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Greenhouse gas emissions during rice crop year affected by management of rice straw and ryegrass

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ABSTRACT: One of the challenges in rice areas is the sustainable post-harvest system, which involves using rice straw management and cover crop species. In this context, this study aimed to evaluate the emission of methane (CH_4) and nitrous oxide (N_2O) with the use of different post-harvest management of rice straw as well as with the combined use of ryegrass. A field experiment was conducted during the 2016 off-season and 2016/17 rice crop season with different post-harvest rice straw management: maintaining rice straw on the soil surface (No-tillage); incorporating straw into dry soil with a disc (Disc); incorporating straw into flooded soil with a roller crimper (Roller Crimper); maintaining rice straw on the soil surface with subsequent rolling of the soil with a roller (Roller). In each straw management, treatments with and without ryegrass were established. The results demonstrate that incorporating rice straw in flooded soil with a roller crimper increases CH_4 emissions in the off-season, and used in combination with ryegrass, proved to be the most significant contributor to partial global warming potential. Most annual N_2O emissions occur in the off-season for all management treatments, especially for the no-tillage treatment, which showed increased emissions when combined with the use of ryegrass. However, as global warming potential is influenced mainly by emissions of CH_4, the no-tillage system showed the best mitigation potential on greenhouse gas emissions.

Keywords: methane, nitrous oxide, no-tillage.

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INTRODUCTION

The sowing season is the main factor for the productivity of rice (*Oryza sativa* L.). This is because the grain-filling stage of plants must coincide with the period of the year of maximum solar radiation (Cruz, 2010). One determining factor in delaying sowing time is essentially the lack of adequate post-harvest management and preparation of such areas during the off-season. In this scenario, the traditional form of soil preparation is to incorporate rice straw into dry or flooded soil, followed by planing. In the fall, this system is considered minimum tillage system and represents 70 % of the rice areas in southern Brazil, while in the spring, it is known as conventional system (Sosbai, 2018).

Rice has a harvest index of 0.50 (Bird et al., 2001), which means that every 10 Mg ha^{-1} of grain produces around 10 Mg ha^{-1} of low-quality straw, with a high lignin content and a high C/N ratio (Massoni, 2011; Redin, 2014). Moreover, the harvesting occurs when the temperatures begin to fall, and the photoperiod is lower, causing a reduction in the decomposition rate by microorganisms (Lobo Júnior et al., 2004). The effect of different post-harvest management practices of rice straw was studied by Massoni (2011), who concluded that during the off-season, regardless of the type of management, there is a reduction in only half of the dry matter of the remaining rice straw, irrespective of whether it is left on the soil surface or is incorporated. In this sense, maintaining the rice straw on the soil surface could be an alternative to management approaches that involve tillage, thus reducing costs, and avoiding delays in sowing the next crop. Although there is information on the benefits of direct sowing in flooded rice areas, it is not widely adopted in rice farms. This happens because of two key factors: (1) the need to perform the dry soil harvesting operation and (2) the difficulty in decomposing rice straw in the off-season, which should be less than 1 Mg ha^{-1} when sowing the new crop.

Most of the soils in Southern Brazil cultivated with flooded rice show low natural fertility (Boeni et al., 2010), which is aggravated by the intense tillage to incorporate crop residues into soil (Olk et al., 2009). Thus, cultivation systems without soil tillage would provide benefits to this type of soil, such as increasing organic carbon content, enzymatic activity, and nutrient build-up (Huang et al., 2012; Bayer et al., 2014; Motschenbacher et al., 2014), which are considered indispensable factors in the sustainability of rotation and/or succession of crops involving flooded rice (Vernetti Junior et al., 2009). No-tillage systems in lowland areas can be implemented with the use of soil cover crop species after the harvest of the flooded rice (Ferreira et al., 2015). The use of the cover crops for the production of hay or pasture can increase the income of the rural producer. This system can positively impact the sustainability of the production chain, through nutrient cycling from the decomposition of the harvested straw of flooded rice by the succeeding crop, which would optimize these nutrients and minimize losses to the environment. Ryegrass (*Lollium multiflorum* L.) is the most commonly used cover crop in Brazilian lowlands, although its use is restricted to less than one-third of the rice production area.

However, the input of a larger quantity of plant material into an environment that is anoxic most of the year raises another concern: the influence of management on the emission of greenhouse gases, mainly with regard to methane (CH_4). This is because the input of plant residues prior to the cultivation of flooded rice changes the soil redox conditions and may have distinct effects on greenhouse gas emissions (Zschornack et al., 2011; Kim et al., 2013). The addition of organic material not only promotes the processes of reduction in the soil, but also intensifies the emissions of CH_4 by providing labile carbon to methanogenic microorganisms. Different post-harvest management practices of rice straw were investigated by Bayer et al. (2014) and Souza (2013), and they found higher global warming potential in management practices that incorporate the plant material at some point during the off-season compared to the one in which the straw remains on the soil surface, thus suggesting that a no-tillage system can mitigate greenhouse gas emissions. However, most of studies carried out do not consider emissions during the off-season in which a higher amount of nitrous oxide (N_2O) is emitted (Souza, 2013). Nitrous oxide can also absorb infrared radiation, and its potential for promoting atmospheric warming can be 12 times greater than that of CH_4 (Solomon et al., 2007).

In this sense, this study hypothesized that post-harvest management practices that incorporate rice straw into the soil and combine the use of winter cover crops increase carbon availability to microorganisms and contribute to the emission of greenhouse gases. In this context, we aimed to evaluate the influence of post-harvest management practices combined with the use of ryegrass during autumn/winter on the emission of greenhouse gases (CH_4 and N_2O), measured through partial global warming potential.

MATERIALS AND METHODS

Site description and management practices

The field experiment was conducted in experimental lowland areas of the Universidade Federal de Santa Maria, Santa Maria (29° 43’ 08.8” S, 53° 43’ 18.6” W), Rio Grande do Sul, Brazil. It began in the 2016 off-season and ended in the 2016/2017 crop season. The soil of the experimental area is a *Planossolo Eutrófico Arênico* according to Brazilian Soil Taxonomy (Santos et al., 2018), equivalent to a Ultisol (Soil Survey Staff, 2014), with the following physicochemical properties in the 0.00-0.20 m layer: pH (1:1 v/v) = 4.6; phosphorus (P) = 3.7 mg dm^{-3}; potassium (K^+) = 0.14 $cmol_c$ dm^{-3}, and organic matter (OM) = 10.0 g kg^{-1}. The local climate is classified as humid subtropical (Cfa) by the Köppen classification system. The average annual temperature and precipitation are 19.2 °C and 1,708 mm, respectively (Maluf, 2000).

