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MITIGATION OF METHANE AND NITROUS OXIDE EMISSIONS FROM FLOOD-IRRIGATED RICE BY NO INCORPORATION OF WINTER CROP RESIDUES INTO THE SOIL⁽¹⁾

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SUMMARY

Winter cover crops are sources of C and N in flooded rice production systems, but very little is known about the effect of crop residue management and quality on soil methane (CH₄) and nitrous oxide (N₂O) emissions. This study was conducted in pots in a greenhouse to evaluate the influence of crop residue management (incorporated into the soil or left on the soil surface) and the type of cover-crop residues (ryegrass and serradella) on CH₄ and N₂O emissions from a flooded Albaqualf soil cultivated with rice (*Oryza sativa* L.). The closed chamber technique was used for air sampling and the CH₄ and N₂O concentrations were analyzed by gas chromatography. Soil solution was sampled at two soil depths (2 and 20 cm), simultaneously to air sampling, and the contents of dissolved organic C (DOC), NO₃⁻, NH₄⁺, Mn²⁺, and Fe²⁺ were analyzed. Methane and N₂O emissions from the soil where crop residues had been left on the surface were lower than from soil with incorporated residues. The type of crop residue had no effect on the CH₄ emissions, while higher N₂O emissions were observed from serradella (leguminous) than from ryegrass, but only when the residues were left on the soil surface. The more intense soil reduction verified in the deeper soil layer (20 cm), as evidenced by higher contents of reduced metal species (Mn²⁺ and Fe²⁺), and the close relationship between CH₄ emission and the DOC contents in the deeper layer indicated that the sub-surface layer was the main CH₄ source of the flooded soil with incorporated crop residues. The adoption of management strategies in which crop residues are left on the soil surface is crucial to minimize soil CH₄ and N₂O emissions from irrigated rice fields. In these production systems, CH₄ accounts

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for more than 90 % of the partial global warming potential ($\text{CH}_4 + \text{N}_2\text{O}$) and, thus, should be the main focus of research.

Index terms: greenhouse gases, flooded rice, soil management.

RESUMO: *MITIGAÇÃO DAS EMISSÕES DE METANO E DE ÓXIDO NITROSO EM PLANOSSOLO SOB CULTIVO DE ARROZ PELA MANUTENÇÃO DOS RESÍDUOS DE PLANTAS DE COBERTURA EM SUPERFÍCIE*

Plantas de cobertura de inverno são fontes de C e de N em sistemas de produção de arroz irrigado, mas pouco se conhece sobre o efeito do manejo e da qualidade dos seus resíduos culturais nas emissões de metano (CH_4) e de óxido nitroso (N_2O) do solo. O estudo consistiu de um experimento conduzido em casa de vegetação e teve como objetivo principal avaliar a influência do manejo (incorporado ou em superfície) e do tipo de resíduos culturais (azevém e serradela) de plantas de cobertura sobre as emissões de CH_4 e de N_2O de um Planossolo Háplico sob cultivo de arroz irrigado por inundação. Utilizou-se o método da câmara fechada, e as concentrações de CH_4 e de N_2O nas amostras de ar foram determinadas por cromatografia gasosa. Coletas da solução do solo em duas profundidades (2 e 20 cm) foram realizadas simultaneamente às coletas de ar. A manutenção dos resíduos culturais na superfície do solo resultou em menor emissão de CH_4 e de N_2O em comparação à sua incorporação. O tipo de resíduo cultural não teve efeito na emissão de CH_4 , enquanto para o N_2O a distinção entre os resíduos ocorreu apenas quando estes foram mantidos na superfície do solo – condição na qual as maiores emissões ocorreram com a adição dos resíduos da leguminosa (serradela). O processo mais intenso de redução do solo em subsuperfície (20 cm), evidenciado pelos maiores teores de íons reduzidos (Mn^{2+} e Fe^{2+}), e a estreita relação entre a emissão de CH_4 e os teores de C orgânico dissolvido nessa profundidade indicam que a camada subsuperficial foi a principal fonte de CH_4 quando da incorporação dos resíduos culturais. A adoção de estratégias de manejo que promovam a manutenção dos resíduos culturais na superfície do solo é fundamental quando se visa à mitigação das emissões de CH_4 e N_2O em solos sob cultivo de arroz irrigado. O CH_4 compõe mais de 90 % do potencial de aquecimento global parcial ($\text{CH}_4 + \text{N}_2\text{O}$) nesses sistemas de produção e, portanto, deve ser o foco principal da pesquisa.

Termos de indexação: gases de efeito estufa, arroz irrigado, manejo de solo.

INTRODUCTION

The mitigation of greenhouse gases (GHG) emissions from agricultural soil, which is estimated at about 20% in the world and 80% in Brazil (Cerri et al., 2009), is fundamental to decrease the contribution of agriculture and land use changes to global warming, which is estimated at about 20 % in the world and 80 % in Brazil (Cerri et al., 2009). Particularly, methane (CH_4) is a major issue in flooded rice (*Oryza sativa* L.) fields, where this source accounts for 10–40 % of the global CH_4 emissions (Le Mer & Roger, 2001; Dalal et al., 2008). In Brazil, the contribution from paddy rice fields to CH_4 emissions is lower, with about 3 % of the total CH_4 emission only (MCT, 2006). However, in the South, the region of the majority of paddy rice fields in Brazil, flooded rice fields contribute to 12 % of the total CH_4 emissions and this relative contribution increases to 18 % in Rio Grande do Sul State, the largest rice producer in Brazil, where summer rice is grown on more than 1.1 million hectare (CONAB, 2010).

In flood-irrigated rice fields, anaerobic soil conditions lead to CH_4 generation as the final product of organic compost decomposition by methanogenic bacteria (Dalal et al., 2008). Several factors inherent to soil (Wang et al., 1999, Setyanto et al., 2002) and climate (Schütz et al., 1990; Yang & Chang, 1998) affect CH_4 emissions to the atmosphere. Understanding the effects and interactions of soil and irrigation management practices under different conditions is crucial for developing effective strategies of CH_4 emission minimization (Stepniewski & Stepniewska, 2009).

