Revista
Brasileira de
Ciência do Solo

Division – Soil Use and Management | Commission – Soil and Water Management and Conservation

Soil CH_4 and N_2O Emissions from Rice Paddy Fields in Southern Brazil as Affected by Crop Management Levels: a Three-Year Field Study

Tiago Zschornack(1), **Carla Machado da Rosa**(2), **Cecília Estima Sacramento dos Reis**(1), **Gabriel Munhoz Pedroso**(1), **Estefânia Silva Camargo**(1), **Daiane Carvalho dos Santos**(1), **Madalena Boeni**(2) **and Cimélio Bayer**(1)*

(1) Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Departamento de Ciência do Solo, Programa de Pós-Graduação em Ciência do Solo, Porto Alegre, Rio Grande do Sul, Brasil.
(2) Fundação Estadual de Pesquisa Agropecuária, Porto Alegre, Rio Grande do Sul, Brasil.

*** Corresponding author:**
E-mail: cimelio.bayer@ufrgs.br

Received: September 9, 2017
Approved: December 21, 2017

How to cite: Zschornack T, Rosa CM, Reis CES, Pedroso GM, Camargo ES, Santos DC, Boeni M, Bayer C. Soil CH_4 and N_2O emissions from rice paddy fields in Southern Brazil as affected by crop management levels: a three-year field study. Rev Bras Cienc Solo. 2018;42:e0170306.
https://doi.org/10.1590/18069657rbcs20170306

ABSTRACT: Rice yield increases in response to improvements in crop management, but the impact on greenhouse gas (GHG) emissions in the subtropical region of Southern Brazil remains unknown. A three-year field study was developed aiming to evaluate the impact that an increase in crop management levels (high and very high) has on soil methane (CH_4) and nitrous oxide (N_2O) emissions, as compared to the level (medium) currently adopted by farmers in Southern Brazil. Differences in crop management included seed and fertilizer rates, irrigation, and pesticide use. The effect of crop management levels on the annual partial global warming potential (pGWP = $CH_4 \times 25 + N_2O \times 298$) ranged from 7,547 to 17,711 kg CO_2eq ha^{-1} and this effect was larger than on the rice grain yield (9,280 to 12,260 kg ha^{-1}), resulting in approximately 60 % higher yield-scaled GHG with the high crop management level compared to the current level. Soil CH_4 emissions accounted for 98 % of pGWP in the flooded rice season, whereas N_2O prevailed during the drained non-rice season (≈65 %). Although it was impossible to relate emissions to any individual input or practice, soil CH_4 emissions in the rice season were linearly related to the biomass produced by the rice crop ($p<0.01$) and by ryegrass in the previous non-rice season ($p<0.1$), both of which were possibly related to the supply of labile C for methanogenesis. A future increase in rice yield as a result of the adoption of improved crop management may require additional agricultural practices (e.g., intermittent irrigation) to offset the increased GHG emissions.

Keywords: Entisols, flooded rice, greenhouse gases, methane, yield-scaled.

INTRODUCTION

Rice is one of the most important foods in the human diet and the second most frequently grown cereal in the world (Sosbai, 2014). The state of Rio Grande do Sul (RS) in Southern Brazil accounts for more than 65 % of overall Brazilian production (Conab, 2015). Regional research has shown that rice yield may be increased through improvements in management of the rice crop involving integration of variable amounts of inputs, sowing times, and other agricultural practices (Mariot et al., 2009; Menezes et al., 2013). To the best of our knowledge, however, the environmental impact of increased management levels on rice crops has never been assessed on the regional level, especially as regards greenhouse gas (GHG) emissions.

The rice production system in RS, where the rice crop area exceeds 1.0 million hectares each year, requires a 0.05-0.20 m thick layer of water to be maintained on the soil throughout the crop cycle (IRGA, 2006; Sosbai, 2014). These conditions boost production of CH_4 through anaerobic decomposition of soil organic matter or crop straw by methanogens (Le Mer and Roger, 2001). Rice plants also play a key role in the CH_4 emission process by transferring most CH_4 present in the soil to the atmosphere through their aerenchyma (Nouchi et al., 1990). In addition to transferring CH_4 from the soil to the atmosphere, rice plants supply substantial amounts of labile C to methanogens by accumulating likewise substantial amounts of photoassimilated C in their roots (Lu et al., 2000; Aulakh et al., 2001). In this situation, increasing inputs (particularly fertilizers) to a rice crop may boost CH_4 emissions from the soil through the effect of increased exudation of organic compounds by the root system to raise yields (Das and Baruah, 2008).

The increased rates of N applied at higher crop management levels can also favor the production of N_2O and its emission from soil. Nitrous oxide is another major GHG, and it has an infrared radiation absorption capacity approximately 12 times greater than that of CH_4 on a 100-year horizon (Forster et al., 2007). Although N_2O results primarily from denitrification (Pimentel et al., 2015), emissions of this gas from irrigated rice are typically lower than those from rainfed (upland) crops (Linquist et al., 2012a). In fact, N_2O can be reduced to a great extent to N_2 under prolonged soil flooding conditions (Zou et al., 2007; Liang et al., 2013). However, most studies assessing GHG under flooded conditions on the regional level have been restricted to the crop period during which the soil remains under water (flooded), and not many data are available for the non-rice season, when the soil is usually under aerated conditions (drained) - and may thus emit large amounts of N_2O (Moterle et al., 2013; Bayer et al., 2014, 2015).

Our starting hypothesis was that yield-scaled greenhouse gas emission is unaffected by the improvement in crop management level because the resulting increase in CH_4 and N_2O emissions is offset by an increase in rice yields. The aim of this study was to evaluate the effect of crop management levels, integrating management practices and inputs, on CH_4 and N_2O emissions from soil during the flooded rice season and the drained non-rice season in southern Brazil. Rice grain yield and the contribution of each gas to the partial global warming potential (pGWP) were also evaluated.

MATERIALS AND METHODS

Site description and experimental design

The study was conducted at the experimental station of the Rio Grandense Rice Institute (IRGA) in Cachoeirinha, RS, Brazil (29° 57’ 02” S and 51° 06’ 02” W), during the rice growing seasons of 2009/2010, 2010/2011, and 2011/2012, and the non-rice seasons of 2010 and 2011. The region has a humid subtropical climate (Cfa), a mean annual temperature of 20 °C, and mean annual rainfall of 1,394 mm. The field experiment was performed on a Gleysol (*Gleissolo Háplico*) with pH(H_2O) of 5.3, 170 g kg^{-1} clay, 13 g kg^{-1} OM, and 6.7 mg dm^{-3} P, and 29 mg dm^{-3} K (Mehlich-1) in the 0.00-0.20 m layer.

The experiment followed a randomized complete block design with three replicates. Treatments involved three management levels for the rice crop (medium, high, and very high) differing in seeding and fertilizer rates, the beginning of flooding, and pesticide application (Table 1). The medium level was closest to "business as usual" in most rice farms in southern Brazil (IRGA, 2006). For all management levels, no-till rice seeding was performed by using ryegrass (*Lolium multiflorum* Lam.) as a winter cover crop (Table 1), which was desiccated with glyphosate in early spring.