The area was sourced from flooded rice stubble, sown with IRGA 424 RI in the 2015/2016 crop season, with 9.5 Mg ha^{-1} of dry matter from the remaining straw. In the five years prior to our experiment, the area used was cultivated with rice and soybean under conventional tillage, which means that the soil was revolved.

The experimental design was randomized blocks in a two-factorial scheme with four replicates. Factor A consisted of the post-harvest management treatments of rice straw and factor D was composed of the combination of ryegrass (*Lolium multiflorum* L.) (D1) or not (D2) after the application of factor A (Table 1).

To implement the experiment, the area was divided into eight main plots (15 m wide by 35 m in length), where rice straw management was carried out. Rice straw was

Table 1. Post-harvest management in flooded rice crop

Straw management (Factor A)	Cover crop (Factor D)	Soil Tillage
Rice straw on the soil surface	Ryegrass	No-tillage
Rice straw incorporation into dry soil with a disc	Ryegrass	Fall tillage
Rice straw incorporation into flooded soil with a roller crimper	Ryegrass	Fall tillage
Rice straw on the soil surface with subsequent rolling with a roller	Ryegrass	No-tillage
Rice straw on the soil surface	No ryegrass	No-tillage
Rice straw incorporation into dry soil with a disc	No ryegrass	Fall tillage
Rice straw incorporation into flooded soil with a roller crimper	No ryegrass	Fall tillage
Rice straw on the soil surface with subsequent rolling with a roller	No ryegrass	No-tillage

desiccated with glyphosate (dose of 1,800 g i.a. ha^{-1}) 15 days after the harvest in all the treatments. To perform the management with the roller crimper, the area was divided with levees to enable flooding. Three days after the flooding, a roller crimper was used for rolling the straw. The water was drained one week later, totaling 10 days of flooding. The management treatment that incorporated the straw into dry soil with a disc was carried out in two phases during the fall: one week after the harvest (03/22/2016) and then on 05/05/2016. In the management treatment that did not incorporate the straw into the soil, the rice straw was rolled twice (by moving in opposite directions). This was carried out two weeks after the desiccation of the straw to keep it in contact with the soil. This was done on the dry soil.

For the post-harvest treatments that combined the use of cover crop, ryegrass was sown a density of 15 kg ha^{-1} on 05/05/2016. On the other hand, management treatments that did not use ryegrass, the desiccated rice straw was kept on the soil surface during the off-season. In the cultivation of ryegrass, fertilization was performed with 2, 8.5, and 13.5 kg ha^{-1} of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O), respectively. In addition to this fertilization, two topdressing N applications were carried out 47 and 86 days after emergence (DAE) at a dose of 22.5 kg ha^{-1} of urea, totaling 50 kg N ha^{-1} during the off-season. The plots containing ryegrass were desiccated using 1,800 g ha^{-1} i.a. of glyphosate 58 days prior to the seeding of the 2016/2017 rice crop.

Rice was sown on 07/11/2016, using the cultivar IRGA 424 RI at a density of 100 kg ha^{-1}, and base fertilization of 16 kg ha^{-1} of N, 68 kg ha^{-1} of P_2O_5, and 108 kg ha^{-1} of K_2O. When the rice was in stage V4 (Counce et al., 2000), an application of 90 kg ha^{-1} N (urea) and post-emergent herbicide were carried out. Irrigation started immediately after those applications, on 12/01/2016. Two additional topdressing N applications were carried out during the crop cycle in stages V6 and R0 (Counce et al., 2000), at a dose of 30 kg N ha^{-1} each, totaling 166 kg N ha^{-1} during the cycle of flooded rice. The experimental area was drained when the rice reached stage R7.

Quantification of greenhouse gas emissions

Throughout the 2016 off-season and 2016/2017 crop season, weekly air sampling was performed for quantification of greenhouse gases (GHG) methane (CH_4) and nitrous oxide (N_2O). The air sampling of the off-season started a week after the harvest of rice (03/22/2016) and ended at the time of sowing of the new crop of flooded rice (11/07/2016) and of the crop season began on 11/14/2016 and ended on the harvest of flooded rice (03/23/2017). Air sampling was performed with a single chamber fixed on a base, as in the static closed chamber method (Mosier, 1989). A galvanized steel square base was fixed permanently into the soil at a depth of 0.12 m. The chamber was fixed to the base at the time of sampling. The chambers were also made of galvanized steel and measured 0.20 × 0.40 × 0.40 m (h × w × l). For the air sampling carried out during crop season, extensors were used to adjust the height of the chamber to the plants (Souza, 2013). During the crop season, the bases were placed so that three sowing lines of rice passed through each chamber. Each chamber had a cooler type fan connected to a 12 V battery. It was turned on for 30 seconds immediately before each air collection to homogenize the internal atmosphere. During the sampling period, each chamber was fixed to a gutter of the metal base, after which water was added to seal the chamber, thus preventing gas exchange between the internal and external environments.

There was a three-way valve on top of the chamber to collect the air samples. Polypropylene syringes were used to collect the air samples from the inside of the chambers. The air sampling was made in four intervals: 0, 15, 30, and 45 min during the off-season and 0, 8, 16, and 24 min during the crop season, after placing the chamber on the base. The air samples were immediately transferred from the syringes to 12-mL pre-evacuated glass vials (Labco, Lampeter, UK) and subsequently sent to the laboratory (*Laboratório de Pesquisa em Biotransformações de Carbono e Nitrogênio*

- *LABCEN*) to determine CH_4 and N_2O concentrations using a gas chromatograph (Shimadzu GC - 2014 Greenhouse model) equipped with an electron capture detector (ECD Electron Capture Detection).