At the international level, the effect of irrigation management on CH_4 emissions has been emphasized, since single or multiple drainages during a rice growing season can reduce net emissions by 17–64 %, in comparison to continuously flooded systems (Minamikawa & Sakai, 2005). In the South of Brazil however, the drainage of flooded rice fields should be absolutely avoided, in view of the environmental risk of water contamination with nutrients (Marchezan et al., 2007) and pesticides (Marchesan et al., 2007;

Silva et al., 2009), significant increases in the volume of irrigation water and higher energy costs due for reflooding (Macedo et al., 2007). This management practice would jeopardize the environmental and economic sustainability. In addition, rice field drainage can on the one hand decrease CH_4 but on the other increase nitrous oxide (N_2O) emissions (Xiong et al., 2007; Johnson-Beebout et al., 2009), diminishing the benefits of drainage for the net global warming potential.

The residue quality and management of the crop preceding rice also deserve attention, as these residues constitute an important source of labile C, which stimulates soil microbial activity and usually intensifies soil CH_4 emissions (Cochran et al., 1997). In Rio Grande do Sul State, ryegrass (*Lolium multiflorum* Lam.) is a grass plant cultivated in large lowland areas during the winter, serving as pasture in this period. The cultivation of winter legume species for forage, such as birdsfoot trefoil (*Lotus corniculatus*), clover (*Trifolium* spp.) and native serradella [*Ornithopus micranthus* (Benth.) Arechavaleta] is still modest, but has been promoted as protein source in integrated rice-pasture systems (Scivittaro et al., 2002; Reis & Saibro, 2004). Therefore, for the development of regional rice production systems with low CH_4 emission, the assessment of the quality and management effect of winter crop residues on the fluxes of this gas is essential.

The quality and management of winter crop residues can also affect soil N_2O emissions by modifying soil NH_4^+ and NO_3^- contents, which in turn are substrate for nitrification and denitrification, respectively. These are the main processes related to the N_2O generation in soil (Khalil et al., 2004). Consequently, legume species could exacerbate N_2O emissions from flooded rice production systems (Aulakh et al., 2001; Kaewpradit et al., 2008), but there is little evidence regarding the effect of different residue management systems on the emission of these greenhouse gases (Shan et al., 2008; Kaewpradit et al., 2008).

This greenhouse study aimed to evaluate (i) the influence of crop residues (legume and grass species) and their management (incorporated into the soil or left on the soil surface) on CH_4 and N_2O emissions from an Albaqualf soil under flooded rice, (ii) their influence on soil reduction and interaction with the soil CH_4 and N_2O emission, and (iii) the contribution of these gases to the partial global warming potential, in equivalent CO_2 , taking their respective warming potentials into account.

MATERIAL AND METHODS

Experiment

The study was carried out in a greenhouse of the Soil Science Department of the Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, RS, Brazil,

from October 2007 to January 2008. The treatments consisted of two crop residue managements (incorporated into the soil or left on the surface) using residues of ryegrass (grass) and of serradella (legume), both winter cover crop species. The treatments were arranged in a completely randomized design, with three replications.

The soil was classified as Albaqualf (US Soil Taxonomy) or Planossolo Háplico eutrófico arênico, according to Brazilian Soil Classification System (Embrapa, 2006). Soil was collected from the Experimental Field of Rice Research of the Instituto Rio Grandense do Arroz (EEA/IRGA), close to Cachoeirinha, State of RS, in the 0–20 cm layer. Soil analysis determined the following chemical and physical properties: 210 g kg^{-1} clay; 31 g kg^{-1} organic matter; 18 mg dm^{-3} P (Mehlich-1); 38 mg dm^{-3} K (Mehlich-1); 0.9 and 0.3 $\text{cmol}_c \text{ dm}^{-3}$ exchangeable Ca and Mg (KCl 1.0 mol L^{-1}), respectively; $\text{CEC}_{\text{pH } 7} = 11 \text{ cmol}_c \text{ dm}^{-3}$ and $\text{pH}_{\text{water}} = 4.4$. The soil was previously sieved (10 mm) and filled into PVC pots (22 L), forming a 20 cm layer (about 12 kg). Crop residues were dried (60 °C), chopped (50 mm) and applied to the soil in each pot at quantities equivalent to 7.5 Mg ha^{-1} . After crop residue addition, the soil moisture was maintained near field capacity for 25 days.

Rice seedlings (cv IRGA 417) were transplanted to the pots after emergence and primary root emission, at about 30 °C in water. Ten seedlings were initially planted in each pot, in a circle. At the stage of the third leaf emission, uniform seedlings were selected and only five plants were maintained in each pot. Then the soil was flooded with a water layer of 10 cm that was maintained until the end of the study. Soil fertilization consisted of the application of 960 and 1,440 mg/pot of K_2O and P_2O_5 , respectively, with potassium chloride and triple superphosphate before transplanting. At planting, 240 mg N and 180 mg sulfur were applied per plot, using urea and ammonium sulphate. When the rice plants had three to four leaves, 1,200 mg N and 720 mg K_2O were applied per plot, as urea and potassium chloride, respectively. The fertilizer quantities in this study were calculated for an optimum rice development, estimated based on a previous study using the same soil (Fraga et al., 2010).

Air sampling and gas analysis

PVC cylinders (height 45 cm, diameter 25 cm) were used as pots, by closing the bottom with a PVC cap, while a drain channel (depth 20 mm) was fixed at the top. On this channel, a closed chamber was placed for each air sampling. The system was hermetically closed by water in the channel (Gomes et al., 2009) (Figure 1).