Air sampling and gas analysis

Air was sampled on a weekly basis during the flooded rice season (spring-summer), biweekly during the drained non-rice season (fall-winter), and daily after the N application events, using the static closed chamber method (Bayer et al., 2014). Each chamber consisted of an aluminum base (0.60 × 0.60 × 0.20 m) and an aluminum top of the same size. The bases were driven 0.05 m into the soil before permanent flooding in the rice season and after rice harvest in the non-rice season, and left in the soil throughout the seasons.

Each base had an open bottom and sealable channels on the sides to facilitate free flowing of irrigation water in the rice season. The channels on the sides were sealed during air sampling events. Each base covered three rows of rice plants. In the rice season, additional 0.20 or 0.30 m aluminum extensions were stacked on the bases as the plants grew taller. The chamber volume was considered in estimating all GHG emissions. Each chamber top had a rubber septum sampling port, a stainless steel thermometer, and a battery operated fan to circulate and homogenize air within the chamber (Bayer et al., 2014). Chamber closing and initial air sampling began at 9:00 am, which was followed by five air samplings at intervals of 5 min (Bayer et al., 2014). Air samples were withdrawn with polypropylene syringes, transferred to the Biogeochemical Laboratory at Ufrgs and analyzed for CH_4 and N_2O on the same day in a gas chromatograph (Shimadzu Corp. 2014) equipped with flame ionization (250 °C) and electron capture (325 °C) detectors.

Calculations

Methane and N_2O fluxes were calculated according to equation 1:

$$f = \frac{\Delta Q}{\Delta t}\frac{PV}{RT}\frac{M}{A} \qquad \text{Eq. 1}$$

in which: *f* is the gas production rate (g m^{-2} h^{-1}); $\Delta Q/\Delta t$, the change in gas concentration (mol h^{-1}); *P*, the atmospheric pressure in the chamber (1 atm); V, the chamber volume (L); R, the ideal gas constant (0.0825 atm L mol^{-1} K^{-1}); T, the chamber temperature (K); M, the gas molar mass (g mol^{-1}); and A, the chamber basal area (m^2).

The flux rate of GHG as estimated from air samples collected from 9:00 to 11:00 a.m. was used as a measure of mean daily flux (Costa et al., 2008). Seasonal emissions (rice and non-rice periods) were calculated by trapezoidal interpolation of the daily CH_4 and N_2O flux rates throughout each period (Bayer et al., 2014). Annual GHG emissions were obtained by combining the emissions for the rice and non-rice seasons. A partial global warming potential was calculated according to the equation 2:

$$pGWP = (CH_4 \times 25) + (N_2O \times 298) \qquad \text{Eq. 2}$$

in which pGWP is the partial global warming potential (kg CO_2eq ha^{-1}), CH_4 and N_2O are the seasonal emissions of the gases (kg ha^{-1}), and 25 and 298 are the radiative forcing potential of CH_4 and N_2O, respectively.

Table 1. Inputs and operations for paddy rice at three crop management levels (medium, high, and very high) in three crop seasons in southern Brazil

Inputs/operations	2009/2010			2010/2011-			2011/2012		
	Medium	High	Very high	Medium	High	Very high	Medium	High	Very high
Desiccation (L ha^{-1} glyphosate)	3	3	3	4	4	4	4	4	4
Cultivar	IRGA 424	IRGA 424	IRGA 424	IRGA 424	IRGA 424	IRGA 424	IRGA 424	IRGA 424	IRGA 424
Seeding rate (kg ha^{-1})	120	100	80	120	100	80	120	100	80
Seed treatment(1)	Insecticide	Insecticide + Fungicide	Insecticide + Fungicide + Micronutrients	Insecticide	Insecticide + Fungicide	Insecticide + Fungicide + Micronutrients	Insecticide	Insecticide + Fungicide	Insecticide + Fungicide + Micronutrients
Fertilizer at sowing 5-20-30 (kg ha^{-1})	200	350	500	200	350	500	200	350	500
Broadcast N fertilization (kg ha^{-1})	60	105	150	60	105	150	60	105	150
First broadcast N application (kg ha^{-1})(2)	40	70	100	40	70	100	40	70	100
Application of herbicide	cyhalofop-butyl + penoxsulam	cyhalofop-butyl + penoxsulam	cyhalofop-butyl + penoxsulam	cyhalofop-butyl + penoxsulam	cyhalofop-butyl + penoxsulam	cyhalofop-butyl + penoxsulam	cyhalofop-butyl + penoxsulam	cyhalofop-butyl + penoxsulam	cyhalofop-butyl + penoxsulam
Beginning of flooding(3)	V4	V3	V3	V4	V3	V3	V4	V3	V3
Second broadcast N application (kg ha^{-1})(4)	20	35	50	20	35	50	20	35	50
Sprayed insecticide	thiamethoxam + lambda-cyhalothrin	thiamethoxam + lambda-cyhalothrin	thiamethoxam + lambda-cyhalothrin	thiamethoxam + chlorantraniliprole	thiamethoxam + chlorantraniliprole	thiamethoxam + chlorantraniliprole	-	-	-
Sprayed fungicide	-	epoxiconazole + kresoxim-methyl	epoxiconazole + kresoxim-methyl	-	epoxiconazole + kresoxim-methyl	epoxiconazole + kresoxim-methyl	-	epoxiconazole + kresoxim-methyl	epoxiconazole + kresoxim-methyl
Ryegrass seeding rate (kg ha^{-1})	20	20	20	40	40	40	40	40	40
Ryegrass N fertilization (kg ha^{-1})	-	25	25	-	37.5	37.5	-	-	-

(1) Insecticide: fipronil; fungicide: carboxin + thiram. (2) Performed at stages V_4, V_3, and V_3 according to the scale of Counce et al. (2000) at the medium, high, and very high level, respectively. (3) According to the scale of Counce et al. (2000). (4) Performed at stages V_7-V_8 according to the scale of Counce et al. (2000) at all levels. - : not applied.

Yield-scaled pGWP was calculated as the ratio of pGWP to rice grain yield, according to equation 3:

$$\text{YpGWP} = \frac{\text{pGWP}}{\text{Y}} \qquad \text{Eq. 3}$$

in which YpGWP denotes yield-scaled GHG emission (kg CO_2eq kg^{-1} rice); pGWP, the partial global warming potential (kg CO_2eq ha^{-1} season^{-1}); and Y, the rice grain yield (kg ha^{-1}).

Meteorological variables and supplementary determinations

Figure 1 shows daily solar radiation, average air temperature, and rainfall during the study period obtained from an automatic meteorological station installed at the experimental site. The temperature at a soil depth of 0.05 m was monitored at the site by using a digital thermometer in each air sampling event.

Aboveground biomass of ryegrass was assessed at the flowering stage in the 2010 and 2011 non-rice seasons. The rice biomass was evaluated at the R_4 stage [anthesis, according to Counce et al. (2000)] in the 2009/10 and 2010/11 rice seasons. In both determinations, a 0.5 m^2 area was sampled and the biomass was oven dried at 60 °C to constant weight. Grain yield was measured in a 15 m^2 area and expressed at 13 % moisture.