Calculations

The fluxes of the gases were calculated according to the equation: $f = \Delta Q/\Delta t \times PV/RT \times M/A$; in which "f" is the flux of N_2O or CH_4 (g ha^{-1} day^{-1}); $\Delta Q/\Delta t$ is the variation in gas concentration (mol h^{-1}) in the chamber at the time of collection; P is the atmospheric pressure (atm) inside the chamber (1 atm); V is the volume of the chamber (L); R is the ideal gas constant (0.08205 atm L mol^{-1} K^{-1}); T is the temperature inside the chamber at the time of collection (K); M is the molar mass of the gas (μg mol^{-1}); and A is the base area of the chamber (m^2). The cumulative emissions of CH_4 and N_2O were calculated from the integral of the area under the curve, established by the interpolation of daily emission values (Bayer et al., 2014).

Based on cumulative emissions of CH_4 and N_2O and considering the global warming potential (GWP) of each gas, we calculated the partial global warming potential (pGWP) in CO_2 equivalent (kg CO_2eq ha^{-1}) by the equation: $pGWP = (CH_4 \times 25) + (N_2O\times 298)$ in which CH_4 and N_2O are the emissions measured in the evaluation period (kg ha^{-1}) and the factors of 25 and 298 are the default GWP of CH_4 and N_2O, respectively, in a 100-year time horizon (Solomon et al., 2007). The ratio between pGWP and grain yield (kg ha^{-1}) was calculated according to the equation: pGWPYield = pGWP/yield.

Grain yield was determined through manual harvesting in an area of 9.50 m^2 of each plot. Subsequently, the material was separated, weighed, and the moisture was determined to obtain grain yield in kg ha^{-1}.

Meteorological data

Meteorological data was obtained from a weather station (*Estação Automática de Meteorologia do Departamento de Fitotecnia da UFSM*) located 0.5 km from the experimental area (Figure 1).

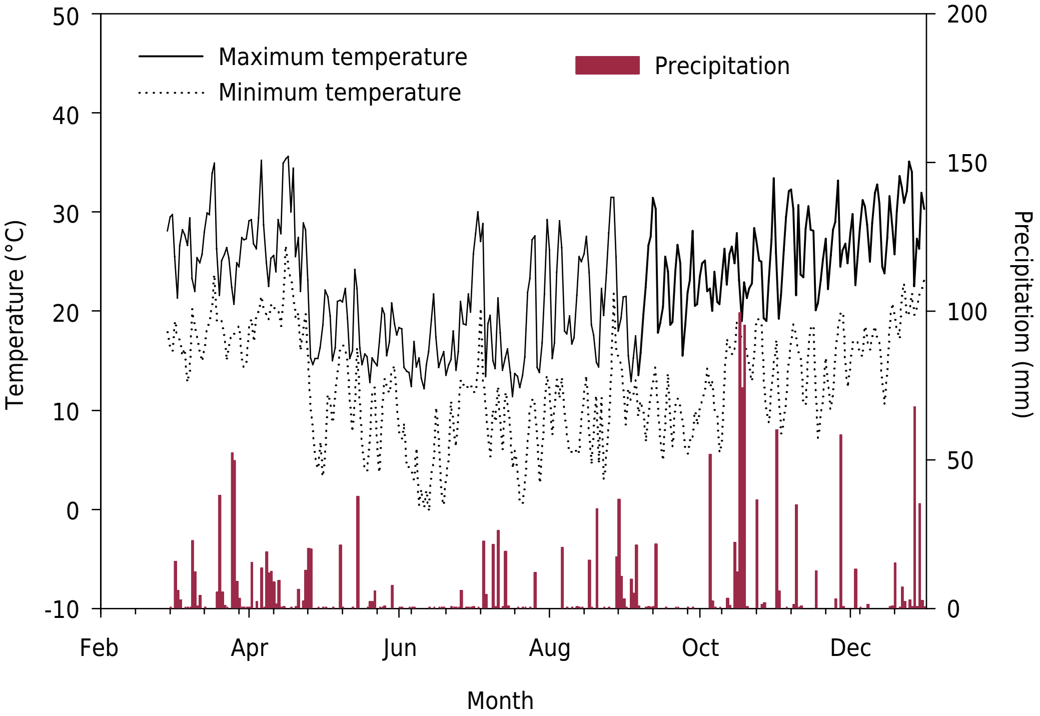

Figure 1. Maximum and minimum temperature and precipitation during the experiment.

Statistical analysis

The daily fluxes of CH_4 and N_2O were calculated by linear interpolation and the cumulative emission of each gas was calculated by adding the amounts emitted in each collection interval. To do this, the average flux of each gas was calculated between two consecutive collections, multiplying the resulting value by the time interval elapsed between such collections, then adding the cumulative value of the previous collection. Data on cumulative emissions was submitted to the Scott-Knott test at 5 % for means comparison (without data transformation) using the procedures available in SISVAR statistical software (Ferreira, 2014).

RESULTS

Off-season

In the off-season, CH_4 emissions (Figure 2) were significant only under the incorporation treatment with the roller crimper in the flooded soil. The largest daily flux recorded in this treatment was 40,000 g ha^{-1} day^{-1}, which is difficult to be found even during the crop season, when there is a greater cumulative emission of CH_4 (Souza, 2013; Bayer et al., 2014). For the other treatments, there were CH_4 emissions for 20 days after the beginning of the collections, reaching 1,196 g ha^{-1} day^{-1} in the incorporation treatment with a disc, while no-tillage treatments reached maximum values of 489.9 g ha^{-1} day^{-1}.

The flux of N_2O varied from -1.9 to 47.9 g ha^{-1} day^{-1} during the off-season (Figure 3). Unlike CH_4, N_2O emissions presented three significant peaks in the off-season: soon after the addition of rice straw, after N fertilization of ryegrass, and after the desiccation of ryegrass.