The PVC chambers, with the same diameter as the pots and a height of 60 cm, were equipped with three-way valves coupled to the syringes for air

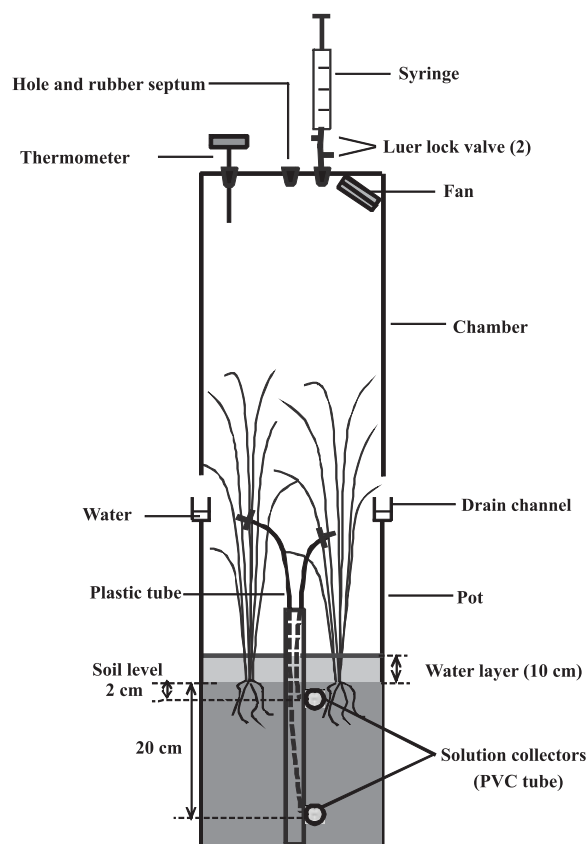


Figure 1. Closed chamber for air sampling and soil solution collectors.

sampling, with digital thermometers to monitor the inner chamber temperature, and a hole (diameter 10 mm) to equilibrate the internal pressure of the system when closed by a rubber septum for air sampling. On the inside, a 12 V fan was installed, which was turned on 30 s before each air sampling to homogenize the inner atmosphere of the chambers.

The CH_4 and N_2O emissions were analyzed in two sampling events before soil flooding (8 and 1 days before flooding) and in seven sampling events after that (1, 6, 13, 20, 28, 58, and 86 days after flooding-DAF). Air was sampled within the chambers by polypropylene syringes (20 mL) with valves at 5, 10, 15 and 20 min after closing the chamber. Further details related to the sampling procedure were described by Gomes et al. (2009).

The syringes containing the air samples were stored in a cooling box, maintained at low temperature and taken to the Environmental Biogeochemical Laboratory of UFRGS, where they were analyzed by gas chromatography within no more than 24 h after sampling. The chromatograph (Shimadzu GC 2014 “Greenhouse”) was equipped with three packed columns at 70 °C, N_2 as carrier gas at a flow of 26 mL min^{-1} , an injector with 1 mL sample loop for

direct injection at 250 °C, an electron capture detector (ECD) at 325 °C for N_2O detection and flame ionization detector (FID) at 250 °C for CH_4 .

The N_2O and CH_4 fluxes were calculated based on the following equation:

$$f = \frac{\Delta Q}{\Delta t} \frac{PV}{RT} \frac{1}{A}$$

where f is the nitrous oxide or methane flux ($\mu\text{g m}^{-2} \text{h}^{-1}$ N_2O or CH_4), Q is the gas quantity ($\mu\text{g N}_2\text{O}$ or CH_4) in the chamber at sampling, P is the atmospheric pressure (atm) in the inner chamber - assumed as 1 atm, V is the chamber volume (L), R is the constant for ideal gases (0.08205 atm L $\text{mol}^{-1} \text{K}^{-1}$), T is the temperature within the chamber at sampling (K) and A is the basal area of the chamber (m^2). Increase rates of the gas concentration within the chamber were estimated by the angular coefficient of the linear regression adjusted by the ratio between time and gas concentrations. From the rates of CH_4 and N_2O fluxes, daily emissions were estimated and emission for the total period (90 days) was calculated by integrating the daily emissions (Gomes et al., 2009). Based on the accumulated CH_4 and N_2O emissions and taking into account the global warming potential of each gas in comparison to carbon dioxide – CO_2 (25 times for CH_4 and 298 times for N_2O ; Forster et al., 2007), the emissions were calculated in equivalent CO_2 and the sum was called “partial Global Warming Potential” (partialGWP).

Soil solution sampling and analysis

The soil solution was sampled simultaneously to the air. Individual collectors were placed in each pot at a soil depth of 2 and 20 cm (Figure 1). Collectors consisted of PVC cylinders (diameter 25 mm, length 50 mm), both ends covered by a nylon mesh of 0.1 mm pore size. The two collectors of each pot were horizontally fixed to another PVC tube (diameter 25 mm, length 40 mm), in order to maintain them at the desired depth of 2 and 20 cm. In the center of the cylinder, a plastic tube was connected to the collectors at each depth and extended to about 30 cm above the soil surface. The upper end was closed by a valve to prevent oxygen diffusion.

The soil solution was sampled 1, 6, 13, 20, and 28 DAF, by suction using syringes (60 mL) equipped with three-way valves, coupled to the upper end of the plastic tubes. Solution samples were immediately filtered through regenerated cellulose (pore diameter 0.45 μm) to determine dissolved organic C (DOC) in a Shimadzu – TOC VCSH analyzer. Twenty mL of each solution sample was frozen at about -5 °C for subsequent analysis of NH_4^+ and NO_3^- concentration by distillation, while 10 mL were stored in a refrigerator at 1–2 °C after adding 1 mL HCl 2 mol L^{-1}

for Fe^{2+} and Mn^{2+} determination by atomic absorption spectrometry (Tedesco et al., 1995).

Statistical analysis

The CH_4 and N_2O total emissions were submitted to ANOVA and differences among means were evaluated by the Tukey test at 5 %. Relationship among soil solution variables and CH_4 and N_2O fluxes were evaluated by the statistical significance of linear and exponential coefficients, using SigmaPlot for Windows 11.0 (Systat Software, Inc.). When both models were significant, the one with the higher R^2 was chosen.