Statistical analysis

Data were visually analyzed for normality and constant variance of errors. Visual analysis of normality consisted of constructing a stem and leaf plot and a histogram of the model predicted values by the residual values (observation minus predicted). The shape of the data points indicated whether the data set is normally distributed. Constant variance of errors was assessed by making a box plot of the residuals for each treatment. Again, the shape of the data points (heights of the box plot) indicated whether the errors are constant and homogenous among treatments. Appropriate transformations were applied if either assumption was violated. Analyses of variance for the dependent variables (seasonal N_2O and CH_4 emissions, and pGWP) were conducted separately for each period (rice and non-rice seasons, and annual results), whereas grain yield and YpGWP were only analyzed in the rice season. Treatment, year, and their mutual interaction were used as fixed effects, and block was the random effect. The general linear model of the GLM Procedure in the SAS software suite was used in all cases. Differences between treatment means were evaluated via Tukey's test at $p<0.1$.

RESULTS AND DISCUSSION

Soil CH_4 and N_2O fluxes

Methane fluxes occurred mainly during the rice season and ranged from -0.80 to 855.50 g ha^{-1} h^{-1}, and their behavior at that time was similar for all crop management levels (Figure 2). For the 2010/11 and 2011/12 rice seasons, CH_4 fluxes were low (<40 g ha^{-1} h^{-1}) during the first six weeks after rice seeding, but gradually increased from the fourth week after flooding and remained high thereafter - especially during the second half of the rice cycle (reproductive stage). For the 2009/10 rice reason, no analysis of the initial emissions was possible, because flux measurements started only after flooding. The gradual increase in CH_4 emissions after flooding are consistent with anoxic conditions in flooded soil, once pH and E_h have leveled off and oxidized species such as NO_3^-, Mn^{4+}, and Fe^{3+} have been microbially reduced (Silva et al., 2011). In addition, the presence of rice plants influences CH_4 production by exudation of photoassimilated C from their roots for use by methanogens (Lu et al., 2000; Das and Baruah, 2008) and by transfer of the CH_4 - primarily through the aerenchyma (Nouchi et al., 1990).

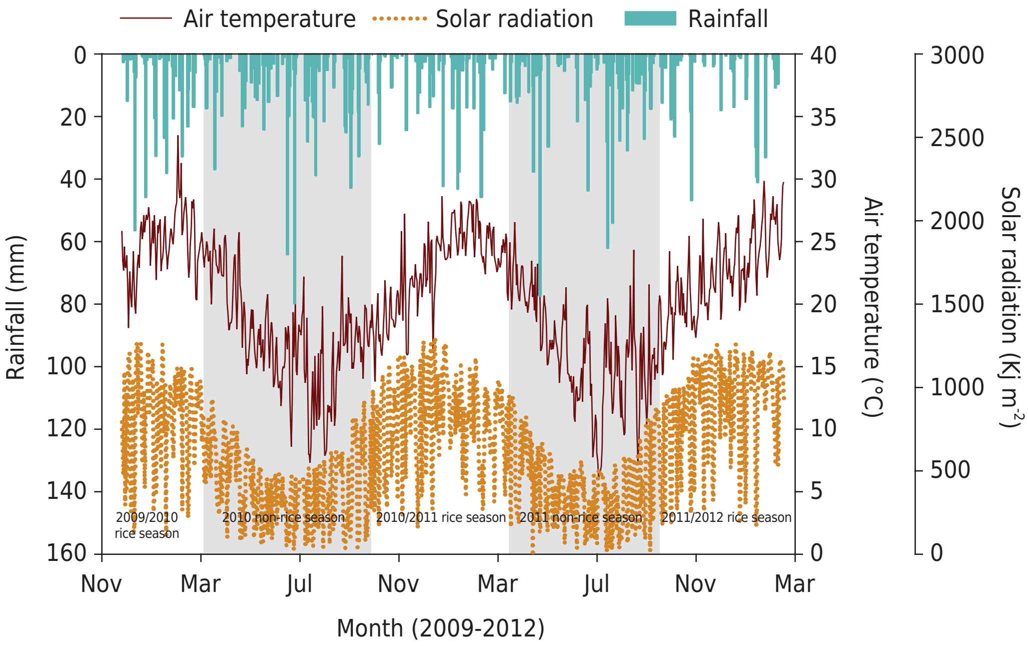

Figure 1. Rainfall, air temperature, and solar radiation during the period studied.

Our results also showed that soil drainage before harvest significantly increased CH_4 fluxes to levels above 500 g ha^{-1} h^{-1} for most treatments in all three rice seasons (Figure 2). As previously suggested (Yagi et al., 1996; Liang et al., 2013), the increased emissions may have resulted from the release of CH_4 trapped in the soil during flooding. After peaking during soil drainage, CH_4 fluxes decreased to near-zero levels until harvest and remained low during the non-rice season. Soil CH_4 fluxes for the two non-rice seasons (2010 and 2011) ranged from -8.27 to 90.26 g ha^{-1} h^{-1}. The lower CH_4 fluxes relative to the rice season were related to unfavorable conditions for CH_4 production and emission (e.g., the absence of an anaerobic environment) (Zhang et al., 2014) and also to the milder prevailing temperatures (Figure 1).

Soil temperatures ranged from 6 to 28 °C, and soil CH_4 fluxes were virtually zero below 20 °C during the period studied (2009-2012). In the rice seasons, soil temperature ranged from 18 to 28 °C (Figure 3) and CH_4 emissions increased exponentially with increasing temperature ($p<0.0001$). The increase was more marked in the reproductive stage than in the vegetative stage, probably because of the effect of C exudation from roots and increased development of plant aerenchyma (Das and Baruah, 2008). The ability of rice plants to transport CH_4 increases along with the increasing number and size of tillers, leaves, and roots (Gogoi et al., 2005; Das and Baruah, 2008), and also of the structures involved in CH_4 transport from the soil to the atmosphere. In addition, a substantial fraction of photoassimilated C is translocated to roots in the reproductive stage, and they provide a source of labile C for methanogens (Lu et al., 2000).

