properties in the field experiment.

pH (H_2O)	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	P Bray ($\mu g g^{-1}$)	Available K (meq $100g^{-1}$)
5.4±0.17	19.0±1.7	1.7±0.1	7.8±0.9	14.6±4.8

The treatments were the factorial arrangement of two soil managements during the winter, ryegrass (*Lolium multiflorum* Lam.) as cover or bare soil, and two doses of nitrogen fertilization, 0 and 82 kg N ha^{-1}. The design was of random plots of 10 m x 9.2 m with four replications and two chambers in each plot. The ryegrass was sown on March 30 at a density of 20 kg of seeds ha^{-1}, 10 days after an application of 1.5 kg ia ha^{-1} of glyphosate (Terra and others, 2009). The bare soil treatment (without vegetation) received a second dose of glyphosate on June 20, apart from that of March 20. In both treatments, the chemical fallow began on September 19 with an application of 2.5 kg ha^{-1} of glyphosate. The total dry matter harvested from ryegrass was 4940 kg ha^{-1} with a C/N ratio of 47/1 (Terra and others, 2009).

The soil tillage was carried out the previous summer (January 2008) and consisted of a heavy eccentric run, two runs of disc track, and two runs of *landplane.*

The cultivation of rice (cv. INIA Olimar) was installed on October 13 with no-till at a density of 150 kg of seed ha^{-1}. The flooding was performed 22 DAE and a 10 cm sheet of water was maintained until five days before harvest. Two pre-flood flushings of the crop were performed at 1 and 4 DAE.

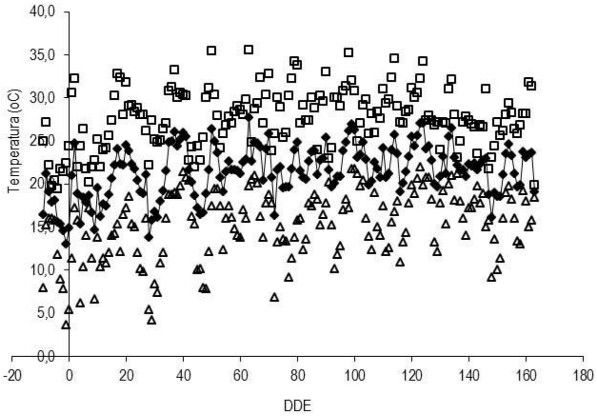
The fractional nitrogen fertilization consisted of the application, at sowing, of ammonium phosphate (22 kg N ha^{-1}, 23 DAE), urea to the tillering (21 DAE) 30 kg N ha^{-1} on dry soil, and to the primordium (51 DAE) 30 kg N ha^{-1}. Treatments without N did not receive any application of nitrogen fertilizer.

Yield parameters such as 13% adjusted grain weight, number of stems m^{-2}, grains per panicle, dry matter in flowering stages, and primordium, were evaluated according to Terra and others (2009). The estimation of the chlorophyll content of the rice leaves was measured in the most developed upper leaf with a SPAD 502 Plus Chlorophyll meter (Terra and others, 2009).

The weather information was recorded at the station located at "Paso de la Laguna".

The average temperature was 21.5 °C during the crop cycle (Figure 1) and the precipitation 576 mm, of which only 36 mm were recorded before flooding. The thermal amplitude had an average value of 12 °C throughout the rice cycle.

Figure 1. Daily temperature during the rice production cycle. Black rhombuses indicate the average temperature, squares the maximum and triangles the minimum. DAE: days after emergence.