After the incorporation of rice straw into dry soil with a disc, there was a fast emission of N_2O, showing a flux of 46.9 g ha^{-1} day^{-1}, whereas the incorporation with a roller crimper resulted in the lowest emission of 16 g ha^{-1} day^{-1}. Due to the need for a second intervention (incorporation with a disc) to finish the preparation of the area, N_2O emission was collected again 44 days after the beginning of the collections. Emissions were constant for two weeks, although values were lower than the first flux (3.79 g ha^{-1} day^{-1}). Significant emissions in these treatments were once again recorded 142 days after the harvest, possibly influenced by the release of N from the straw associated with the constant precipitation during this period. During this collection, the roller and no-tillage

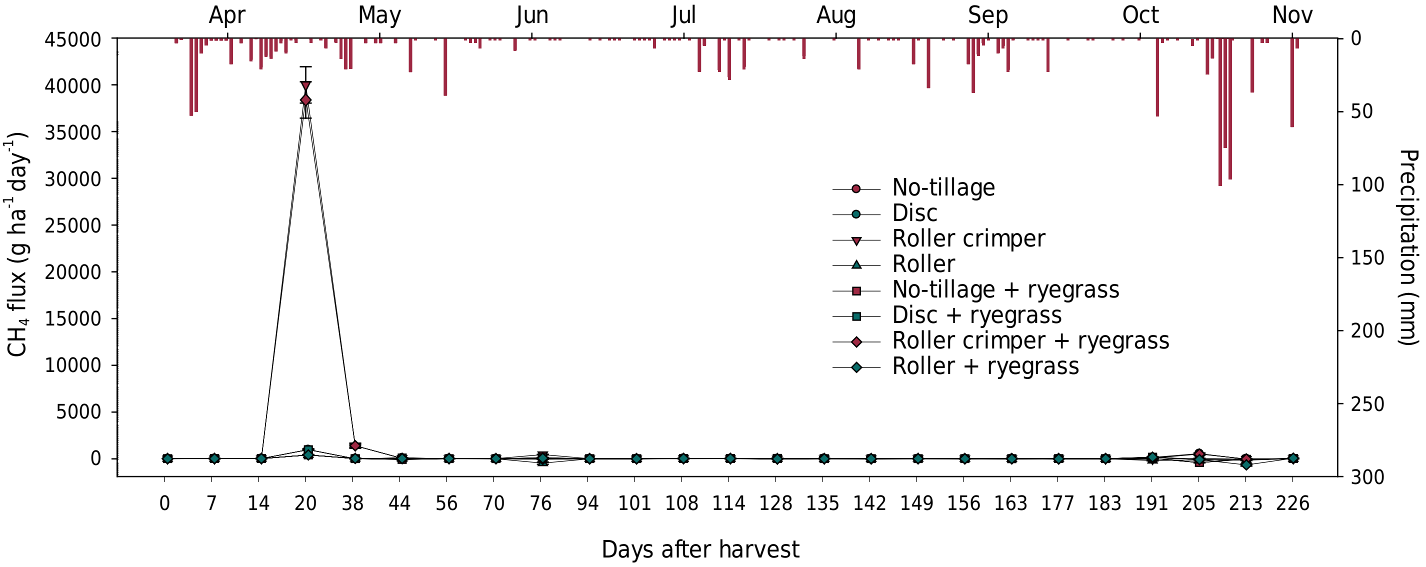

Figure 2. Methane flux - CH_4 (g ha^{-1} day^{-1}) - of different post-harvest management treatments during the off-season.

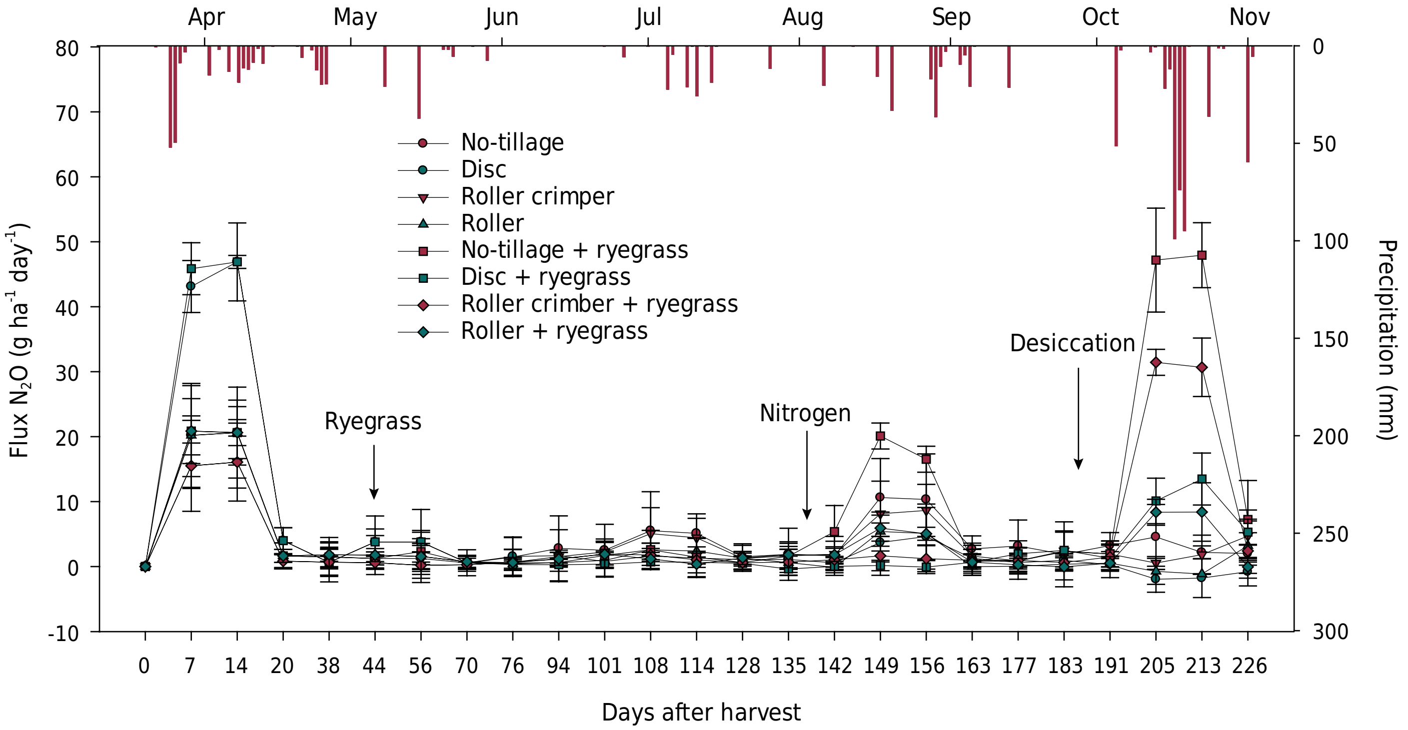

Figure 3. Nitrous oxide flux – N_2O (g ha^{-1} day^{-1}) – of different post-harvest management treatments during the off-season.

treatments combined with the use of ryegrass also showed an increase in N_2O emissions influenced by topdressing N fertilization.