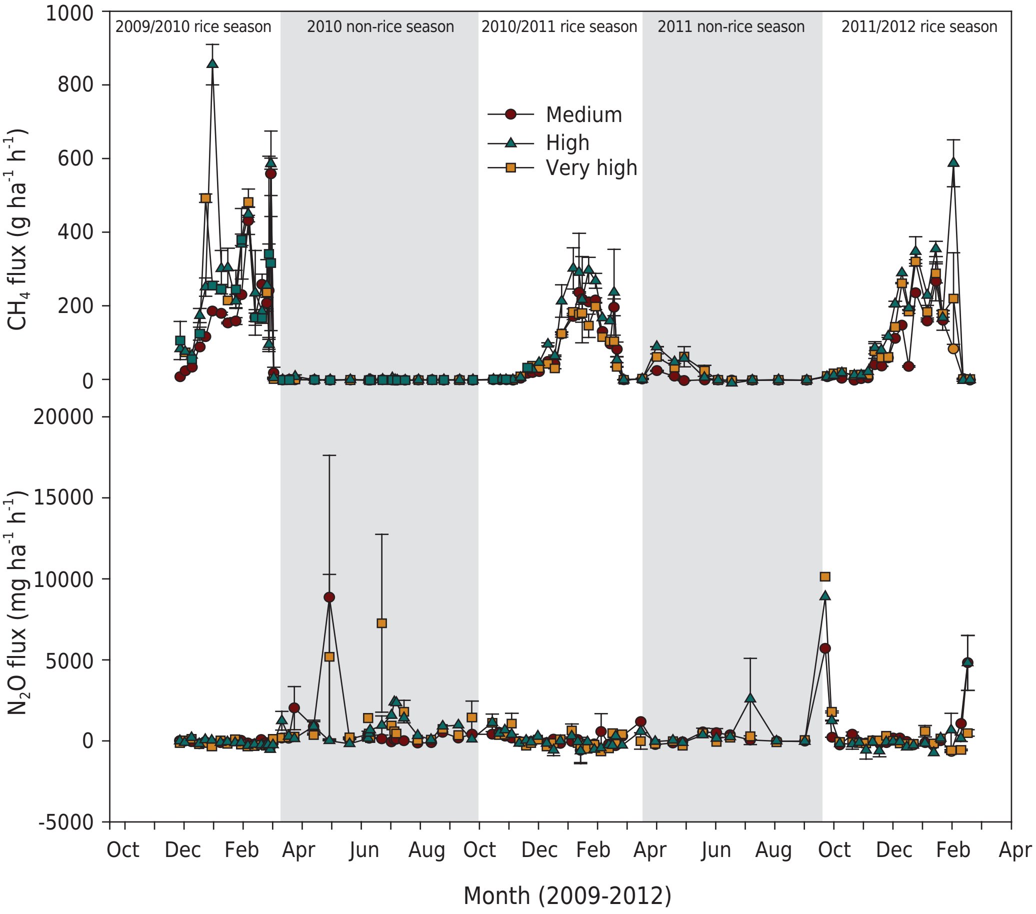

Figure 2. Methane and N_2O fluxes from rice paddy soil over three cropping seasons (unshaded bands) and two non-rice seasons (shaded bands) under medium, high, and very high crop management levels in southern Brazil. Vertical bars represent standard errors.

Unlike CH_4, N_2O fluxes peaked during the non-rice season and before flooding in the rice season; furthermore, they were unrelated to soil temperature or fertilizer N added to the rice or ryegrass crops (Figure 2, Table 1). The average soil N_2O flux was 30.2 g ha^{-1} day^{-1} for the non-rice season and 2.08 g ha^{-1} day^{-1} for the rice season. Flooding is known to reduce N_2O fluxes to near-zero levels (Johnson-Beebout et al., 2009; Liu et al., 2010); and nitrification is restricted by the absence of O_2, which precludes NO_3^- production and denitrification. Also, prolonged flooding results in an increased proportion of N_2O being reduced to N_2 (Reddy and DeLaune, 2008; Liang et al., 2013).

Seasonal soil CH_4 and N_2O emissions

Cumulative soil CH_4 emissions in the rice season were significantly influenced ($p<0.001$) by the management level and differed over the years (Table 2), ranging from 250.9 to 671.5 kg ha^{-1} (Table 3), within the range previously reported for southern Brazil (Moterle et al., 2013; Bayer et al., 2014, 2015). The considerable differences in cumulative soil CH_4 emissions between rice seasons may have been related to the specific weather conditions and to differences in rice crop development (Liang et al., 2013) and ryegrass biomass in the previous winter.

On average for the three rice seasons, the highest soil CH_4 emissions occurred at the high crop management level (546.6 kg ha^{-1}), and were 34 and 69 % higher than those for the very high and medium level, respectively, with no significant difference between the last two (Table 3). The combined effect of the inputs and their respective amounts at the high crop management level probably provided better development conditions for the rice plants and methanogenic activity through more extensive allocation of C to the root system (Liang et al., 2013). This assumption is strengthened by the significant positive relationship ($p<0.01$) between the amount of aboveground biomass of the rice crop and cumulative CH_4 emissions during the crop season (Figure 4), mainly upon comparing the medium and high crop management levels. Increased plant growth probably boosted production and release of organic compounds through the root system.

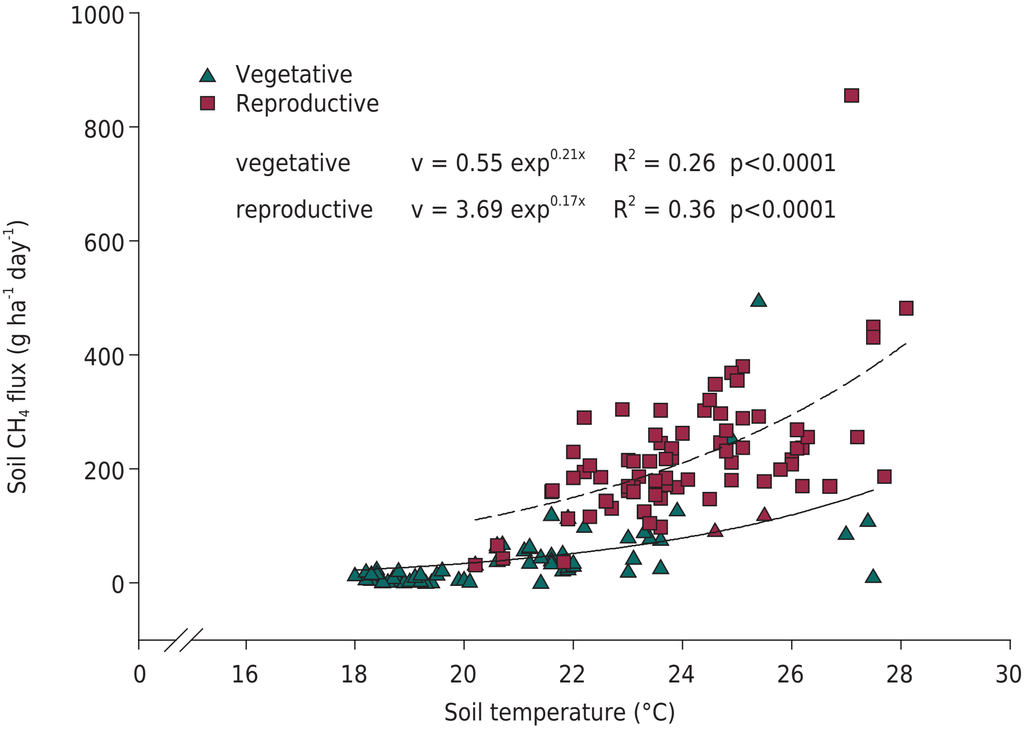

Figure 3. Relationship between soil temperature and CH_4 fluxes in the vegetative and reproductive stages of rice in southern Brazil.