RESULTS AND DISCUSSION

Soil CH_4 emission

The variations in CH_4 soil emissions, after flooding, were similar in time but different in magnitude, according to the crop residue management (Figure 2a). The incorporation of ryegrass and serradella into the soil induced greater CH_4 emissions than residues left on the soil surface. However, there was no effect of the crop residue type (grass or legume) on CH_4 soil emissions (Figure 2a). Crop residue applications increased CH_4 production and emissions from the soil after flooding because the anaerobic decomposition of residues does not only provide substrate for methanogenesis, as labile organic C compounds, but also induces a reduction of the soil redox potential (Dalal et al., 2008).

The management of crop residues affected the beginning of emissions as well as the emission rates (Figure 2a). In soils with incorporated crop residues, CH_4 emissions were very low up to 6 DAF, increasing markedly thereafter and peaking in $353 \text{ mg m}^{-2} \text{ h}^{-1} \text{ CH}_4$ 28 DAF. In the soil with residue maintenance on the surface, in turn, CH_4 emissions were low up to 20 DAF and only thereafter the emission rates increased, although the values were consistently lower than from soils with incorporated residues. The maximum emission rate from the non-incorporated residue treatment was measured 58 DAF and its magnitude was about four times lower ($98 \text{ mg m}^{-2} \text{ h}^{-1} \text{ CH}_4$) than the highest rate in the residue-incorporated treatment (Figure 2a). The maintenance of crop residues on the surface diminishes the contact between residues and soil in comparison to incorporated residues, which presumably delays and decreases the intensity of anaerobic decomposition and soil reduction, reducing the CH_4 production/emission (Harada et al., 2007).

As a consequence of the anticipated emission and higher emission rates, greater accumulated emissions were observed from soils with incorporated crop residues than from soil with residues left on the surface

(mean of 356 and $111 \text{ g m}^{-2} \text{ CH}_4$, respectively; Figure 2b). However, the type of crop residue had no effect on total CH_4 emission for the period, as the mean values (incorporated and on surface) were 236 and $230 \text{ g m}^{-2} \text{ CH}_4$ for ryegrass and serradella, respectively (Figure 2b). The greater CH_4 emissions after crop residue incorporation in comparison to their maintenance on the surface contribute to the understanding of why CH_4 emissions from flooded no-tillage rice fields are lower than from conventional systems, as verified for a Gleysol in the South of Brazil (Costa, 2005). The results of this study clarify that crop residue incorporation by plowing and disking, typical for conventional tillage systems in the region, leads to an increase in soil CH_4 emissions, since labile C is added to subsurface soil layers, increasing the potential for soil reduction (lower Eh values) and, in

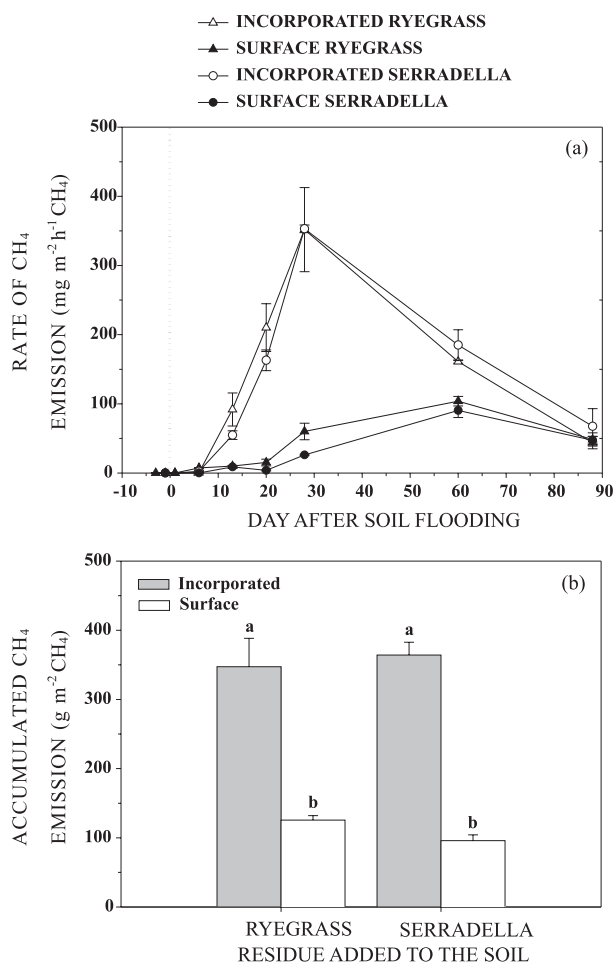


Figure 2. Emission rates (a) and accumulated emission (b) of CH_4 from a flooded Albaqualf cultivated with rice as affected by management (incorporation or maintenance on soil on the soil surface) of ryegrass and serradella residues. Vertical bars indicate standard deviation. Different letters on bars indicate statistical difference by Tukey's test at 5 %.

this condition, contribute effectively to CH_4 production. On the other hand, crop residues left on the soil surface in no tillage keep this C source in the top soil layer, where methanogenesis is limited by the presence of oxygen dissolved in the water (Conrad, 2002; Dalal et al., 2008).

The effect of crop residue management on the moment of beginning of CH_4 emissions was related to the different intensity of the soil reduction process when residues had been incorporated or left on the surface, which was evaluated in this study based on NO_3^- disappearance (reduction) and the increment of reduced species of Mn^{2+} and Fe^{2+} in the soil solution. Based on the changes in these ions, the reduction process was less intense in the surface layer (2 cm) than at 20 cm depth (Figure 3). At 20 cm, the reduction was intensified by crop residue incorporation into the soil, as labile C stimulated the anaerobic microorganisms to sequentially reduce NO_3^- to $\text{N}_2/\text{N}_2\text{O}$, Mn^{4+} to Mn^{2+} , and Fe^{3+} to Fe^{2+} (Figure 3d,e,f). The fast decrease of NO_3^- concentration indicates its use as the first alternative electron acceptor, followed by Mn^{4+} , but the high Mn^{2+} concentrations observed one (1) DAF evidence that this element was reduced concomitantly to NO_3^- . According to Huang et al. (2009), the NO_3^- contents in soil decrease markedly within less than 48 h after flooding, while the reduction of the other ions occurs subsequently to nitrate reduction.

