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Article

Emission of greenhouse gases and yield-scaled global warming potential of rice cultivars under permanent and intermittent irrigation

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ABSTRACT: Irrigated rice cultivation is an important source of greenhouse gas emissions. Among the main greenhouse gases, there are carbon dioxide, methane, and nitrous oxide, with the emission of each gas varying according to the management of the crop, cultivar and irrigation management. In this context, the present study aimed to quantify the partial global warming potential (pGWP) measured by CH_4 and N_2O emissions in conventional and hybrid cultivars under two irrigation management, as well as the relation with grain yield (pGWP/Y). For this, a field experiment was conducted during the 2016/17 and 2017/18 crop seasons, with an experimental design of randomized blocks in a factorial arrangement (2×4), with four replications using water and rice cultivars. The water was managed through permanent and intermittent irrigation, with one conventional cultivar (IRGA 424 RI) and three hybrid cultivars (XP 113, Titan CL and Lexus CL). The pGWP can be reduced by up to 18% depending on the cultivar used and 11.8% through the adoption of intermittent irrigation management. More than 90% of the pGWP is due to methane emission, and the management actions of the rice crop should be directed towards the mitigation of this gas. In relation to the pGWP/Y index, the cultivar XP 113 had presented the best results.

Key words: methane, *Oryza sativa*, nitrous oxide.

INTRODUCTION

The greenhouse effect is a natural phenomenon that occurs due to the concentration of certain gases in the atmosphere, which can occur naturally and anthropically. Regarding the emission of greenhouse gases (GHG) of anthropogenic form, agricultural soils have significantly contributed through the emission of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). When the contribution of each GHG is separated, agriculture accounts for about 60% and 50% of total anthropogenic N_2O and CH_4 emissions, respectively (Tubiello et al. 2013).

In this context, rice cultivation (*Oryza sativa* L.) is an important source of GHG emissions. According to Smith et al. (2014), rice cultivation accounted for 11% of global CH_4 emissions in 2010. Although it is not the largest source of emissions, it is one of the few that can be managed, since the emission of CH_4 occurs due to anaerobic decomposition of organic matter. Its global warming potential (GWP) is also 25 times greater than CO_2. Emissions of N_2O are of great importance as well, because of their high GWP, which is 298 times greater than CO_2 (Bayer et al. 2015). In soils cultivated with flooded rice, submersion causes changes in the conditions of soil oxidation, promoting alternation in the microbial processes that are mainly responsible for the production of CH_4 and N_2O in the soil (Signor et al. 2013).

With the growing demand for more efficient management of water resources, alternatives have been sought to reduce the use of water without affecting the productivity of rice cultivation (Avila et al. 2015). Water management has been recognized as an important practice that affects CH_4 and N_2O emissions from rice crops. Aiming at sustainable management, the use of different irrigation systems and rice cultivars can be cited (Sartori et al. 2013). Regarding irrigation systems, the flood system in rice cultivation requires the use of large amounts of water. This results in the development of efficient irrigation and water management practices, such as the use of intermittent flooding and modification of the CH_4 and N_2O emission standards of lowland soils (Hou et al. 2012).

Alternatively, the selection of rice cultivars is an agronomic option that also affects CH_4 and N_2O emissions. In this sense, future consumer policies and demands can influence the choice of cultivars, based on the carbon balance in the production system (Brye et al. 2017). In studies with hybrid and conventional cultivars, hybrids have resulted in a lower CH_4 emission than conventional cultivars (Rector et al. 2018), due to increased CH_4 oxidation rates during the latter part of the growing season (Ma et al. 2010). However, Simmonds et al. (2015) reported that there was no difference in N_2O emissions by area and scale, between a hybrid cultivar and conventional cultivars, and that rice cultivars had high phenotypic plasticity due to interactions with the environment. They also reported that the differences in CH_4 emissions between hybrid and conventional cultivars depend on environmental conditions, plant growth and their morphological characteristics. Rector et al. (2018) evaluated the emission of N_2O and the GWP of rice cultivars under different irrigation management and observed a difference only in the GWP of cultivars with lower values for the hybrid cultivar evaluated. Therefore, the study of different managements of irrigation and cultivars is of great importance, because they serve as an alternative to increase productivity without increasing planted area and water consumption.