Sampling and flux measurements of CH_4 and N_2O

The gas fluxes emitted were monitored using the static closed chamber technique described for rice by Lindau and others (1991) on the dates indicated for each experiment in Figures 3 and 4 and between 13 and 15 h. The chambers consisted of stainless steel bases of 40 cm in diameter and 20 cm in height partially inserted (5 cm) in the soil that remained installed throughout the cultivation cycle. On each sampling date, 60 cm high acrylic cylinders were placed on the bases with a water seal to prevent the escape of gases. The chambers had a battery-operated fan that was switched on five minutes before each measurement to ensure the homogeneity of the atmosphere inside the chamber and a device to balance the internal and external pressure (Figure 2). Gas samples from inside the chambers were taken with 25 mL plastic syringes at 0, 30, and 60 minutes and stored in vacuum tubes (10mL) until analysis. The temperature of the chambers, the depth of flood water, and the height of air space in each chamber were recorded to calculate the gas fluxes over time. Concentrations of CH_4 were analyzed with a Chrompack CP 9001 gas chromatograph equipped with an FID detector (flame ionization detector). The analysis of N_2O was performed with a modified 14B Shimadzu gas chromatograph with an ECD detector (electronic capture) described in Perdomo and others (2009). The emission rate of both gases was calculated according to Watanabe and others (2000): F = ñ.h(dC/dt); where *F* corresponds to the emission rate of N-N_2O or C-CH_4 in g ha^{-1} d^{-1}; *ñ* is the density of N-N_2O or C-CH_4 corrected by the temperature inside the sampling chamber; *h* is the height of the chamber from the ground or the water level, and *dC/dt* is the increase in the concentration of N_2O or CH_4 inside the chamber over time. Before calculating the emission rates, the existence of a linear relationship between the concentration of the corresponding gas and time was confirmed for each case. The emission rate obtained for the replications of each treatment was averaged to determine the final emission value per treatment.

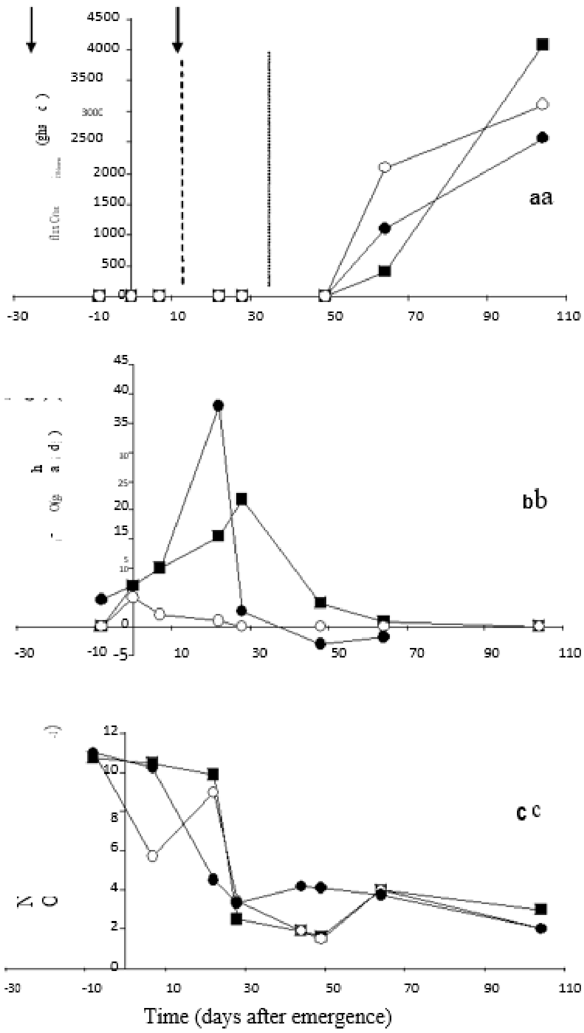
Figure 2. Photo of acrylic cylinders used for gas measurements.

The emitted seasonally integrated flux (Esif) was calculated from the areas under the gas emission figures for the entire time of rice cultivation for each of the chambers.

Soil Analysis

Random composite samples of eight cylinders 0-10 cm deep were collected to determine nitrate (NO_3^-). Samples were dried in a forced-air oven at 40°C, passed through 2 mm sieve and NO_3^- was analyzed by colorimetry after extraction with 2M KCl at 5:1 ratio. The content of NO_3^- was determined after reduction through a Cd column (Griess-Ilosvay reaction; Mulvaney, 1996).

Figure 3. Evolution of CH_4 and N_2O flux and content of NO_3^- in the soil in the greenhouse experiment according to the moment of flooding (DAE: days after emergence) and nitrogen fertilization. (a) Emission of CH_4; (b) emission of N_2O; (c) concentration of NO_3^- in soil. Treatments: 21 DAE (empty circles); 21 DAE + N (full circles); 45 DAE + N (full squares). Arrows indicate the application time of the fertilizer. Vertical lines indicate the moment of flooding: (—) 21 days and 45 days. Each point of the graphs corresponds to the mean of the flux calculated from eight static chambers (two in each plot).