The highest N_2O emissions were observed 149 days after the harvest in the no-tillage + ryegrass treatment (20.10 g ha^{-1} day^{-1}), unlike the data recorded in the other treatments with ryegrass (disc + ryegrass and roller crimper + ryegrass). Even with top-dressing N fertilization, these treatments had lower N_2O emissions in comparison to the same treatments without the presence of this cover crop. For the roller treatment, the presence of ryegrass did not influence the emissions of N_2O. The no-tillage and roller crimper treatments showed differences in N_2O emission soon after the dessication of ryegrass. The no-tillage treatment showed a peak of 47.17 g ha^{-1} day^{-1} compared to 31.44 g ha^{-1} day^{-1} for the roller crimper treatment. This result is linked to soil moisture, which is usually higher when the straw is kept on the soil surface. In contrast, when ryegrass was combined with the disc or the roller treatments, N_2O emissions were nearly five times lower in comparison to the no-tillage treatment.

Crop season

After the sowing of rice, there was a significant change in N_2O emission pattern in the first collection of the management treatments without ryegrass (Figure 4). This is most likely a consequence of the turning of the soil in the sowing line, as well the moving of the chambers around the plots for the passage of the machines. After this initial evaluation, the treatments with ryegrass and rice straw on the soil surface once again showed the highest N_2O emissions, especially the roller compaction treatment (61.47 g ha^{-1} day^{-1}) which had the highest value recorded during the evaluation period. After these first two emission peaks, N_2O fluxes in all management treatments remained close to zero until the start of irrigation.

Regarding the CH_4 emissions during the crop season, all management treatments showed similar behavior, but with different amplitudes (Figure 5). The average fluxes of CH_4 during the crop season were 1.34; 1.50; 1.66; 2.02; 2.26; 2.71; 3.29; and 3.45 kg ha^{-1} day^{-1} in the following treatments: no-tillage, roller, disc, roller crimper, no-tillage + ryegrass, roller + ryegrass, disc + ryegrass, and roller crimper + ryegrass, respectively.

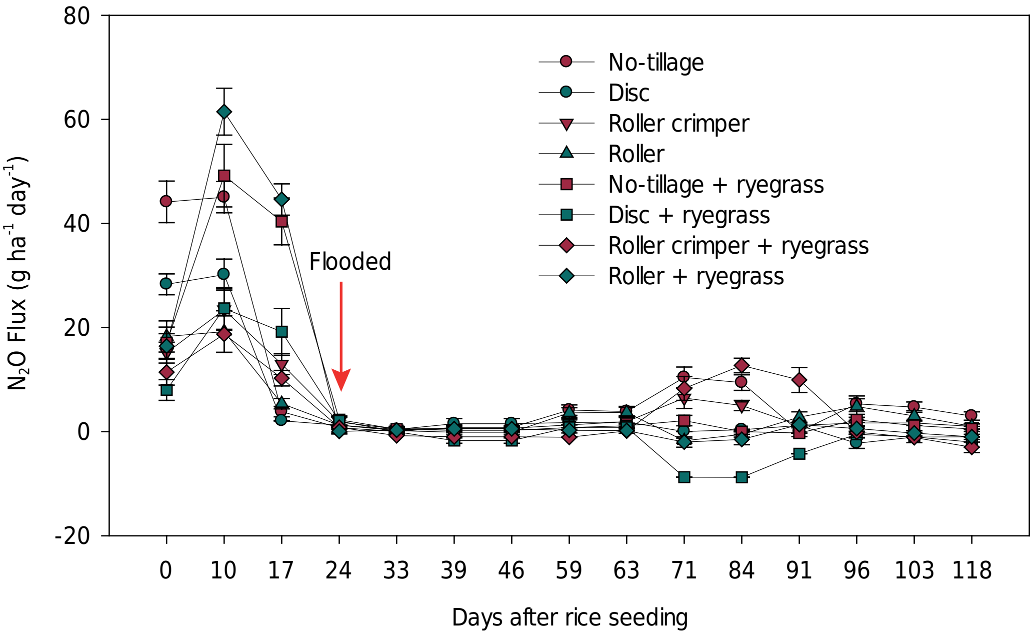

Figure 4. Nitrous oxide flux – N_2O (g ha^{-1} day^{-1}) – of different post-harvest management treatments during the crop season.

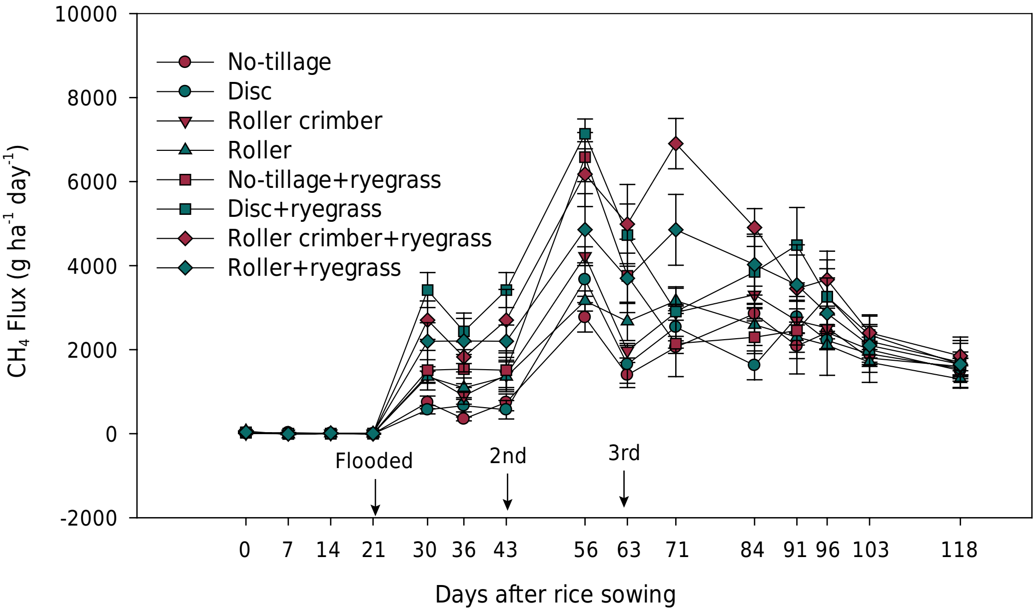

Figure 5. Methane flux – CH_4 (g ha^{-1} day^{-1}) – of different post-harvest management treatments during the crop season. 2nd and 3rd: second and third nitrogen application.