In this sense, the objective of this study was to quantify the CH_4 and N_2O emissions in the rice crop, when submitted to different irrigation management methods, by evaluating the grain yield and the GWP of the different managements.

MATERIAL E METHODS

Experimental procedures and design

The experiment was conducted in the municipality of Santa Maria/RS, Brazil (29°43’08.8”S, 53°43’18.6”W), in the 2016/17 and 2017/18 growing seasons. The climate of the area is humid subtropical (Cfa in the Köppen classification), with an average annual precipitation of 1,686 mm and average annual temperature of 19.3ºC. The soil where the experiment was conducted is classified as sandy Eutrophic Haplic Planosol with the following characteristics:

- pH_{water} (1:1) = 4.6;
- P = 3.7 mg·dm^{-3};
- K = 0.14 cmolc·dm^{-3};
- Organic matte = 10 g·kg^{-1}.

The experiment site was kept fallow during the 2016 and 2017 off-seasons, and before sowing, the land was leveled, and after these operations, the earth dikes and the drainage channels were built, with each plot delimited by earth dikes.

In the growing season prior to the implantation of the experiment, the area was cultivated with rice. The two years of experiment were conducted in the same place.

The experimental design used was randomized blocks in a factorial scheme (2×4), referring to water management and rice cultivars, with four replications. The evaluated treatments related to the cultivar factor were composed of four cultivars of rice: one conventional (IRGA 424 RI) and three hybrids (XP 113, Titan CL, and Lexus CL). Regarding the water management factor, two treatments were applied: a permanent irrigation and an intermittent irrigation. In permanent irrigation, the soil was flooded at the V3 development stage according to the scale of Counce et al. (2000) and maintaining a water depth of approximately 10 cm to the R8 stage. In intermittent irrigation the soil was flooded in V3, maintaining the water depth of approximately 10 cm up to the V6 stage and applying intermittent irrigation to the R3 stage by restarting the permanent irrigation until the R8 stage.

In the 2016/17 crop season, the sowing of the rice was carried out on November 6, 2016, and in the 2017/18 crop season, on November 1, 2017. In both crops, the seeding densities used were 90 kg ha-1 for cultivar IRGA 424 RI and 45 kg·ha^{-1} for cultivars XP 113, Lexus CL, and Titan CL, with a spacing of 0.17 m between rows and a total of 18 rows for 13.77 m^2 (3.06 × 4.5 m). The fertilization was provisioned with 400 kg·ha^{-1} from the formula 05-20-20 (N-P-K). The emergence of plants occurred on November 14, 2016 and November 10, 2017, in the 2016/17 and 2017/18 crop seasons, respectively. In both crops, the first nitrogen fertilization of the cover was carried out in the V3 stage, providing 100 kg of N·ha^{-1}, as well as potassium fertilization of 40 kg K_2O·ha^{-1}. In the V8/R0 stage, the second nitrogenous fertilization was carried out with a dose of 50 kg of N·ha^{-1}, providing a total of 170 kg of N.·ha^{-1}, 80 kg of P_2O_5·ha^{-1} and 120 kg of K_2O·ha^{-1} in both crops seasons. The other crop treatments were performed in accordance with the technical recommendations of SOSBAI (2018).

Water management

Irrigation was started at the V3 stage, at 17 and 14 days after emergence of plants (DAE), in the 2016/17 and 2017/18 harvests, respectively. Water supply through irrigation was also performed up to the V6 stage. After that, the water supply by irrigation with intermittent management was ceased.

In the 2016/17 crop season, due to the meteorological conditions (Fig. 1), three soil drainages were performed (December 28, 2016; January 5, 2017; and January 17, 2017), so that the intermittent irrigation treatment did not remain flooded. The first drainage was performed one day after precipitation of 67.6 mm, but, due to precipitation on the following days, the soil remained saturated. Eight days after the first drainage, a new soil drainage was performed, due to the accumulated precipitation of 80.4 mm during this interval of days. The third drainage was performed after a cumulative precipitation of 146.2 mm, with no precipitation above 1 mm in the following week, remaining without the presence of flooding until the R3 stage.