The Fe^{3+} reduction is fundamental for CH_4 production (Ali et al., 2009; Huang et al. 2009) and, according to some studies, the methanogenesis process is only activated after the reduction of about 90 % of Fe^{3+} to Fe^{2+} (Setyanto et al., 2002) and organic compounds begin to be used as electron acceptors by anaerobic bacteria (Conrad, 2002). In this way, the CH_4 emission increased from 13 DAF onwards in the soil with incorporated residues, coinciding with an intense Fe^{3+} reduction to Fe^{2+} at 20 cm depth. At this time, more than 90 and 70 % of Fe^{3+} at 20 cm depth had already been reduced to Fe^{2+} in the treatments with incorporated ryegrass and serradella residues, respectively. On the other hand, the CH_4 emission from soil with residues on the surface began only 28 DAF, which is also coherent with the Fe^{3+} reduction to Fe^{2+} , 20 DAF (Figure 3f). Despite the coherence between CH_4 emissions and Fe^{3+} reduction, the results of this study suggest that CH_4 production set in before the complete reduction of Fe^{3+} to Fe^{2+} , which can be explained by the possible occurrence of anaerobic activity and CH_4 production at soil microsites, where the reduction process was faster than in the soil matrix (Conrad, 2002).

In general, the application and maintenance of crop residues on the soil surface resulted in greater DOC contents at 2 cm depth (Figure 4a), although the changes in their contents were not related to the CH_4 emission from the soil (Figure 4b). The incorporation of residues into the soil, in turn, led to increases in

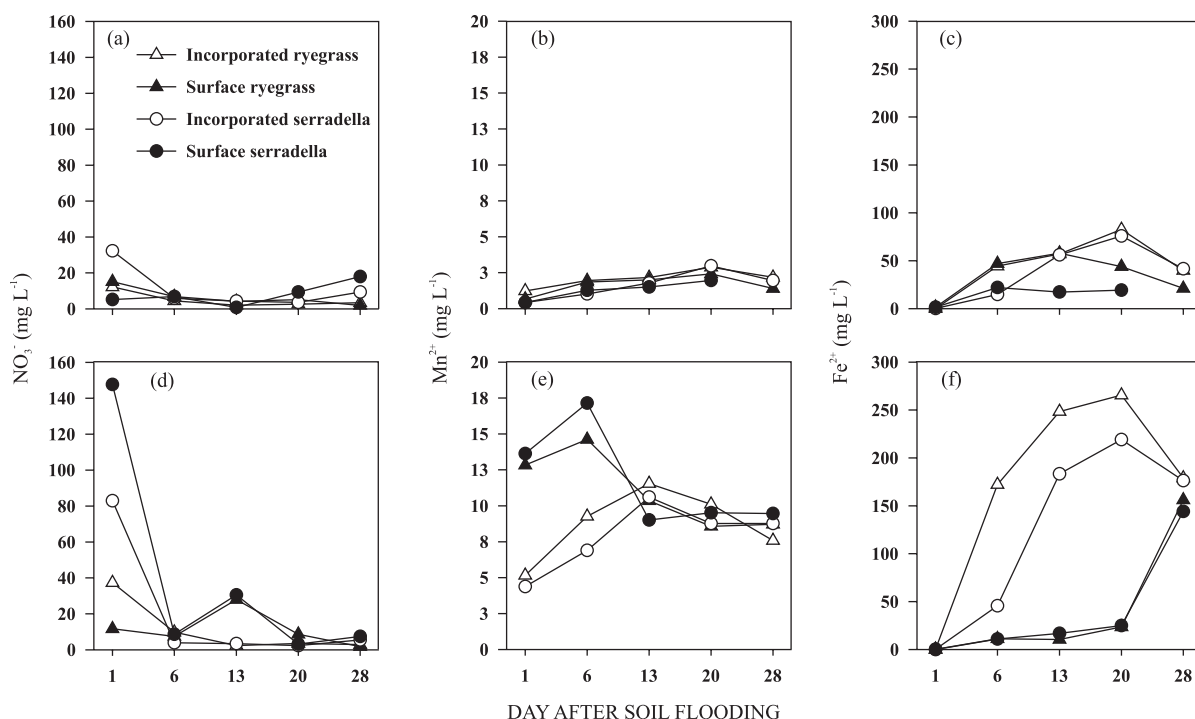


Figure 3. Concentration of nitrate (NO_3^-), manganese (Mn^{2+}) and iron (Fe^{2+}) in the solution of a flooded Albaqualf at depth of 2 (a, b, c,) and 20 cm (d, e, f) affected by the residue management (incorporated or left on the soil surface) of ryegrass and serradella.

DOC contents at 20 cm depth (Figure 4c), in an exponential relationship with soil CH_4 emissions ($R^2=0.90$; $p < 0.0001$) (Figure 4d). DOC is one of the major sources of labile C in flooded soils and is therefore strongly related with the CH_4 production (Lu et al., 2000).

The main CH_4 source, according to the results, was the subsurface soil layer, where the reduction process was more intense, as evidenced by the contents of NO_3^- , Mn^{2+} and Fe^{2+} in soil solution. This soil reduction condition is crucial for methanogenesis, which only occurs at Eh values below -150 mV (Minamikawa & Sakai, 2006; Stepniewski & Stepniewska, 2009). On the other hand, the occurrence of oxygen dissolved in the water of the surface soil layer due to the diffusion of O_2 by the aerenchyma of rice plants (Stepniewski & Stepniewska, 2009) possibly restricted methanogenesis in the surface soil layer, despite the availability of substrate (DOC) for this process.