In all the collections performed during the crop season, higher emissions were recorded in the management treatments associated with ryegrass. The disc + ryegrass treatment reached a maximum daily flux of 7,135 g ha^{-1} day^{-1}. This was 49 % more CH_4 emission in comparison to the disc treatment (3,668 g ha^{-1} day^{-1}) both measured 56 days after sowing.

The lowest CH_4 fluxes were found prior to the start of irrigation and at the end of the crop cycle, after the drainage of the plots. On the other hand, the highest fluxes of CH_4 were observed in flooded soil after the second N topdressing (43 days after sowing) and remained high until the beginning of the reproductive period (R0 -71 days after sowing), at which point values tended to fall. During the crop season, CH_4 fluxes ranged from -17.43 to 7,135 g ha^{-1} day^{-1}.

Cumulative emissions, partial global warming potential (pGWP), and yield-scaled pGWP

The roller crimper treatment contributed the most to CH_4 emissions. It was enhanced when combined with ryegrass (Figure 6a). Considering the roller crimper treatment, 58 % of CH_4 emissions occurred in the off-season. However, when combined with the ryegrass, most emissions occurred during the crop season (approximately 54 %). If we compare the presence or absence of ryegrass specifically in this treatment, there was a 25 % increase in total CH_4 emissions throughout the evaluation period.

Except for the roller crimper treatment, most treatments concentrated CH_4 emissions during the crop season (between 88 and 99 % of total emission) and such emissions were enhanced when combined with ryegrass. Ryegrass had a significant influence on CH_4 emissions, especially in the disc and roller crimper treatments (fluxes had an additional 161 and 150 kg ha^{-1}, respectively).

Most N_2O emissions were recorded in the off-season, especially the disc + ryegrass and no-tillage + ryegrass treatments (86 and 70 %, respectively) (Figure 6b). The exceptions to this finding were the no-tillage and roller + ryegrass treatments, which showed more than half of the emissions during the crop season. It is worth noting that the highest emissions of N_2O in these treatments occurred prior to irrigation but after sowing.

The highest N_2O emissions were recorded in the no-tillage + ryegrass treatment (2,725 g^{-1} ha^{-1}), while the lowest were found in the roller treatment (954 g^{-1} ha^{-1}). The presence of ryegrass also increased N_2O emission. However, unlike what was recorded for CH_4, the no-tillage and roller combined with ryegrass showed the highest emission

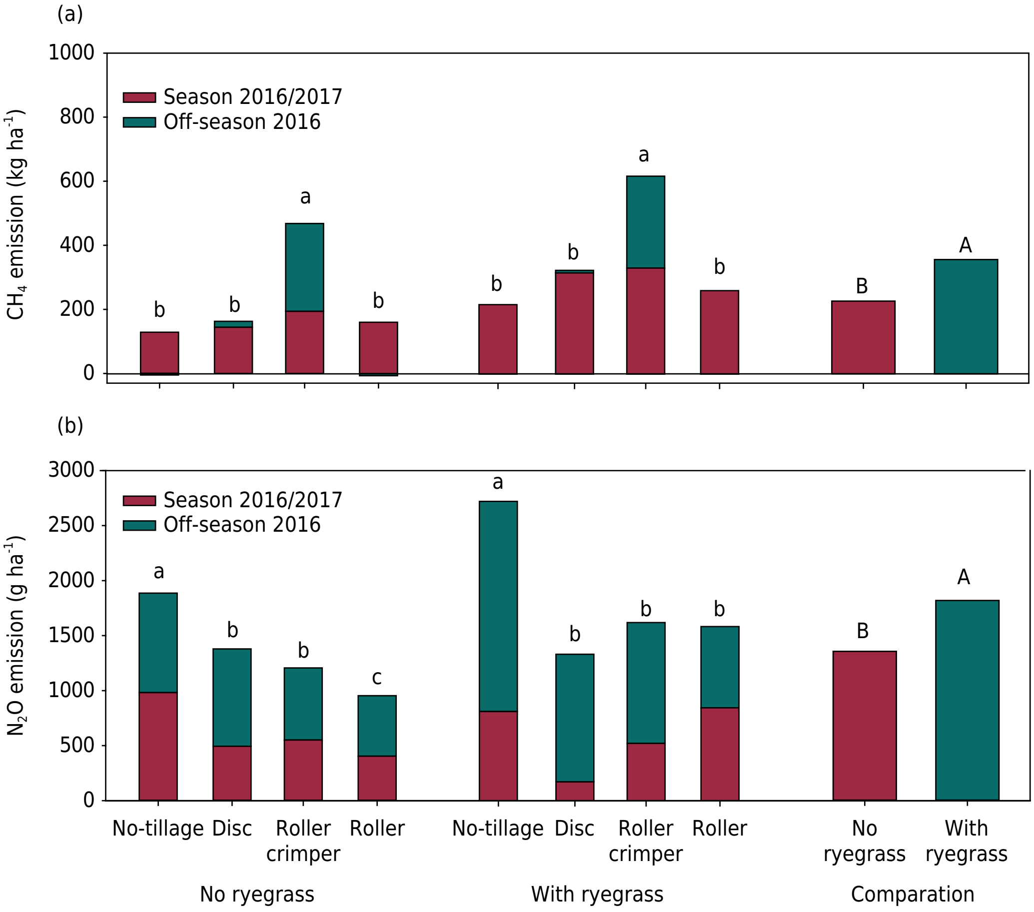

Figure 6. Cumulative emissions of methane –(kg CH_4 ha^{-1})- (a), and nitrous oxide - (g N_2O ha^{-1})- (b), of different post-harvest management treatments during the experimental period.