Statistical analysis

The emission data obtained in the greenhouse and field experiments were evaluated by adjusting Mixed Effects Models using Software R (2009). For the analysis of the results obtained in greenhouse, treatments (combinations of different moments of flooding and levels of nitrogen fertilization), the time covariate, and their interaction were considered as fixed effects, while replications were considered as random effects. Field experiment data were analyzed considering the time covariate, winter covers, the level of nitrogen fertilization, and the interaction between the two last variables as fixed effects.

The adjustment of alternative models to the data groups was compared using variance analysis (ANOVA) and the most appropriate model was selected. A variance analysis (P=0.05) was applied to the results obtained with the final adjusted model.

Results and discussion

Greenhouse experiment

Figure 3a shows the CH_4 fluxes from the greenhouse experiments. No emissions of CH_4 were detected during the rice vegetative growth period (0 to 50 DAE), regardless of the flooding date. This period covered up to 34 days after flooding in early flood treatment and five days in late flooding. The rice was at advanced tillering at 50 DAE in both treatments when the emission of CH_4 was detected.

For early flood treatment, the first emission value was detected five weeks after the flood, while for late flood it was two weeks after the crop was flooded. On that date (64 DAE), with both treatments in the flowering initiation stage, there were no significant differences between the emissions. At 104 DAE, rice was in the flowering stage in the late flood treatment, but plants of the early flooding were more advanced, in the ripening stage. The practice of advancing the flooding has been reported as promoting crop maturity (Deambrosi, 2003). Coinciding with our results, it has been reported that about 90% of the total CH_4 in the entire crop cycle is emitted in the flowering, due to the maximum increase in biomass at that stage (Holzapfel-Pschorn and others, 1986; Schütz and others, 1989; Neue and others, 1997).

Table 2 shows the positive effect of nitrogen fertilization on the rice yield with early flooding. However, differences were not significant in the CH_4 fluxes between these treatments. The reported results on the effect of mineral N-fertilizers and the emission of CH_4 in flooded rice fields are contradictory (Wassmann and others, 1993). Different studies revealed that it is a relatively complex effect that is not yet fully understood (Bodelier and others, 2000), either because it stimulates or represses the main microbial populations involved in the generation and oxidation of CH_4. It should also be considered that fertilization not only affects microorganisms but also plants, adding complexity to the final result. These results suggest that the CH_4 fluxes are dependent on the plant development stage and that flooding would have an indirect influence on the emission of CH_4 when regulating the crop cycle.

Figure 4. Evolution of the flux of CH_4 and N_2O and content of NO_3^- in the soil in the field experiment according to the previous winter cover (DAE: days after emergence) and nitrogen fertilization. (a) Emission of CH_4; (b) emission of N_2O; (c) concentration of NO_3^- in soil. Treatments: Ryegrass (empty circles); Ryegrass+ N (full circles); Soil without vegetation (empty squares); Soil without vegetation + N (full squares). Arrows indicate the application time of the fertilizer. Vertical lines indicate the moment of flooding: (—) 21 days DAE, flushing (-.-) and drainage (…) before harvest. Each point of the graphs corresponds to the mean of the flux calculated from eight static chambers (two in each plot).