Regarding the type of crop residue, a larger CH_4 emission rate could be expected from soils under legume crops than under grass, due to the faster decomposition rate mainly attributed to the lower C/N ratio and, therefore, greater labile C production for methanogenesis (Kaewpradit et al., 2008). A plausible explanation for the absence of difference between crop residue types in terms of CH_4 soil emissions is the interval of 25 days between the time of crop residue

application and transplanting of rice seedlings to the pots. The residue decomposition in this period, before the experiment, probably induced the great similarity of emissions between the two crop residues after flooding. However, it is noteworthy that the applied procedure is similar to the usually applied in rice fields, where the crop residue management (tillage in conventional systems or herbicide application in no-till) is performed in non-flooded soil conditions, then the rice is sown and flooded about 20 days after plant emergence (Macedo et al., 2007).

The increase in CH_4 emissions was exponential with increasing air temperature in the treatments with residue incorporation and applied to the surface (Figure 5), which can be due to both the increase in the soil methanogenic activity (van Hulzen et al., 1999) and the increase in the gas transport through the aerenchyma in the rice plants (Hosono & Nouchi, 1997). From the exponential equation coefficients, adjusted to air temperature and CH_4 emission rates, the value of the Q_{10} factor was estimated at 10 and 35, respectively, for the treatments with crop residues incorporated into the soil or left on the surface. These values represent a 10 and 35 fold increase in CH_4 emissions with an 10°C increase in the air temperature. The Q_{10} values estimated in this study are coherent with the range of 1.5 to 28 reported in literature for Q_{10} values for CH_4 production in flooded soils (Segers, 1998; Rath et al., 2002). On the other

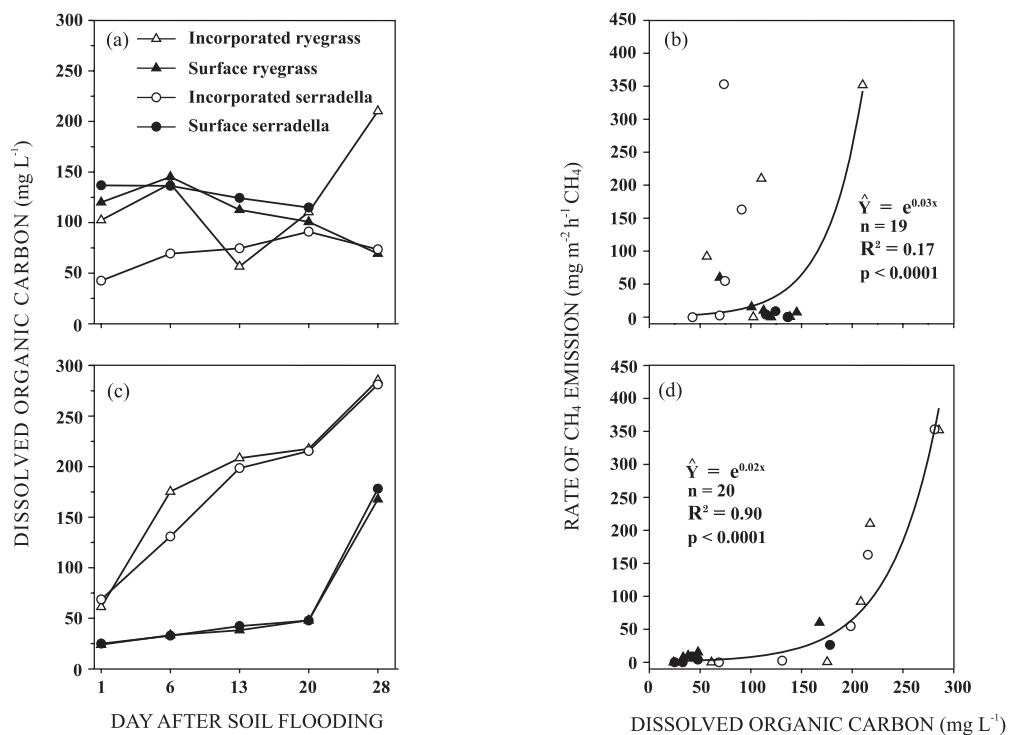


Figure 4. Concentration of dissolved organic carbon at depths of 2 and 20 cm (a and c, respectively) in a flooded Albaqualf under residue managements (incorporated or left on the soil surface) of ryegrass and serradella, and its relationship with CH_4 emission rates (b and d, respectively).

hand, the greater effect of air temperature on the CH_4 emissions from soil with crop residue on the surface ($Q_{10} = 35$) than from incorporated residue ($Q_{10} = 10$) is likely due to the greater influence of air temperature on the surface (2 cm) than the subsurface soil layer (20 cm). However, it is important to note that, at the same air temperature, the soil with incorporated residues emitted more CH_4 than soil with residues on the surface.

Because of the close relation between CH_4 emission and temperature, the magnitude of emissions verified in this study are probably consistently larger than those under field conditions, as the temperature in the pot experiment was markedly higher due to the warming of the greenhouse by the accumulation of solar energy and due the exposure of the pot walls. For these reasons, studies carried out in the field normally indicate maximum CH_4 emission rates of about $80 \text{ mg m}^{-2} \text{ h}^{-1}$ (Le Mer & Roger, 2001; Costa, 2005), while in this study the emission rates peaked near $350 \text{ mg m}^{-2} \text{ h}^{-1} \text{ CH}_4$, i.e., about four times the fluxes usually observed under field conditions.

Soil N_2O emission

In the soils with residues on the surface, the N_2O emission rates did not exceed $500 \mu\text{g m}^{-2} \text{ h}^{-1}$ in the entire experimental period (Figure 6a). From the residue-incorporated soils, in turn, N_2O emissions were low until 6 DAF, but emission peaks of up to $5,180 \mu\text{g m}^{-2} \text{ h}^{-1} \text{ N}_2\text{O}$ were observed 13 and 20 DAF. Afterwards, the emission rates decreased to values similar to those of soils with surface residue. Presumably, most of the N_2O emissions until 6 DAF was originated by denitrification of NO_3^- to N_2O , as suggested by the marked drop in NO_3^- contents at 20 cm soil depth (Figure 3d). Nevertheless, from 6 DAF on, the soil had negligible NO_3^- contents at 2 and 20 cm depths and therefore, the N_2O emitted in the subsequent period was most likely not originated from denitrification.