Table 2. Partial global warming potential (pGWP), grain yield, and pGWP/grain yield (pGWP/yield) of post-harvest management treatments

Post-harvest management	pGWP		Grain Yield		pGWP/yield	
	no ryegrass	ryegrass	no ryegrass	ryegrass	no ryegrass	ryegrass
	Mg CO$_2$ eq ha^{-1}		kg ha^{-1}		kg CO$_2$eq kg^{-1} grain	
No-tillage	3.91b(1) B(2)	6.34 bA	9118.2^{ns} A	8598.2 bB	0.43 bB	0.74 cA
Disc	4.49 bB	8.50 bA	9317.2 A	7799.6 cB	0.48 bB	1.09 bA
Roller crimper	12.06 aB	15.93 aA	9118.3 A	8548.6 bB	1.32 aB	1.86 aA
Roller	4.46 bB	7.07 bA	9375.8 A	9083.6 aB	0.48 bB	0.78 cA
Mean	6.23 B	9.46 A	9232.39 A	8507.58 B	0.68 B	1.12 A
CV (%)	10.9		5.47		8.04	

(1) Lowercase letters compare management treatments within each column. (2) Uppercase letters compare the average of the post-harvest management treatments with or without ryegrass. ns: not significant.

values (815 and 849 g ha^{-1}, respectively). The disc treatment suffered the least influence of ryegrass (an increase of N_2O flux of 156 g ha^{-1}).

These results show that pGWP was influenced more by CH_4 emission in all the treatments (Table 2). The contribution of CH_4 ranged from 85 to 97 % in the no-tillage and roller crimper treatments, showing that CH_4 has a greater influence in the rice cropping system, even with an eight-month off-season in which the soil is under aerobic conditions.

The roller crimper + ryegrass treatment showed the highest pGWP, followed by the roller crimper treatment. The use of ryegrass as cover crop increases pGWP regardless of which post-harvest management treatment is used. Except for the roller crimper treatment, all the other management treatments without ryegrass contributed to the reduction of pGWP when performed immediately after the crop season.

Ryegrass decreased grain yield in 7.8 % on average (Table 2). Without the use of ryegrass, grain yield did not vary among treatments, remaining at 9,232 kg ha^{-1} on average. However, the treatments did influence grain yield in the area with ryegrass in which the disc treatment had the lowest yield (7,800 kg ha^{-1}) and the roller, the highest (9,084 kg ha^{-1}).

As grain yield influences pGWP, the treatments combined with ryegrass showed a pGWP/yield of 1.2. This means that for the production of 1 Mg of flooded rice, 1.2 Mg CO_2 eq ha^{-1} will be emitted. On the other hand, this ratio was 0.68 in the area without ryegrass, which is 60 % less. In comparing post-harvest management treatments with ryegrass to those with rice straw (no-tillage), the lowest pGWP/yield (0.74 and 0.78 kg CO_2eq kg^{-1} grain for no-tillage and roller, respectively), followed by the disc (1.09 kg CO_2eq kg^{-1} grain), and the roller crimper (1.86 kg CO_2eq kg^{-1} grain) treatments.

DISCUSSION

Off-season

The input of large quantities of crop residues in environments with anaerobic conditions increases the production and the emission of CH_4 because it stimulates the activity of methanogenic microorganisms by adding labile C. In addition, the residues reduce the soil redox potential, accelerating the reduction of inorganic oxidized ions (NO_3^-, Mn^{+4}, Fe^{+3}, and SO_4^{-2}), because of the fast consumption of oxygen (O_2) during the decomposition of waste (Dalal et al., 2008; Kim et al., 2012; Gaihre et al., 2013).

The increased emission of CH_4 found in the flooded soil management treatment (roller crimper) was 40 times greater than data previously reported in the literature (Fitzgerald et al., 2000; Souza, 2013). This is a consequence of how management was carried out, using water to help to incorporate all the rice straw, keeping it at a depth of ± 2 cm. In the flooded area, the environment becomes anoxic, which is an essential condition for CH_4 emission. Moreover, due to a large number of suspended solids that remain after the turning of the soil, there is a need to maintain the water until this material is decanted, which prolongs anaerobiosis, totaling 10 days of flooding. In comparing post-harvest management in the United States, Fitzgerald et al. (2000) reported an increase in cumulative emissions of CH_4 of nearly 20 times when the area is flooded area to incorporate the straw.

Using the disc after the harvest promoted the initial emission of CH_4, possibly due to the rupture of the soil structure, releasing the gas contained in the pore space (Piva, 2010). In addition to this, accumulated precipitation of 189 mm was recorded during the first 20 days of the evaluation period. The consequence of high temperatures, regular rainfall, and the addition of crop residues may be higher emissions of CH_4 during the off-season (Souza, 2013).

The emissions of N_2O corroborated findings in the literature in which the highest variation in fluxes occurred during the off-season. Initially, the incorporation of the straw into dry soil (disc treatment) showed the highest influence on N_2O emission. This is most likely due to the decomposition rate during the initial days of evaluation. This was a result of the breakdown of the straw and incorporation into the soil, thus increasing contact area for microbial attack (Massoni, 2011), in addition to the turning of the soil, which causes the release of the gas contained in the pore space.

The literature suggests that regardless of the post-harvest management, when there is an input of rice straw after the harvesting operation, there is an increase in soil mineral N. It is then followed by a gradual decrease, characterizing the reduction in the mineralization of straw, together with the environmental characteristics during the off-season (low temperatures and high humidity) (Bird et al., 2001; Massoni et al., 2013). Nitrogen available in soil can undergo transformations. Depending on the environmental conditions, it can be nitrified or denitrified (Moreira and Siqueira, 2006; Van Groenigen et al., 2015). As previously stated, the high precipitation during the first few weeks of the experiment contributed to the maintenance of an environment with low oxygen availability, thus promoting the process of denitrification and the release of N_2O.

According to Souza (2013), N_2O emission is predominant when the soil reaches 60 % of the field capacity. This reduces O_2 availability and could form micro anaerobic sites (hotspots), which favor the process of denitrification (Baggs et al., 2003; Van Groenigen et al., 2015). Examining rainfall and N_2O emission data (Figure 3), one can perceive the absence of high precipitation rates for 50 days between May and July (totaling 27.8 mm). This had a direct influence on the low emissions of N_2O during the off-season. The increase in precipitation caused emission peaks of N_2O in the no-tillage and roller crimper treatments (108 days after the harvest). This result is a consequence of straw decomposition in these two treatments, which provided N to the soil. This nutrient can be absorbed by the cover crop or lost through denitrification, depending on the environmental conditions (Bird et al., 2001).