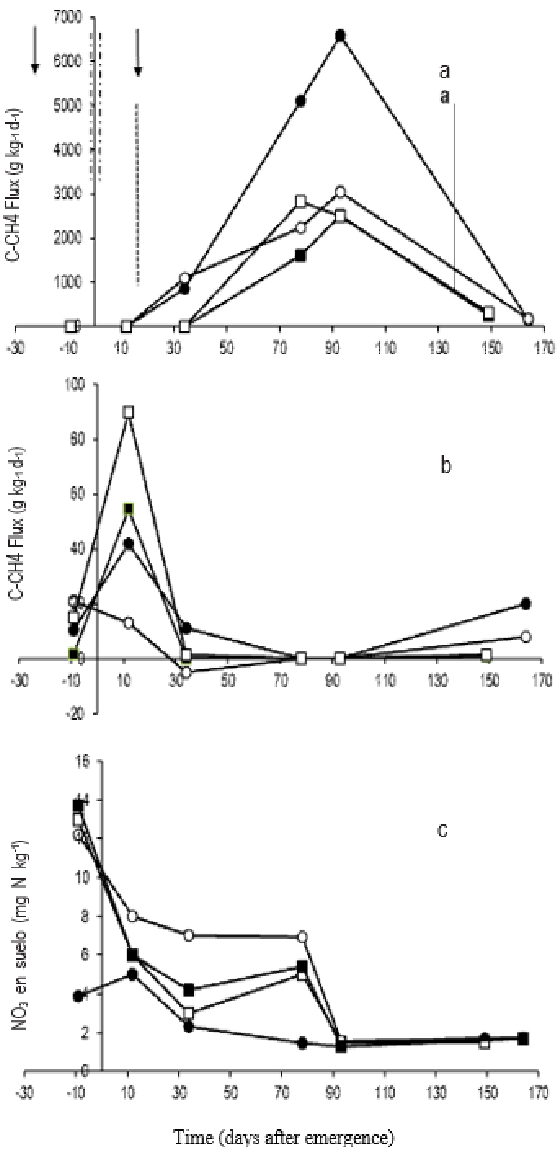


Table 2. Rice grain yield in the greenhouse experiment[1].

Treatment[2]	kg ha^{-1}
21 DAE	6709 ± 666 b
21 DAE+N	8084 ± 897 a
45 DAE+N	8457 ± 807 a

[1]The yield values and their error are presented. Different letters indicate significant differences ($p<0.01$).

[2]Treatment: combination of moment of the flood establishment (DAE: days after emergence) and application of nitrogen fertilizer (+ N).

The highest peak of N_2O (38 g N ha^{-1} day^{-1}) was recorded in the early flood treatment the day after urea fertilization and flooding (Figure 3b) and this flux was significantly different from that of the other treatments ($p<0.01$). This event coincided with a decrease in soil NO_3^-concentration (Figure 3c). This emission peak of N_2O could be attributed to the application of N-fertilizer if compared to the treatment with the same flood date but unfertilized and in which the emissions of N_2O remained low and constant throughout the crop cycle. However, the flooding itself contributed to this emission increase if we compare both fertilized treatments. On the same date, for the treatment that remained unflooded, there was a lower flux of N_2O (14 g N ha^{-1} day^{-1}).

During the period without flooding, emissions of N_2O were probably due to the nitrification of NH_4^+. When the soil was flooded early (21 DAE), denitrifying microorganisms acted on the pool of NO_3^- released by nitrification producing N_2O. Denitrification is normally considered the main source of N_2O in soils (Kravchenko and Yu, 2006). The flux of N_2O decreased dramatically after the soil was flooded permanently (10 cm water sheet) (Figure 3b), which can be attributed to the recapture of N_2O and reduction to N_2 under strictly anaerobic conditions. In fact, one of the currently studied ways to mitigate N_2O emissions is to increase the reduction from N_2O to N_2 (Baggs and others, 2010). In the 45 DAE treatment, the flooding was done with the rice in late tillering, when the NO_3^- available for denitrification was lower probably due to greater absorption by the plants. The N_2O fluxes were barely detectable during the rest of the rice crop cycle (Figure 3b).

Field experiment

The emission patterns of CH_4 were similar for rice cultivation with the two soil managements in the previous winter: ryegrass and soil without vegetation (Figure 4a). However, the records of CH_4 emissions began two weeks after flooding (34 DAE) on plots that had had ryegrass as cover, while at that time the emission was negligible for sown plots in soil without vegetation. As in the greenhouse experiment, CH_4 flux increased in the reproductive phase (onset of flowering, 78 DAE) and the maximum peak was recorded at 93 DAE (flowering) in all treatments. These results agree with previous reports that showed a positive correlation between a high production of CH_4 and the flowering stage, due to the increase of organic root exudates in this stage of the plant (Holzapel-Pschorn and others, 1986).

Several studies have emphasized that increased fluxes of CH_4 in late stages of plant growth would be caused by the proliferation of root exudates or products of root autolysis (Holzapfel-Pschorn and others, 1986; Lindau and others, 1991; Neue and Sass, 1994; Chidthaisong and Watanabe, 1997). Table 3 indirectly illustrates this point since a considerable increase in the dry matter of all treatments was observed during flowering. As a consequence of this increase in biomass, there was a greater availability of decomposable carbon from root exudates which, in turn, serve as a source of carbon and energy to microflora. After harvest (149 and 163 DAE, for bare soil and ryegrass respectively) very few emissions were recorded.