In the 2017/18 crop season, treatments with intermittent irrigation were used to irrigate the soil on only one occasion between the V6 and R3 stages, with water supply on January 9, 2018, as on this date the soil moisture was without the presence of a water depth. At the R3 stage (January 30, 2017; and January 23, 2018, in the 2016/17 and 2017/18 seasons, respectively), the water supply was reintroduced to the treatments with intermittent irrigation management, thus maintaining a constant water depth until the R8 stage when the water supply for both irrigation managements was suppressed.

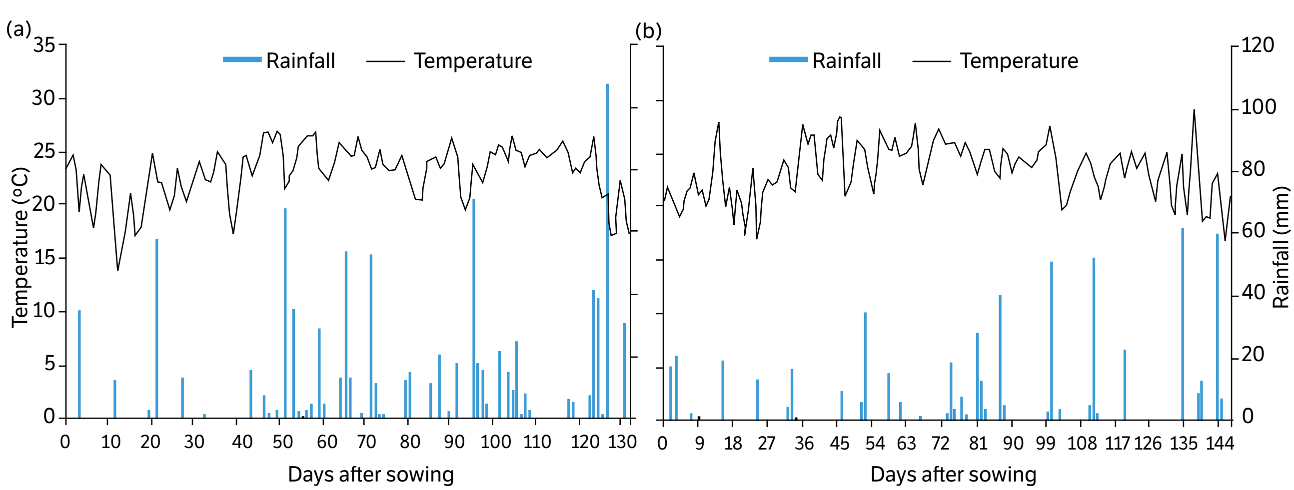

Figure 1. Variation of mean temperature and rainfall in Santa Maria, RS, Brazil, in the (a) 2016/17 and (b) 2017/18 crop seasons.

Gas collection

Gas samples were collected weekly, starting one and seven days before irrigation in the 2016/17 and 2017/18 seasons, respectively, from 9 a.m. to noon, using a system composed of a base and chamber according to the method of the closed static chamber proposed by Mosier (1989). The dimensions of the galvanized steel square chambers were 0.20 m in height and 0.40 m in width and length. In order to carry out the evaluations during the rice cultivation after plant growth, extensions were inserted (0.50 × 0.40 × 0.40 m, height, width and length, respectively) next to the base (0.40 × 0.40 × 0.40 m, height, width and length, respectively) and fixed at 0.10 m depth to adapt the chamber height to the rice plants. During the period of GHG emission assessments, the bases were allocated in the plots, so that three rows of sowed rice were inside each base.

The air circulation was performed in a 30-second interval for the homogenization of the internal atmosphere, immediately prior to sampling. Aiming for isolation between the external and internal atmosphere, each chamber was fitted to the base chute, and then water was added to seal it. The air samples inside the chambers were collected with 20-mL polypropylene syringes at four instances (0, 8, 16 and 24 min) after placing the chamber on the base. After each collection, the samples were transferred to previously evacuated glass tubes and taken to the laboratory for analysis.