Table 2. Summary statistics: significance of the fixed effects treatment (T), year (Y), and T × Y interaction on the dependent variables (cumulative soil CH_4 and N_2O emissions, pGWP, rice grain yield, and YpGWP) in the rice and non-rice seasons, and annual results (rice + non-rice seasons), for a paddy rice field at different crop management levels in southern Brazil

Fixed effect	Period		Cumulative CH_4	Cumulative N_2O	pGWP	Yield	YpGWP
Treatment (T)	Rice season	df	2	2	2	2	2
		F value	28.280	0.290	13.680	7.02	28.23
		p value	0.0002	0.754	0.009	0.007	0.0002
	Non-rice season	df	2	2	2		
		F value	15.990	0.070	0.390		
		p value	0.007	0.931	0.696		
	Annual	df	2	2	2		
		F value	16.690	0.070	7.850		
		p value	0.006	0.932	0.029		
Year (Y)	Rice season	df	2	2	1	2	2
		F value	30.340	45.430	57.080	6.67	47.50
		p value	0.0002	<0.0001	0.009	0.008	<0.0001
	Non-rice season	df	1	1	1		
		F value	78.000	3.150	0.130		
		p value	0.0003	0.136	0.738		
	Annual	df	1	1	1		
		F value	33.860	2.380	26.540		
		p value	0.002	0.184	0.004		
T × Y	Rice season	df	4	4	2	4	4
		F value	2.40	0.56	3.39	0.85	3.23
		p value	0.14	0.70	0.12	0.51	0.074
	Non-rice season	df	2	2	2		
		F value	13.480	0.460	0.950		
		p value	0.010	0.656	0.446		
	Annual	df	2	2	2		
		F value	1.250	0.420	0.780		
		p value	0.363	0.679	0.509		

The increase in crop management level from medium to high, and the resulting impact on the production of rice biomass (Figure 4), may also have contributed to the increased CH_4 emissions observed during the next non-rice season (Tables 2 and 3). Thus, the combined cumulative soil CH_4 emissions at these two levels in the two non-rice seasons were 609 % higher ($p<0.01$) than they were at the medium management level. In a previous study, Xu and Hosen (2010) found that rice straw input significantly increased CH_4 emissions during the fallow period, but only when the soil had water content exceeding 79 % of its retention capacity.

Another factor that significantly ($p<0.1$) influenced CH_4 emissions from the soil in the rice season was ryegrass biomass produced in the previous non-rice season (fall-winter, Figure 5). Based on the results, adding 1 Mg ha^{-1} ryegrass to the soil increased CH_4 emissions by more than 210 kg ha^{-1} in the subsequent rice crop. The addition of residues of a cover crop to soil is known to boost CH_4 emissions by increasing the supply of labile C to methanogens and enhancing soil reduction as a result (Kim et al., 2013).

We found a decrease of 25 % in cumulative CH_4 emissions (average of the three rice seasons) from high to very high crop management levels. This decrease in CH_4 emissions may be at least partially related to the lower production of biomass by rice observed

Table 3. Cumulative soil CH_4 and N_2O emissions, partial global warming potential (pGWP), rice grain yield, and yield-scaled pGWP (YpGWP) for an irrigated rice field at different crop management levels

Year/Parameter	Rice Season			Non-rice Season			Annual Cumulative		
	Medium	High	Very high	Medium	High	Very high	Medium	High	Very high
2009/2010									
Cumulative CH_4 (kg ha^{-1})	407.1	671.5	550.8	0.9	5.7	0.5	408.0	677.2	551.3
Cumulative N_2O (kg ha^{-1})	-0.16	-0.22	-0.32	5.53	2.84	6.46	5.37	2.62	6.14
CH_4 (kg CO_2eq ha^{-1})	10,178	16,788	13,770	23	143	13	10,201	16,931	13,783
N_2O (kg CO_2eq ha^{-1})	-48	-66	-95	1,648	846	1,925	1,600	780	1,830
pGWP (kg CO_2eq ha^{-1})	10,130	16,722	13,675	1,671	989	1,938	11,801	17,711	15,613
Rice yield (kg ha^{-1})	9,280	9,703	10,024	-	-	-	-	-	-
YpGWP (kg CO_2eq kg^{-1} rice)	1.09 a	1.72 a	1.36 a	-	-	-	-	-	-
2010/2011									
Cumulative CH_4 (kg ha^{-1})	282.7	396.5	250.9	7.6	57.6	58.1	290.3	454.1	309.0
Cumulative N_2O (kg ha^{-1})	0.46	0.14	0.27	0.51	1.81	0.30	0.97	1.95	0.57
CH_4 (kg CO_2eq ha^{-1})	7,068	9,913	6,273	190	1,440	1,453	7,258	11,353	7,726
N_2O (kg CO_2eq ha^{-1})	137	42	80	152	539	89	289	581	169
pGWP (kg CO_2eq ha^{-1})	7,205	9,955	6,353	342	1,979	1,542	7,547	11,934	7,895
Rice yield (kg ha^{-1})	10,133	11,267	12,167	-	-	-	-	-	-
YpGWP (kg CO_2eq kg^{-1} rice)	0.71 ab	0.88 a	0.52 b	-	-	-	-	-	-
2011/2012									
Cumulative CH_4 (kg ha^{-1})	282.0	571.9	421.8	-	-	-	-	-	-
Cumulative N_2O (kg ha^{-1})	0.93	1.03	1.04	-	-	-	-	-	-
CH_4 (kg CO_2eq ha^{-1})	7,050	14,298	10,545	-	-	-	-	-	-
N_2O (kg CO_2eq ha^{-1})	277	307	310	-	-	-	-	-	-
pGWP (kg CO_2eq ha^{-1})	7,327	14,605	10,855	-	-	-	-	-	-
Rice yield (kg ha^{-1})	10,140	10,343	12,260	-	-	-	-	-	-
YpGWP (kg CO_2eq kg^{-1} rice)	0.72 b	1.41 a	0.89 b	-	-	-	-	-	-
Average (2009-2012)									
Cumulative CH_4 (kg ha^{-1})	323.9 b	546.6 a	407.8 b	4.3 b	31.7 a	29.3 a	328.2 b(1)	578.3 a	437.1 b
Cumulative N_2O (kg ha^{-1})	0.41 a	0.32 a	0.33 a	3.02 a	2.33 a	3.38 a	3.43 a	2.65 a	3.71 a
CH_4 (kg CO_2eq ha^{-1})	8,099 b	13,666 a	10,196 b	107 b	792 a	733 a	8,206 b	14,458 a	10,929 b
N_2O (kg CO_2eq ha^{-1})	122 a	94 a	98 a	900 a	693 a	1,007 a	1,022 a	787 a	1,105 a
pGWP (kg CO_2eq ha^{-1})	8,221 b	13,761 a	10,294 b	1,007 a	1,484 a	1,740 a	9,228 b	15,245 a	12,034 ab
Rice yield (kg ha^{-1})	9,851 b	10,438 ab	11,484 a	-	-	-	-	-	-
YpGWP (kg CO_2eq kg^{-1} rice)	0.84	1.34	0.92	-	-	-	-	-	-

(1) Annual average values from three rice seasons and two non-rice seasons. Different letters in a row for each period (rice season, non-rice season, or annual) indicate differences between treatments by Tukey's test at $p<0.1$. - : not determined.

under very high crop management in the two seasons that this variable was evaluated (Figure 4). The lower crop development may result in lower allocation of C to the root system, with a negative impact on methanogenic activity, as discussed previously. However, it is not clear why rice development decreased under very high management compared to high crop management.