When there is an input of organic matter into the soil, such as in the disc and roller crimper treatments, the microorganisms remove carbon and energy so that they can be converted into cell tissue. For this process to occur, microorganisms require nutrients (especially N) for the synthesis of proteins, nucleic acids, and other cell compounds. When crop residues with higher N contents, such as those with low C/N ratio, the microbial needs for this nutrient are, and excess N is released in mineral form, characterizing the process of mineralization (Hirsch and Mauchline, 2015).

In contrast, residues low in N with high C/N ratios make microorganisms search for additional N in the soil to synthesize organic nitrogenous compounds from the carbon and energy extracted from the residues. Therefore, microorganisms assimilate soil mineral N as nitrate (NO_3^-) and (especially) ammonium (NH_4^+) to incorporate them into organic nitrogenous compounds in the cell, resulting in N immobilization in soil (Singh, 2001). There is possibly a link between the lower emission of N_2O in treatments with rice straw incorporation and the immobilization effect.

Crop season

Methane emission was influenced by crop residues, especially when ryegrass was combined with treatments with rice straw incorporation in the off-season. This is due to the stimulation of methanogenic microorganism activity by the addition of labile carbon and also by the reduction of soil redox potential by accelerating the reduction of oxidized inorganic ions (NO_3^-, Mn^{+4}, Fe^{+3}, and SO_4^-), as there is rapid oxygen (O_2) consumption during the decomposition of the cover crop (Dalal et al., 2008; Kim et al., 2012; Gaihre et al., 2013).

The influence of N fertilization on CH_4 emission has been reported in the literature, although with controversial conclusions. In studying doses of N in flooded rice, Pittelkow et al. (2013) concluded that the annual emissions of CH_4 tended to increase with the addition of N during the crop season. The increased biomass of rice plants facilitates CH_4 transport through the plants via aerenchyma (Silva et al., 2014). In contrast, studies showed that high concentrations of ammonium (NH_4^+) in the soil could stimulate methanotrophic activity and CH_4 oxidation in soils cultivated with rice, thus reducing overall CH_4 emissions (Yao et al., 2011). Banger et al. (2012) conducted a study using a database of 33 articles relating the influence of N fertilization in rice cultivation on CH_4 emissions. The authors concluded that N fertilizers increase CH_4 emissions, especially using doses higher than 140 kg N ha^{-1}. This is comparable to this study, as a total of 166 kg ha^{-1} was used throughout cultivation.

Regarding N_2O emission dynamics during the crop season, a slight increase in emissions was recorded 71 days after sowing (Figure 5), indicating that part of the N fertilizer was transformed into N_2O, even with the use of irrigation during the whole cycle. This can occur because of the proximity of the soil surface and rhizosphere (both oxidized) to the anaerobic region where there is a higher likelihood of losses by nitrification-denitrification (Borin, 2014). This transforms NH_4^+ to NO_3^- which, in turn, is a final electron acceptor.

The highest peaks of N_2O emission during the flooded rice cycle are linked to a greater presence of NO_3^- in the soil solution (Zhao et al., 2011) and to the possibility that plants have a mechanism in the rhizosphere that controls NH_4^+ and NO_3^- uptake rates to avoid NH_4^+ toxicity. However, if uptake by the roots is insufficient (i.e., if there is NO_3^- available for the denitrifying microorganisms), there will be N loss via N_2O or N_2 in function of the anoxic environment.

Cumulative emission, pGWP and pGWP/yield

In general, the cumulative emissions found in this study corroborate the findings previously cited in the literature. That is, most CH_4 emissions occurred during the crop season and N_2O emissions in the off-season, as well as the greater influence of CH_4 emission on the constitution of the partial global warming potential (Zschornack et al., 2011; Kim et al., 2013; Zschornack et al., 2016). Management that aims at the conventional cropping system, which includes the incorporation of straw into the soil as part of the preparation, are referred to as practices with high CH_4 emission (Bird et al., 2001; Zschornack et al., 2011; Souza, 2013; Bayer et al., 2014), especially when combined with the use of cover crops (Kim et al., 2012, 2013; Zschornack et al., 2016). Thus, management that converges to the no-tillage system are indicated to mitigate the global warming potential in flooded rice areas (Bayer et al., 2014; Zhang et al., 2015; Zschornack et al., 2016).

Experiments that use cover crops in lowlands have not achieved satisfactory results regarding the potential benefits that crop succession could bring to the species in terms of fertility and increased yields (Menezes et al., 2001; Ferreira et al., 2015). Some studies in Brazil have reported a decrease of 8 to 30 % in flooded rice yields after the cultivation of ryegrass (Menezes et al., 2001; Ferreira et al., 2015). Depending on the species and soil management, there may be increased CH_4 emissions and global warming potential when there is a negative influence on grain yield. In this study, the presence of ryegrass increased pGWP by 35 %, regardless of post-harvest management. When considering the effect of ryegrass on yield, there was a greater influence on pGWP/yield, reaching a 40 % increase. This demonstrates that when rice season for an early cover crop, there should be associated with mitigatory practices. These practices should be focused on methane, given its high contribution to pGWP. An example is intermittent irrigation, which can be reduced by up to 90 % as methane when used during the rice season (Zschornack et al., 2016).

However, this study showed that although ryegrass increases the partial global warming potential, this influence can be minimized when using soil tillage systems that keep the rice straw on the soil surface. Although our study was conducted during a crop season and post-harvest period (off-season), it corroborates the results found in studies under similar conditions (Bayer et al., 2014, 2015; Zhang et al., 2015; Zschornack et al., 2016).

CONCLUSIONS

The emission of methane is stimulated when the rice straw is incorporated soon after the harvest with flooded soil, which is heightened by the association with ryegrass during the off-season. As for nitrous oxide, the maintenance of the rice straw on the soil surface in combination with the use of ryegrass enhances its emission, but it has little influence on the partial global warming potential.

The partial global warming potential is minimized when no-tillage without ryegrass is employed, thus contributing to the mitigation of greenhouse gases. When ryegrass is used, no-tillage decreases the partial global warming potential considering the rice grain yield.

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