The concentration of CH_4 and N_2O was determined by means of gas chromatography (Shimadzu GC – 2014 Greenhouse model). The flows (F) of N_2O and CH_4 were calculated (Equation 1) considering the chamber volume, the occupied soil area, the molecular weight of the gases, and the variation of the gas concentrations within the chamber during the closed period. The cumulative emissions were calculated from the average of the N_2O and CH_4 between two consecutive collections and multiplying the resulting value by the interval of time, in days, between the two collections.

$$F = \frac{dC}{dt} \frac{\underline{M}PV}{RT} \frac{1}{A} \tag{1}$$

in which: dC/dt = the change in the concentration of CH_4 or of N_2O ($mmol \cdot mol^{-1}$) in the time interval t (min); $\underline{M}$ = the molecular weight of the respective gas ($g \cdot mol^{-1}$); P = the pressure (atm) inside the chamber (assumed as 1.0 atm); V and T = the volume of the chamber (L) and the internal temperature (K); R = the universal gas constant (0,08205 $atm\ L \cdot mol^{-1} \cdot K^{-1}$).

The partial global warming potential (pGWP) was calculated for the period of rice cultivation, according to Bayer et al. (2015), through the conversion of emissions of CH_4 and of N_2O to CO_2 equivalent (kg CO_2 equiv.$\cdot ha^{-1}$), according to Eq. 2.

$$pGWP = (CH_4 \times 25) + (N_2O \times 298) \tag{2}$$

in which: CH_4 and N_2O = the cumulative emissions of each gas during a crop season ($kg \cdot ha^{-1}$); 25 and 298 = the respective values of GWP to CH_4 and N_2O.

Weather data were obtained from an Automatic Meteorological Station 500 m from the experiment site.

Harvesting of grains

The experimental harvest was carried out when the humidity of the rice grains was between 20 and 24%, and performed manually in the useful area of each experimental plot (4.25 m^2). The mass was threshed and corrected to 13% moisture to determine grain yield. In the 2016/17 crop season, the cultivar Titan CL was harvested on March 8, 2017, while the cultivars XP 113, Lexus CL and IRGA 424 RI were harvested on March 17, 2017. In the 2017/18 crop season, the cultivars Titan CL, XP 113, and Lexus CL were harvested on March 12, 2018, and the cultivar IRGA 424 RI was harvested on March 16, 2018. The relation between pGWP and grain yield was calculated (Y – $kg \cdot ha^{-1}$) according to Eq. 3.

$$YpGWP = pGWP/Y \tag{3}$$

Statistical analysis

The analyzed variables were submitted to test the assumptions of the mathematical model (normality of the errors and homogeneity of the variances). The variance analysis of experimental data was performed using the F test ($p < 0.05$), and when significant the Tukey's test ($p < 0.05$) for the comparison of means, using the statistical program SISVAR.

RESULTS AND DISCUSSION

There was no interaction between the factors for any of the analyzed variables, with an isolated effect for the cultivars and water management in both crop seasons.

Methane emission

In the 2016/17 crop season, the flows of CH_4 varied from 0.17 to 7.47 $kg{\cdot}ha^{-1}{\cdot}day^{-1}$, and between -0.06 and 7.02 $kg{\cdot}ha^{-1}{\cdot}day^{-1}$ during the cultivation cycle of the 2017/18 crop season. Regarding water management, the variation was 0.04 to 6.36 $kg{\cdot}ha^{-1}{\cdot}day^{-1}$ in the 2016/17 crop season, and between 0.03 and 6.74 $kg{\cdot}ha^{-1}{\cdot}day^{-1}$ in the 2017/18 crop season. In the 2017/18 crop season, there was a negative flow of CH4 after the rice harvest, according to the results already reported by Meijide et al. (2017).

The redox potential is one of the main factors controlling the formation of CH4 in flooded soils. Such intensification occurs after the reduction of nitrate (III), Mn (IV) and Fe (III), which takes about 20 days to occur, depending on soil characteristics (Silva et al. 2011). When the maximum redox potential and the formation of CH_4 by the mineralization of organic matter present in the soil are reached, the availability of soil-labile carbon increases, and serves as a substrate for the methanogenic bacteria (Cai et al. 1997).

The first emission peaks were at 33 and 28 days after irrigation (DAI) in the 2016/17 (Fig. 2a) and 2017/18 (Fig. 2b) crop seasons, respectively. The difference of CH_4 flows, in relation to the cultivars during the initial period of cultivation, may be related to the initial population of plants. In hybrid cultivars, it is inferior to cultivar IRGA 424 RI, and the beginning of irrigation coincides with the beginning of tillering of the rice crop. The ability of rice plants to transport CH_4 increases with the amount and size of the tiller, leaves and roots, and also of the structures involved in the transport of CH_4 from the soil to the atmosphere. In the initial phase of tillering, the morphological structures are not fully developed. For this reason, the plant's potential to transport CH_4 to the atmosphere is low, no matter the emission potential of the cultivars or of the soil reduction conditions. The CH_4 emissions are greater when the anaerobic conditions allow the formation, but also when the plant is fully developed, so that the main route of transport of CH_4 to the atmosphere is available (Meijide et al. 2017).