An additional factor that may be related to the lower CH_4 emissions under very high management compared to high crop management is the higher amount of inorganic N fertilizer applied. Although controversial, recent field studies (Dong et al., 2011; Liang et al., 2013) and extensive literature reviews (Xie et al., 2010; Linquist et al., 2012b) have found that an increased inorganic N rate (especially one from ammonium-based fertilizers or amide forms) can help mitigate CH_4 emissions through CH_4 oxidation by methanotrophic microorganisms. However, the potential effect of urea application on CH_4 fluxes was not evident in the subsequent days after fertilizer application in our study nor in previous studies carried out in this same region (Bayer et al., 2014, 2015). So, this specific issue should be addressed in future studies.

The similarity of N_2O emissions among management levels suggests that increasing N input by fertilization (base and topdressed) had no effect on soil N_2O emissions (Tables 2 and 3) in any of the periods studied (rice and non-rice season, and annual results). The average of cumulative N_2O emissions for the three rice seasons were 0.41, 0.32, and 0.33 kg ha^{-1} at the medium, high, and very high crop management levels, respectively (Table 3). Our results are consistent with those of Zou et al. (2007) and Liu et al. (2010), who found no relationship between N_2O emissions and N fertilizer applied during flooded rice cultivation - not even under increased amounts of N. The negative emission values obtained in the 2009/2010 season (-0.16 to -0.32 kg ha^{-1}) indicate that the soil acted as a sink for atmospheric N_2O. However, this N_2O influx may have resulted from the fact that gas measurements during that crop season were carried out only after flooding. Therefore, as in the other crop seasons, N_2O emissions peaked after the 4-week period between seeding and flooding, when the soil was dry or alternatively dry and moist because of rainfall events (Figures 1 and 2).

Annual GHG emissions, calculated as a combination of the results for the rice and non-rice season, highlighted the importance of expanding studies beyond the rice season. Thus, cumulative soil CH_4 emissions for the annual period ranged from 290.3 to 677.2 kg ha^{-1} yr^{-1}, the non-rice season accounting for 0.1-19 % (Table 3). By contrast, cumulative soil N_2O emissions ranged from 0.57 to 6.14 kg ha^{-1} yr^{-1}, the non-rice season accounting for over 90 % (Table 3). In a study conducted in California (USA) to evaluate the effect of applying different amounts of N during rice farming on CH_4 and N_2O emissions, Pittelkow et al. (2013) found the non-rice season accounted for 16-30 % of the annual CH_4 emissions and 22-79 % of the annual N_2O emissions, and stressed the importance of GHG measurements beyond the rice season.

Partial global warming potential (pGWP), rice yield, and yield-scaled pGWP

Averaged across rice seasons, the high management level resulted in the highest pGWP value: 13,761 kg CO_2eq ha^{-1}, which is 67 and 34 % higher than the value for the medium and very high crop management levels, respectively ($p<0.01$, Tables 2 and 3). Methane emissions during the rice season accounted for more than 98 % of the annual pGWP, which is consistent with previous results of Bayer et al. (2014) for the same soil and climate conditions.

The average annual pGWP was 12,084 kg CO_2eq ha^{-1} yr^{-1} and largely (>90 %) the result of CH_4 emissions in the rice season - which accounted for more than 80 % of the annual figure. The average pGWP for the non-rice season was 1,410 kg CO_2eq ha^{-1} and, unlike the rice season, it consisted mainly of soil N_2O emissions (≈65 %). Maintaining the soil drained during the non-rice season provided better conditions for N_2O production by nitrification and denitrification but attenuated CH_4 production owing to the anaerobic character of methanogenic microorganisms (Reddy and DeLaune, 2008; Xu and Hosen, 2010).

Our results suggest that strategies to mitigate GHG emissions from Southern Brazilian rice fields are more effective if measures are taken in the rice season, and also that the focus should be placed on CH_4 emissions. In fact, GHG emissions, in CO_2eq, were almost 10 times lower in the non-rice season than in the rice season; however, if measures are also implemented in the fall-winter non-rice season, mitigation of emissions requires shifting the focus to N_2O.

Rice grain yields increased significantly ($p<0.01$) along with increasing management levels, from an average value for the three crop seasons of 9,851 kg ha^{-1} at the medium level to 11,484 kg ha^{-1} at the very high level (Tables 2 and 3). These results are consistent with those obtained by Mariot et al. (2009) in a similar study at the same experimental

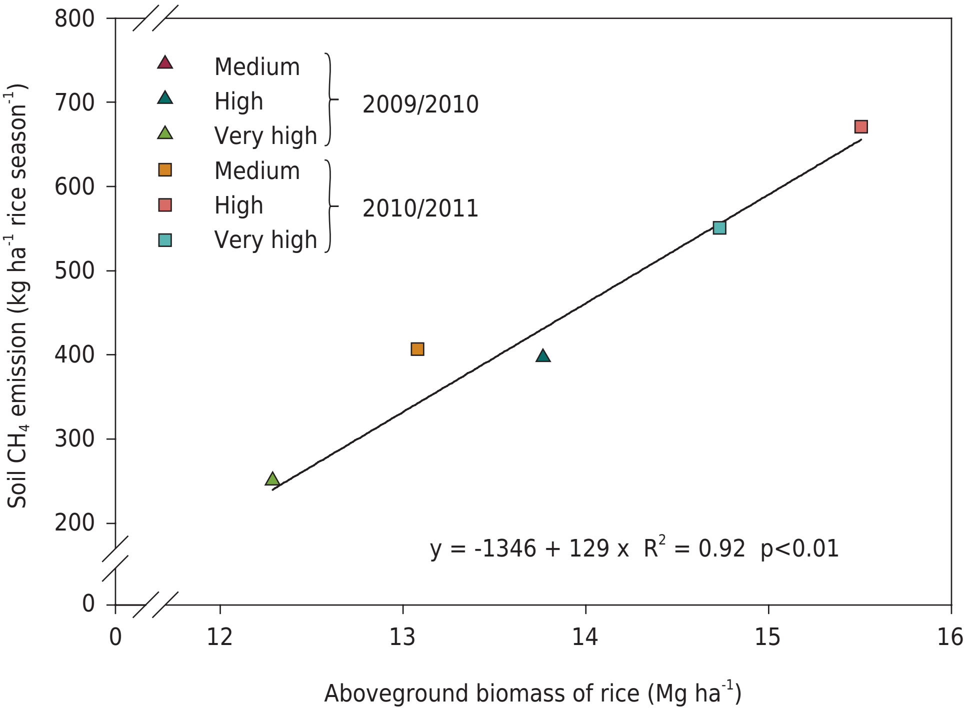

Figure 4. Relationship between aboveground rice biomass (R_4 stage) and CH_4 emissions during the rice season at different crop management levels in southern Brazil.