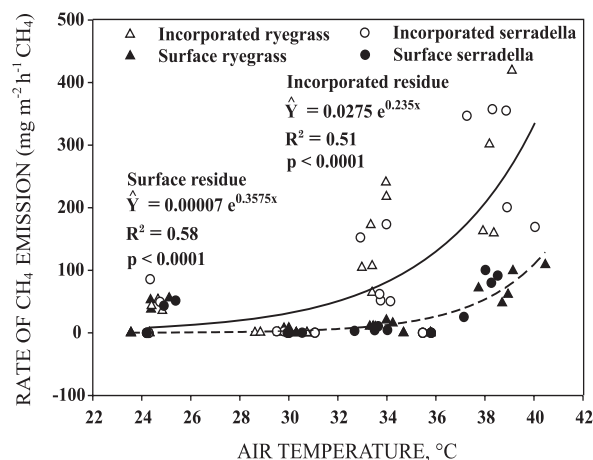


Figure 5. Relationship between CH_4 soil emission rates and air temperature within the chamber.

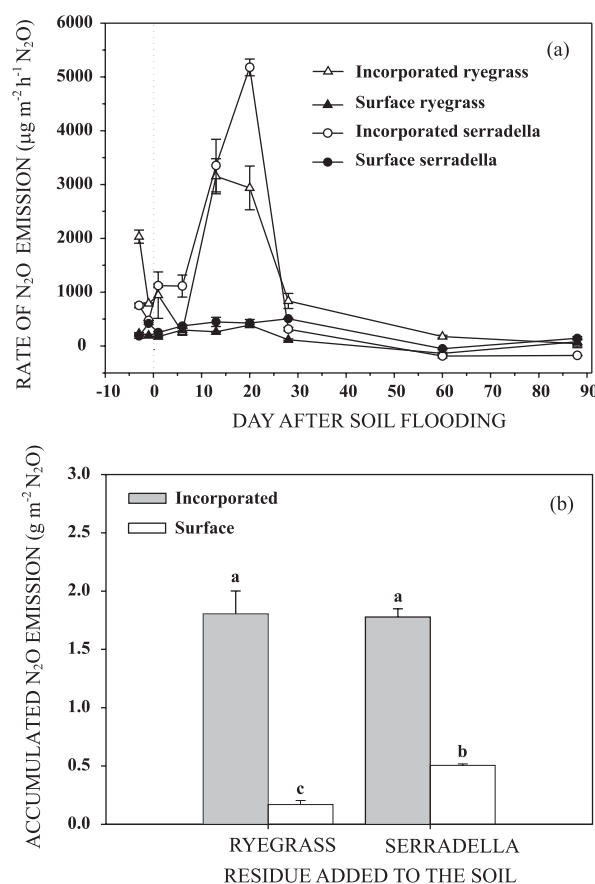


Figure 6. Emission rates (a) and accumulated emission (b) of N_2O from a flooded Albaqualf cultivated with rice as affected by residue management (incorporated or left on the soil surface) of ryegrass and serradella. Vertical bars indicate standard deviation. Different letters on bars indicate statistical difference by Tukey's test at 5 %.

The accumulated N_2O emission from the soil was 3–10 times greater in treatments with incorporated residues of ryegrass ($1.80 \text{ g m}^{-2} \text{ N}_2\text{O}$) and serradella ($1.78 \text{ g m}^{-2} \text{ N}_2\text{O}$) into the soil than when the residues were left on the soil surface. Emissions from soil with serradella residues on the surface were greater than from soil with ryegrass residues (0.51 and $0.17 \text{ g m}^{-2} \text{ N}_2\text{O}$, respectively; Figure 6b). Residue incorporation into the soil probably contributed to decrease the differences in crop residue quality, mainly if the 25 days interval between the residue application to the soil and the beginning of the experiment (rice transplanting) are taken into account. When residues were left on the surface, however, the greater emissions from serradella-amended soils were presumably due to the faster decomposition and N mineralization of this residue with lower C/N ratio (18) than of ryegrass-residues (ryegrass C/N ratio=40) (Toma & Hatano, 2007).

Higher NH_4^+ contents with greater variations were observed at the 2 cm soil depth than at 20 cm (Figure 7a and 7c). However, a positive and close relation between N_2O emission and NH_4^+ contents was only observed at 20 cm (Figure 7d; $R^2 = 0.61$; $p < 0.0001$), suggesting that N_2O was originated by the soil nitrification process. As the low O_2 availability in this soil layer would limit the occurrence of the process, the most plausible hypothesis is that the small soil volume in the pots resulted in a larger concentration of roots. This great root density may have led to high O_2 diffusion through the aerenchyma, facilitating nitrification in the rhizosphere zone, with the generation of N_2O from the reduction of intermediary compounds (HNO and NO_2^-) between NH_4^+ and NO_3^- (Khalil et al., 2004) and also due to the subsequent denitrification of NO_3^- produced (Arth et al., 1998).

Partial global warming potential

The estimation of CH_4 and N_2O emissions in amounts of equivalent CO_2 serves to compare the impact of the treatments regarding the emissions of these two GHG in a combined form, taking into account the warming potential of each gas in comparison to CO_2 (25 times greater for CH_4 and 298 for N_2O), as well as to verify the relative contribution of CH_4 and N_2O to the global warming potential (GWP).

The CH_4 emissions from these flooded rice fields, played a predominant role in the composition of the partial Global Warming Potential (partialGWP), contributing with 94–98.4 % of the $\text{CH}_4 + \text{N}_2\text{O}$ emissions, in equivalent CO_2 amounts (Figure 8). Evaluating the influence of soil tillage systems on CH_4 and N_2O emissions during rice cultivation in Japan, Harada et al. (2007) also reported proportionally larger CH_4 emissions, where N_2O emissions (in equivalent CO_2) reached a maximum relative participation of 3 % of the emissions.