In both crop seasons, there was reduction in CH_4 flow after the first peak, but in the 2017/18 season the reduction was lower than in the previous harvest. This is probably due to soil drainage in the 2016/17 season, because in the 2017/18 season the soil was not drained, and the intermittency occurred due to the suppression of irrigation. However, in both crops, there was a new peak near the R4 stage, mainly for the cultivar Lexus CL. At this stage, the plants meet their highest indexes of leaf area (SOSBAI 2018), contributing for greater passage of the gases from the soil to the atmosphere. The aerenchyma, fully developed in rice plants during flowering stage, has increased transport capacity of CH_4 from soil to atmosphere (Kludze et al. 1993). In addition, a fraction of photo-assimilated carbon is translocated to the roots at the reproductive stage, which provides a labile carbon source for methanogenic bacteria (Zschornack et al. 2018). The intense photosynthetic activity of the plant near its flowering increases the release of root exudates, which serve as a carbon source. Under equal soil reduction conditions, the availability of substrate for methanogenic bacteria is one of the factors that determine the intensity of the CH_4 (Wassmann and Aulakh 2000). Regarding the irrigation management during the whole 2016/17 crop cycle, intermittent irrigation treatment had lower CH_4, even with precipitations that left the soil only partially aerated. When drainage is carried out, the soil surface layer tends to have greater aeration, which may result in changes in the soil oxidation-reduction processes and in the activity of methanogenic microorganisms. There was a trend of higher flow of CH_4 in the treatment with intermittent irrigation when compared to treatment with permanent irrigation at only 97 DAI (Fig. 2c), and also reduction in emissions at 70 DAI. This decrease can be attributed to the temporary aeration of the soil caused by the partial drying, which in turn suppresses methanogenic activity and may increase aerobic methanotrophic activity (Tarlera et al. 2016). In the 2017/18 season after the period of intermittence, when the soil had a constant water depth, the soil oxidation process alternatively resulted in an increase in the CH_4 flow. A greater flow of CH_4 was also observed in the treatment of intermittent irrigation (Fig. 2d) in the collections at 84 and 94 DAI.

In years subject to high rainfall, there is the possibility that the intermittent irrigation system does not mitigate the emission of CH_4 in relation to permanent irrigation, due to reduced soil maintenance (Moterle et al. 2013). In addition, rice plants under aerobic soil conditions may show less developed aerenchyma compared to those under anaerobic conditions (Kludze et al. 1993), which may further reduce transport and emissions of CH_4.