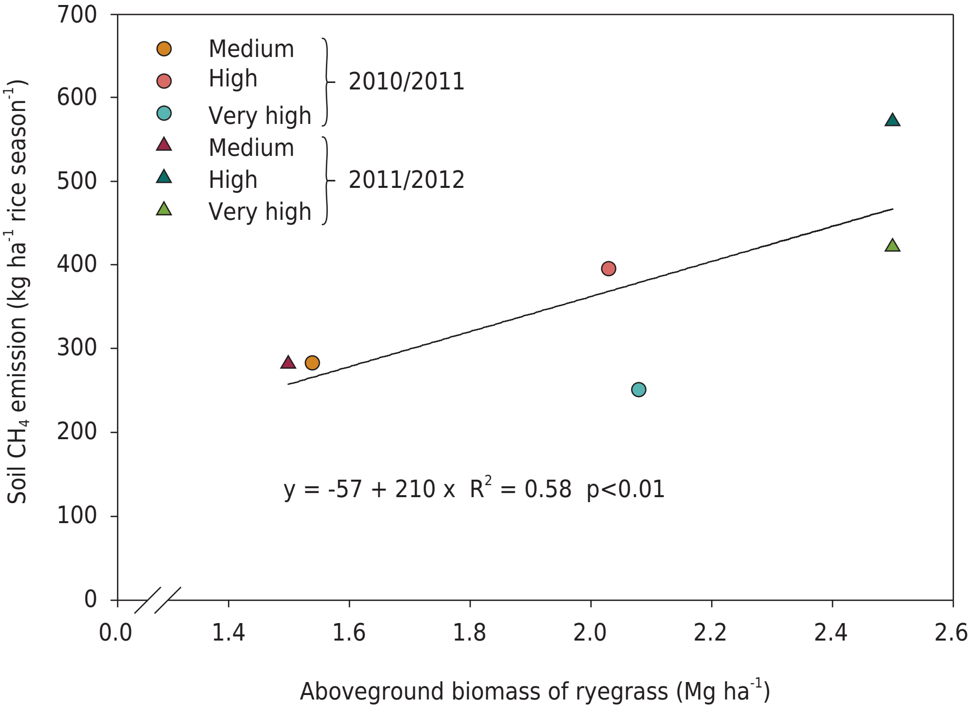

Figure 5. Relationship between aboveground ryegrass biomass in the previous winter (non-rice season) and cumulative soil CH_4 emissions during the subsequent rice season in southern Brazil.

site, in which they found that increasing the crop management level increased rice yield by 65 % and increased profits.

Yield-scaled pGWP (YpGWP) was significantly higher ($p<0.1$, Tables 2 and 3) at the high crop management level in two of the three crop seasons (Table 3). The YpGWP at the medium and very high crop management levels was similar in the three crop seasons (0.71-1.09 and 0.52-1.36 kg CO_2eq kg^{-1} rice, respectively). The effect on rice yield of increasing the crop management level from medium to high was less pronounced than the effect on soil GHG emissions, resulting in an increase of 60 % in YpGWP. Thus, due to this larger impact on GHG emissions than on crop yields, a future increase in rice yield as a result of adoption of improved crop management levels, along with no negative impact on GHG emissions in the regional production systems, may require adopting other additional agricultural practices that have a mitigating effect on GHG emissions, such as intermittent irrigation.

CONCLUSIONS

Partial global warming potential (CO_2eq) resulting from CH_4 and N_2O emissions in flooded rice in Southern Brazil is approximately 10 times higher in the rice season (spring/summer) than in the non-rice season (fall/winter). Since CH_4 emissions account for more than 90 % of pGWP, strategies for mitigating GHG from this production system should focus mainly on the rice season and, specifically, on CH_4 emissions.

Although GHG emissions may not be associated with specific agricultural practices or inputs, CH_4 emissions were related to aboveground biomass of rice and winter ryegrass, probably as a result of the supply of labile C to methanogens by exudation from rice roots or decomposition of ryegrass straw from the previous winter.

Improvement in the crop management level resulted, in general, in a larger increase in GHG emissions than in rice yield. Therefore, in order to avoid an associated rise in GHG emissions, future increases in rice yield through elevating crop management levels may require adoption of other additional agricultural practices to mitigate this effect, such as intermittent irrigation systems, in rice production systems in southern Brazil.

ACKOWLEDGMENTS

This project was funded by the Brazilian Council for Scientific and Technological Development (CNPq) and the Foundation for Research Support of the State of Rio Grande do Sul (Fapergs). The authors thank the staff at IRGA, whose help and support were essential, and the Coordination for the Improvement of Higher Education Personnel (Capes) for awarding postdoctoral scholarships to D. C. dos Santos, C. M. da Rosa, C. E. S. dos Reis, G. M. Pedroso, and E. S. Camargo.

REFERENCES

Aulakh MS, Wassmann R, Bueno C, Rennenberg H. Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. Plant Soil. 2001;230:77-86. https://doi.org/10.1023/A:1004817212321

Bayer C, Costa FS, Pedroso GM, Zschornack T, Camargo ES, Lima MA, Frigheto RTS, Gomes J, Marcolin E, Macedo VRM. Yield-scaled greenhouse gas emissions from flood irrigated rice under long-term conventional tillage and no-till systems in a Humid Subtropical climate. Field Crop Res. 2014;162:60-9. https://doi.org/10.1016/j.fcr.2014.03.015

Bayer C, Zschornack T, Pedroso GM, Rosa CM, Camargo ES, Boeni M, Marcolin E, Reis CES, Santos DC. A seven-year study on the effects of fall soil tillage on yield-scaled greenhouse gas emission from flood irrigated rice in a humid subtropical climate. Soil Till Res. 2015;145:118-25. https://doi.org/10.1016/j.still.2014.09.001

Costa FS, Bayer C, Lima MA, Frighetto RTS, Macedo VRM, Marcolin E. Variação diária da emissão de metano em solo cultivado com arroz irrigado no Sul do Brasil. Cienc Rural. 2008;38:2049-53. https://doi.org/10.1590/S0103-84782008000700041

Companhia Nacional de Abastecimento - Conab. Acompanhamento da safra brasileira: Grãos: Safra 2014/15 [internet]. Brasília, DF: 2015 [acesso em 18 de nov de 2015]. Disponível em: http://www.conab.gov.br/OlalaCMS/uploads/arquivos/15_08_18_10_30_18_boletim_graos_agosto_2015.pdf.

Counce PA, Keisling TC, Mitchell AJ. A uniform, objective, and adaptive system for expressing rice development. Crop Sci. 2000;40:436-43. https://doi.org/10.2135/cropsci2000.402436x

Das K, Baruah KK. A comparison of growth and photosynthetic characteristics of two improved rice cultivars on methane emission from rainfed agroecosystem of northeast India. Agr Ecosyst Environ. 2008;124:105-13. https://doi.org/10.1016/j.agee.2007.09.007

Dong H, Yao Z, Zheng X, Mei B, Xie B, Wang R, Deng J, Cui F, Zhu J. Effect of ammonium-based, non-sulfate fertilizers on CH_4 emissions from a paddy field with a typical Chinese water management regime. Atmos Environ. 2011;45:1095-101. https://doi.org/10.1016/j.atmosenv.2010.11.039

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Dorland R. Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Climate Change 2007: the physical science basis. Cambridge: Cambridge University Press; 2007. p. 129-234.