A significant interaction ($p=0.01$) was observed between the cover with ryegrass and the N-fertilization, with the highest fluxes of CH_4 for the treatment of fertilized rice and with ryegrass as winter cover. Different organic aggregates are generally considered to stimulate the flux of CH_4 by increasing the carbon supply for methanogens (Yagi and others, 1996; Bronson and others, 1997; Wassmann and others, 2000). Especially, if the incorporated material has a high C/N ratio, as in the case of ryegrass stubble. The plant absorption of nutrients leaves less N available to microorganisms and therefore N could be limiting bacterial activity.

Rice yield from ryegrass treatment, regardless of the N dose, was lower (Table 3).

Table 3. Yield parameters in the field trial[1].

Treatment[2]	Grain Yield (kgha-1)[1]	Dry matter at panicle initiation (kg ha^{-1})	Dry matter in flowering (kg ha^{-1})	Chlorophyll content at panicle initiation (SPAD units)	Chlorophyll content in flowering (SPAD units)	Number of panicles m²	Grains per panicle
Without vegetation	10370 ± 925 a	5637 ± 1781 a	9840 ± 1832 b	35.8 ±1.2 bc	36.2 ± 2.6 a	581 ± 146 a	117 ± 8 ab
Without vegetation	11233 ± 324 a	6194 ± 531 a	13375 ± 2839 a	31.8 ± 2.4 c	33.2 ± 2.4 b	510 ± 62 a	100 ± 20 b
Ryegra	8777 ± 1543 b	1837 ± 262 c	5052 ± 1011 c	36.2 ± 3.6 ab	39.9 ± 1.7 a	313 ± 59 b	123 ± 16 a
Ryegrass +	9870 ± 904 ab	3405 ± 706 b	7199 ± 564 bc	36.6 ± 2.2 a	40.8 ± 1.1 a	352 ± 63 b	133 ± 8 a

[1]The values and their standard deviation are shown. Values followed by different letters were significantly different ($p<0.01$).
[2]Treatment: combination of prior winter cover and nitrogen fertilization (+ N) during rice cultivation.

Both treatments showed less accumulation of dry matter, number of panicles per m^2 and grains per panicle. In contrast, the tendency of chlorophyll content was opposite, with the highest values observed in ryegrass treatments regardless of fertilization. Recently, Baruah and others (2010) have reported a positive correlation between CH_4 emission and photosynthetic activity.

As shown in Figure 4b, an initial emission of N_2O could be detected in all treatments. This peak of N_2O occurred immediately after flushing at a time when the contents of soil NO_3^- had decreased (Figure 4c). Under these soil redox conditions, both nitrifying and denitrifying organisms could be the main producers of N_2O (Müller and others, 2004). Although there were no significant differences, treatments that had winter cover showed a tendency to reduce their N_2O emission before the flood was established compared to soils without cover. In fact, the use of non-legume crops in winter has been described as an effective practice to reduce N_2O emissions (Gomes and others, 2009), due to competition with soil microorganisms for the available NO_3^-. There was no significant effect of N fertilization on N_2O fluxes in any treatment. It is generally accepted that the emission of N_2O increases immediately after fertilization in dry soils (Bronson and others, 1997; Yagi and others, 1996; Cai and others, 1997). In the case of rice that was sown directly on the fallow of ryegrass, microorganisms could have immobilized N due to the high C/N ratio of the ryegrass. However, Dobermann and Cassman (2002) suggested that the main factor affecting the emission of N_2O is the N turnover rate, taking into account the synchronization between N mineralization and plant absorption. Fractional application of N, a recommended method of application for this crop, is likely to increase the plant's efficiency of N use (Irisarri and others, 2007), which has an inverse relationship with the N_2O emission (Kroeze and Mosier, 2000). An event of a small flux of N_2O emission was measured after draining the field at the end of the crop. This flux could be due to the release of N_2O trapped in the soil and optimal redox conditions for the production of N_2O. Non-legume crops have been reported as efficient consumers of residual NO_3^- in the soil (Gomes and others, 2009) and therefore able to reduce their losses. Thus, when rice cultivation is not occupying the soil, emissions must be measured in order to consider the entire system.