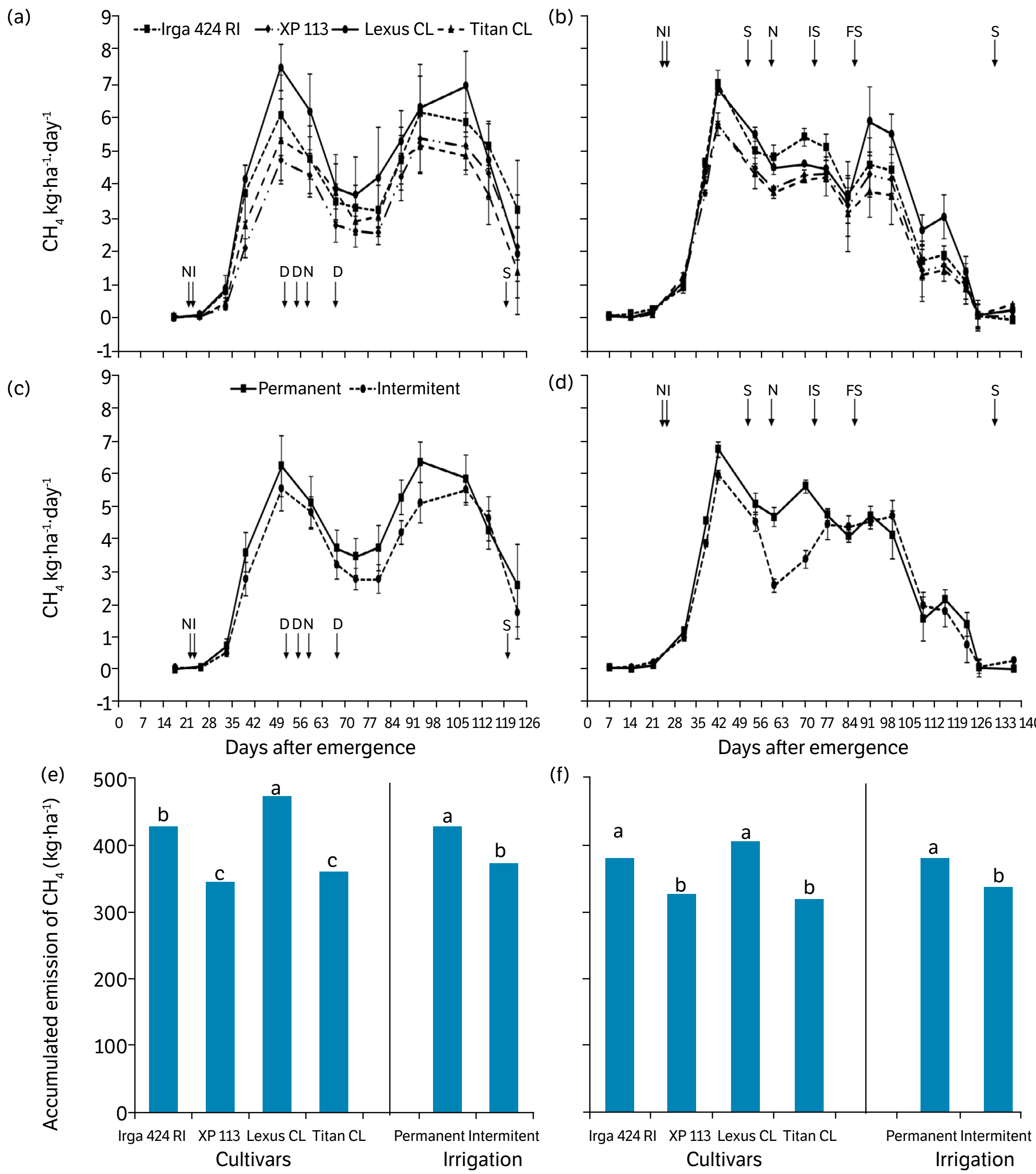

Figure 2. (a, b, c and d) Average daily flow and (e and f) accumulated emission of CH4 in the soil under (a and b) rice cultivars and (c and d) management of water in rice cultivation in the (a, c and e) 2016/17 and (b, d and f) 2017/18 crop seasons*.

*The error bars represent the confidence intervals. Equal letters in the bars do not differ from each other by the Tukey's test ($p < 0.05$); N: nitrogen fertilization; I: beginning of irrigation; D: drainage; S: irrigation suppression; IS: irrigation during suppression; FS: end of irrigation suppression.

In relation to the total emission of CH_4 (Figs. 2e and 2f) during the rice crop cycles in the 2016/17 and 2017/18, the cultivars XP 113 (343.91 and 324.98 kg $CH_4 \cdot ha^{-1}$) and Titan CL (361.63 and 318.03 kg $CH_4 \cdot ha^{-1}$) had lower values, followed by cultivars IRGA 424 RI (425.42 and 377.30 kg $CH_4 \cdot ha^{-1}$) and Lexus CL (474.17 and 404.79 kg $CH_4 \cdot ha^{-1}$). Several authors observed higher emissions of CH4 in rice cultivation with conventional cultivars compared to hybrid cultivars (Rogers et al. 2014; Smartt et al. 2016; Brye et al. 2017). However, in the present study of the 2016/17 and 2017/18 crop seasons, the hybrid cultivar Lexus CL emitted the largest amount of CH_4, not differentiating from the conventional cultivar IRGA 424 RI in the second harvest. Differences in emissions among cultivars may be related to changes in the physiological characteristics of plants associated with the intensity of anaerobic conditions (Kludze et al. 1993) or related to the differences in the microbial communities associated to the rhizosphere of conventional and hybrid cultivars (Ma et al. 2010). In addition, differences in cultivars may be related to other physiological differences, such as tillering ability, root factors and aerenchyma tissue formation (Cai et al. 1997).