Gogoi N, Baruah KK, Gogoi B, Gupta PK. Methane emission characteristics and its relations with plant and soil parameters under irrigated rice ecosystem of northeast India. Chemosphere. 2005;59:1677-84. https://doi.org/10.1016/j.chemosphere.2004.11.047

Haque MM, Kim SY, Ali MA, Kim PJ. Contribution of greenhouse gas emissions during cropping and fallow seasons on total global warming potential in mono-rice paddy soils. Plant Soil. 2015;387:251-64. https://doi.org/10.1007/s11104-014-2287-2

Instituto Rio Grandense do Arroz - IRGA. Censo da lavoura de arroz irrigado do Rio Grande do Sul – Safra 2004/05 [internet]. Porto Alegre: IRGA - Política Setoria; 2006 [acesso em 25 de nov de 2014]. Disponível em: http://www3.irga.rs.gov.br/uploads/anexos/1292592973censodg3.pdf.

Johnson-Beebout SE, Angeles OR, Alberto MCR, Buresh RJ. Simultaneous minimization of nitrous oxide and methane emission from rice paddy soils is improbable due to redox potential changes with depth in a greenhouse experiment without plants. Geoderma. 2009;149:45-53. https://doi.org/10.1016/j.geoderma.2008.11.012

Kim SY, Lee CH, Gutierrez J, Kim PJ. Contribution of winter cover crop amendments on global warming potential in rice paddy soil during cultivation. Plant Soil. 2013;366:273-86. https://doi.org/10.1007/s11104-012-1403-4

Le Mer J, Roger P. Production, oxidation, emission and consumption of methane by soils: a review. Eur J Soil Biol. 2001;37:25-50. https://doi.org/10.1016/S1164-5563(01)01067-6

Liang XQ, Li H, Wang SX, Ye YS, Ji YJ, Tian GM, Kessel C, Linquist BA. Nitrogen management to reduce yield- scaled global warming potential in rice. Field Crop Res. 2013;146:66-74. https://doi.org/10.1016/j.fcr.2013.03.002

Linquist B, Groenigen KJ, Adviento-Borbe MA, Pittelkow C, Kessel C. An agronomic assessment of greenhouse gas emissions from major cereal crops. Glob Change Biol. 2012a;18:194-209. https://doi.org/10.1111/j.1365-2486.2011.02502.x

Linquist BA, Adviento-Borbe MA, Pittelkow CM, Kessel C, Groenigen KJ. Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. Field Crop Res. 2012b;135:10-21. https://doi.org/10.1016/j.fcr.2012.06.007

Liu S, Qin Y, Zou J, Liu Q. Effects of water regime during rice-growing season on annual direct N_2O emission in a paddy rice-winter wheat rotation system in a southeast China. Sci Total Environ. 2010;408:906-13. https://doi.org/10.1016/j.scitotenv.2009.11.002

Lu Y, Wassmann R, Neue H-U, Huang C. Dynamics of dissolved organic carbon and methane emissions in a flooded rice soil. Soil Sci Soc Am J. 2000;64:2011-17. https://doi.org/10.2136/sssaj2000.6462011x

Mariot CHP, Vieira VM, Silva PRF, Menezes VG, Oliveira CF, Freitas TFS. Práticas de manejo integradas para a produção de arroz irrigado. Pesq Agropec Bras. 2009;44:243-50. https://doi.org/10.1590/S0100-204X2009000300004

Menezes VG, Anghinoni I, Silva PRF, Macedo VRM, Petry C, Grohs DS, Freitas TFS, Valente LAL. Projeto 10 - Management strategies to increase productivity and sustainability of irrigated rice growth in the state of Rio Grande do Sul, Brazil: developments and new challenges. Porto Alegre: Companhia Rio Grandense de Artes Gráficas; 2013.

Moterle DF, Silva LS, Moro VJ, Bayer C, Zschornack T, Avila LA, Bundt AC. Methane efflux in rice paddy field under different irrigation managements. Rev Bras Cienc Solo. 2013;37:431-7. https://doi.org/10.1590/S0100-06832013000200014

Nouchi I, Mariko S, Aoki K. Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants. Plant Physiol. 1990;94:59-66. https://doi.org/10.1104/pp.94.1.59

Pimentel LG, Weiler DA, Pedroso GM, Bayer C. Soil N_2O emissions following cover-crop residues application under two soil moisture conditions. J Plant Nutr Soil Sci. 2015;178:631-40. https://doi.org/10.1002/jpln.201400392

Pittelkow CM, Adviento-Borbe MA, Hill JE, Six J, Kessel C, Linquist BA. Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. Agr Ecosyst Environ. 2013;177:10-20. https://doi.org/10.1016/j.agee.2013.05.011

Reddy KR, DeLaune RD. Biogeochemistry of wetlands: science and applications. Boca Raton: CRC Press; 2008.

Silva LS, Griebeler G, Moterle DF, Bayer C, Zschornack T, Pocojeski E. Dinâmica da emissão de metano em solos sob cultivo de arroz irrigado no sul do Brasil. Rev Bras Cienc Solo. 2011;35:473-81. https://doi.org/10.1590/S0100-06832011000200016

Sociedade Sul-Brasileira de Arroz Irrigado - Sosbai. Arroz irrigado: recomendações técnicas da pesquisa para o Sul do Brasil. Bento Gonçalves: Comissão técnica do arroz irrigado; 2014. (Boletim técnico).

Xie B, Zheng X, Zhou Z, Gu J, Zhu B, Chen X, Shi Y, Wang Y, Zhao Z, Liu C, Yao Z, Zhu J. Effects of nitrogen fertilizer on CH_4 emission from rice fields: multi-site field observations. Plant Soil. 2010;326:393-401. https://doi.org/10.1007/s11104-009-0020-3

Xu H, Hosen Y. Effects of soil water content and rice straw incorporation in the fallow season on CH_4 emissions during fallow and the following rice-cropping seasons. Plant Soil. 2010;335:373-83. https://doi.org/10.1007/s11104-010-0426-y

Yagi K, Tsuruta H, Kanda K-i, Minami K. Effect of water management on methane emission from a Japanese rice paddy field: automated methane monitoring. Global Biogeochem Cy. 1996;10:255-67. https://doi.org/10.1029/96GB00517

Zhang X, Yin S, Li Y, Zhuang H, Li C, Liu C. Comparison of greenhouse gas emissions from rice paddy fields under different nitrogen fertilization loads in Chongming Island, Eastern China. Sci Total Environ. 2014;472:381-8. https://doi.org/10.1016/j.scitotenv.2013.11.014

Zou J, Huang Y, Zheng X, Wang Y. Quantifying direct N_2O emissions in paddy fields during rice growing season in mainland China: dependence on water regime. Atmos Environ. 2007;41:8030-42. https://doi.org/10.1016/j.atmosenv.2007.06.049