Concerning the effect of management and composition of crop residue on the CH_4 and N_2O emissions (partialGWP), the results indicated that residues left on the soil surface can potentially mitigate emissions from flooded soil by up to 60 % compared to emissions from soil with incorporated residue (Figure 8). Similar but lower results were reported by Harada et al. (2007). Analogously to the soil tillage systems, it can be inferred that conservation tillage systems characterized by the maintenance of plant residues on the soil surface can significantly minimize GHG emissions from flooded rice fields in RS. Currently, the systems of conventional tillage and minimum tillage are still used in about 80 % of the total area cultivated with rice in the state (IRGA, 2010).

It is noteworthy that, as previously discussed, the retention of solar radiation within the greenhouse, in

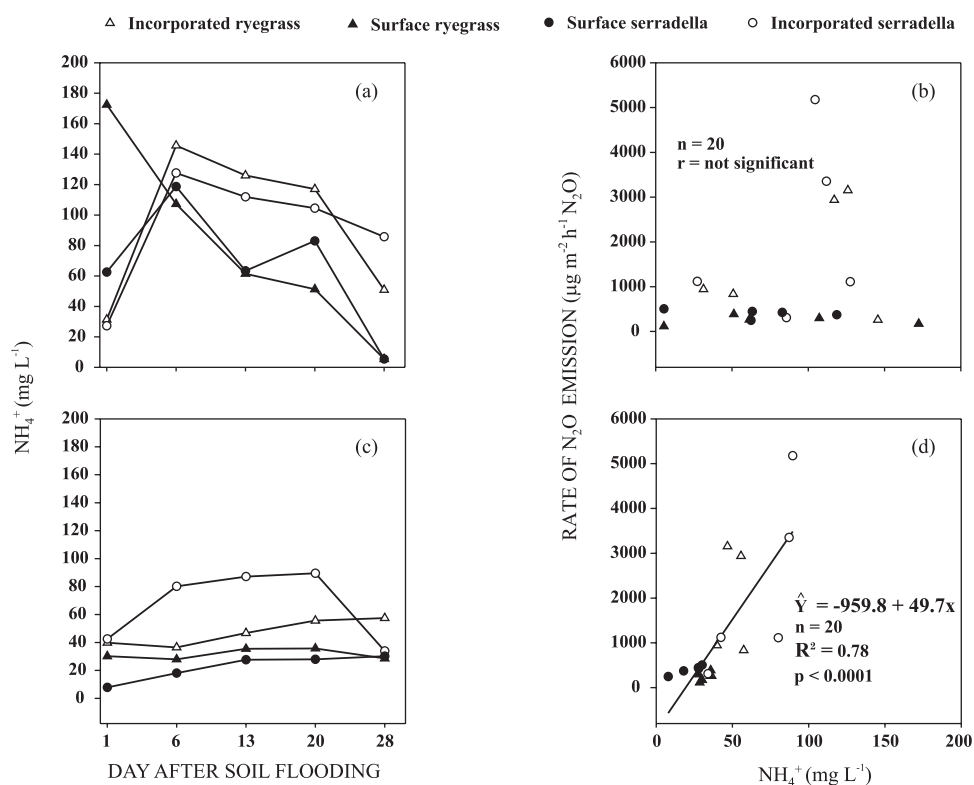


Figure 7. Concentration of ammonium (NH_4^+) at depths of 2 and 20 cm (a and c, respectively) of a flooded Albaqualf as affected by residue managements (incorporated or left on the soil surface) of ryegrass and serradella, and the respective relationships with N_2O soil emissions (b and d, respectively).

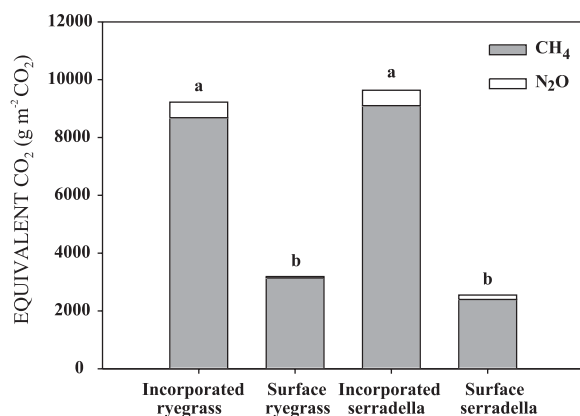


Figure 8. Accumulated CH₄ and N₂O emissions, expressed in equivalent CO₂, from a flooded Albaqualf with rice under residue managements (incorporated or left on the soil surface) of ryegrass and serradella. Different letters on bars indicate statistical difference by Tukey's test at 5 %.

infrared wave form, resulted in higher experimental temperatures, leading in turn to higher CH₄ emissions than under field conditions, which does not allow an individual interpretation of the gas emissions and absolute GWP values related to the impact of flooded rice cultivation on the GHG emissions.

CONCLUSIONS

1. The maintenance of cover crop residues on the soil surface mitigates methane (CH₄) and nitrous oxide (N₂O) emissions from soils cultivated with rice in a flood-irrigation system.

2. The type of crop residue (grass or legume crop residue) does not affect CH₄ emissions from the soil. For N₂O emissions, differences among residue types occur only when left on the soil surface and, under this condition, emissions were greater from soil with legume than with grass residues.

3. The incorporation of crop residues into the soil intensifies soil reduction at 20 cm depth, anticipating the CH₄ emissions in comparison to residues left on the soil surface. For this reason, in addition to the supply of labile C, the subsurface soil layer is possibly the main CH₄ source when crop residues are incorporated into the flooded rice soils.

4. In flooded rice systems, CH₄ emissions are predominant over N₂O emissions, accounting for more than 90 % of the composition of the partial Global Warming Potential.

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