Finally, both experiments, greenhouse and field, showed that the emission of CH_4 coincided with the reproductive stage of rice, while the emission of N_2O was more influenced by agricultural practices such as water management, nitrogen fertilization and previous land use. Although our data were obtained during a single harvest, with particular climatic conditions, the results of the greenhouse and field experiments are consistent.

Seasonal fluxes

Table 4 shows the cumulative fluxes of CH_4 and N_2O throughout the rice crop cycle. While sampling dates are scarce to draw definitive conclusions, the integrated fluxes of CH_4 were in all cases at least 18 times greater than those of N_2O in CO_2 equivalents (in 100 years). Although N_2O is a much more potent greenhouse gas than CH_4 in terms of global warming, its seasonal emission per hectare was much lower.

The Esif (emitted seasonal integrated flux) of CH_4 of fertilized rice after winter covering with ryegrass, was significantly higher than that of the other treatments (Table 4). One possible explanation for this result is that the combination of no-till, ryegrass cover, and nitrogen fertilization may have increased carbon supply to methanogenic organisms (Wassmann and others, 2000). In the case of N_2O, none of the treatments recorded a different seasonal emission than the rest, although the high variability of the Esif may have hidden the potential effects of the treatments. It should also be considered that emission rates may be overestimated since the fluxes were measured in the hottest period of the day (13:00 -15:00 h), when the maximum emission rates occur (Hou and others, 2000).

The median seasonal emissions of other irrigated rice paddies in different parts of the world range from 34 g CH_4 m^{-2} (China) to 25 g CH_4 m^{-2} (USA). Our seasonal data range from 17 to 21 g CH_4 m^{-2} for rice sown on bare soil in winter, and between 32 and 64 g CH_4 m^{-2} for the crop sown on ryegrass cover. According to our results, the establishment of a winter ryegrass cover increased the CH_4 flux.

A recent review of emissions of N_2O from various rice paddies reports seasonal averages of 0.667 ± 0.885 kg N ha^{-1}, revealing the great variability in the flux of this GHG and the consequent difficulty in comparing data (Akiyama and others, 2005). On the other hand, when comparing the emissions per hectare we must consider the high rice yields in Uruguay (8000 - 8500 kg ha^{-1}; ACA 2011) and the average yields of Asian countries (5000 kg ha^{-1}, AFSIS). This would result in lower emissions in CO_2 equivalents per kg of rice in the case of Uruguay, although it would be necessary to increase the sampling dates to validate this conclusion.

Measurements of these gases during the course of the day and in winter would allow obtaining annual emission data that would be comparable to the emissions reported by other countries.

Table 4. Emitted seasonal integrated flux (Esif) of CH_4 and N_2O by rice cultivation in field experiment[1].

Treatment[2]	Fie CH_4 (kg C–CH4 ha^{-1})	Fie CH_4 (CO_2 equiv. 100 years)	Fie N_2O (kg N–N_2O ha^{-1})	Fie N_2O (CO_2 equiv. 100 years)
Without vegetation	156[b]	4368	0,5 [a]	243
Without vegetation + N	129[b]	3612	0,4 [a]	195
Ryegrass	242[b]	6776	0,4 [a]	195
Ryegrass + N	482[a]	13496	1,1 [a]	535

[1]Values followed by different letters were significantly different ($p<0.01$).
[2]Treatment: combination of prior winter cover and nitrogen fertilization (+ N) during rice cultivation.

Conclusions

This first approximation to GHG emission in Uruguayan rice paddies confirmed that CH_4 is the main gas emitted and that the emission patterns of both gases have an opposite behavior throughout the crop cycle. Rice sown on a cover of ryegrass and fertilized with nitrogen emitted more than twice as much CH_4 as rice sown on bare soil. In both the greenhouse and field experiments, the highest emissions of CH_4 coincided with the reproductive stage of rice, while the N_2O emissions peaked at the vegetative phase and were influenced by water management and nitrogen fertilization. These preliminary results on the effect of some crop management practices on GHG emissions reinforce the need for local data, to contribute to the development of the national GHG inventory, the calculation of the C footprint and the design of emission mitigation strategies.

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