The average emission of CH_4 for the two years of cultivars XP 113 (334.45 kg·ha^{-1}), Titan CL (339.83 kg·ha^{-1}), IRGA 424 RI (401.36 kg·ha^{-1}) and Lexus CL (439.48 kg·ha^{-1}), as well as treatments with permanent irrigation (403.84 kg·ha^{-1}) and intermittent (353.72 kg·ha^{-1}), is in the same range as other studies conducted in the Southern region of Brazil. These results are similar to those ones observed when Moterle et al. (2013) evaluated permanent irrigation application (381.90 kg $CH_4 \cdot ha^{-1}$) and intermittent irrigation (313.5 kg $CH_4 \cdot ha^{-1}$). Studying different water management, Camargo et al. (2018) had results that ranged from 237 (two intermittency in the rice cycle) to 623 (permanent irrigation) kg $CH_4 \cdot ha^{-1}$, while Zschornack et al. (2018) verified variation of CH_4 between 250.9 and 671.5 kg $CH_4 \cdot ha^{-1}$. Furthermore, Bayer et al. (2015) evaluated seven crop seasons of the rice and found average emission per crop of 367 kg $CH_4 \cdot ha^{-1}$.

Emission of nitrous oxide

The highest peaks were observed in 16 and seven DAE in the 2016/17 and 2017/18 crop seasons, respectively. In the 2016/17 crop season, these peaks were at 62.60; 54.98; 51.91 and 44.32 g of $N_2O \cdot ha^{-1} \cdot day^{-1}$ for the soils with the cultivars Lexus CL, Titan CL, XP 113 and IRGA 424 RI, respectively (Fig. 3a). In the 2017/18 crop season, the peaks were at 106.96; 98.24; 92.16; and 89.71 g of $N_2O \cdot ha^{-1} \cdot day^{-1}$ for soils with the cultivars IRGA 424 RI, Lexus CL, XP 113, and Titan CL, respectively (Fig. 3b). The high flow of N_2O may be related to the precipitations that occurred before the collection of air, which totaled 58.2 and 18.8 mm, at four days before collection in the 2016/17 crop season and one day before collection in the 2017/18 crop season, respectively.

Precipitation followed by dry days may potentiate losses of N in the form of N_2O, because, in periods without rain, the aerobic conditions favor the nitrification of the N applied, forming NO_3^-. This can be used later (under conditions of low availability of O_2) as an electron acceptor by the facultative anaerobic bacteria responsible for the denitrification process. However, Tarlera et al. (2016) did not relate the emission peaks of N_2O before the beginning of irrigation with precipitation events. In both crops, after the second nitrogen fertilization, no increase in N_2O flows was observed. However, negative flow was noticed in the areas with the cultivars Lexus CL, XP 113 and IRGA 424 RI, as well as during the intermittent period. The flows of N_2O were variable throughout the growing season and were generally low, even in treatment with intermittent irrigation, in which higher emission of N_2O was expected than with permanent irrigation. The cumulative emission of N_2O in the 2016/17 and 2017/18 crop seasons were about 79 and 45% before the beginning of irrigation, respectively.

During the cultivation period, there were negative emissions for both permanent and intermittent irrigation treatment. The highest inflows were at 97 and 56 DAI (2016/17 crop season), respectively (Fig. 3c) and at 63 and 84 DAI (2017/18 crop season), respectively (Fig. 3d). As with the results of Tarlera et al. (2016), the cumulative emission of N_2O was not significantly different with the application of intermittent irrigation treatment.

In two seasons, the values of N_2O emission that accumulated due to water management did not differ, with differences only due to the rice cultivars. The fact of having predetermined the dates for the collection of CH_4 possibly did not favor the detection of the released N_2O in these treatments, whose dynamics and production conditions are quite distinct from CH_4. According to Rector et al. (2018), the weekly gas sampling scheme may have masked potential significant flows or differences in the combination of treatments that may have occurred at shorter time scales when the flows of N_2O are temporarily variable in rice fields (LaHue et al. 2016).

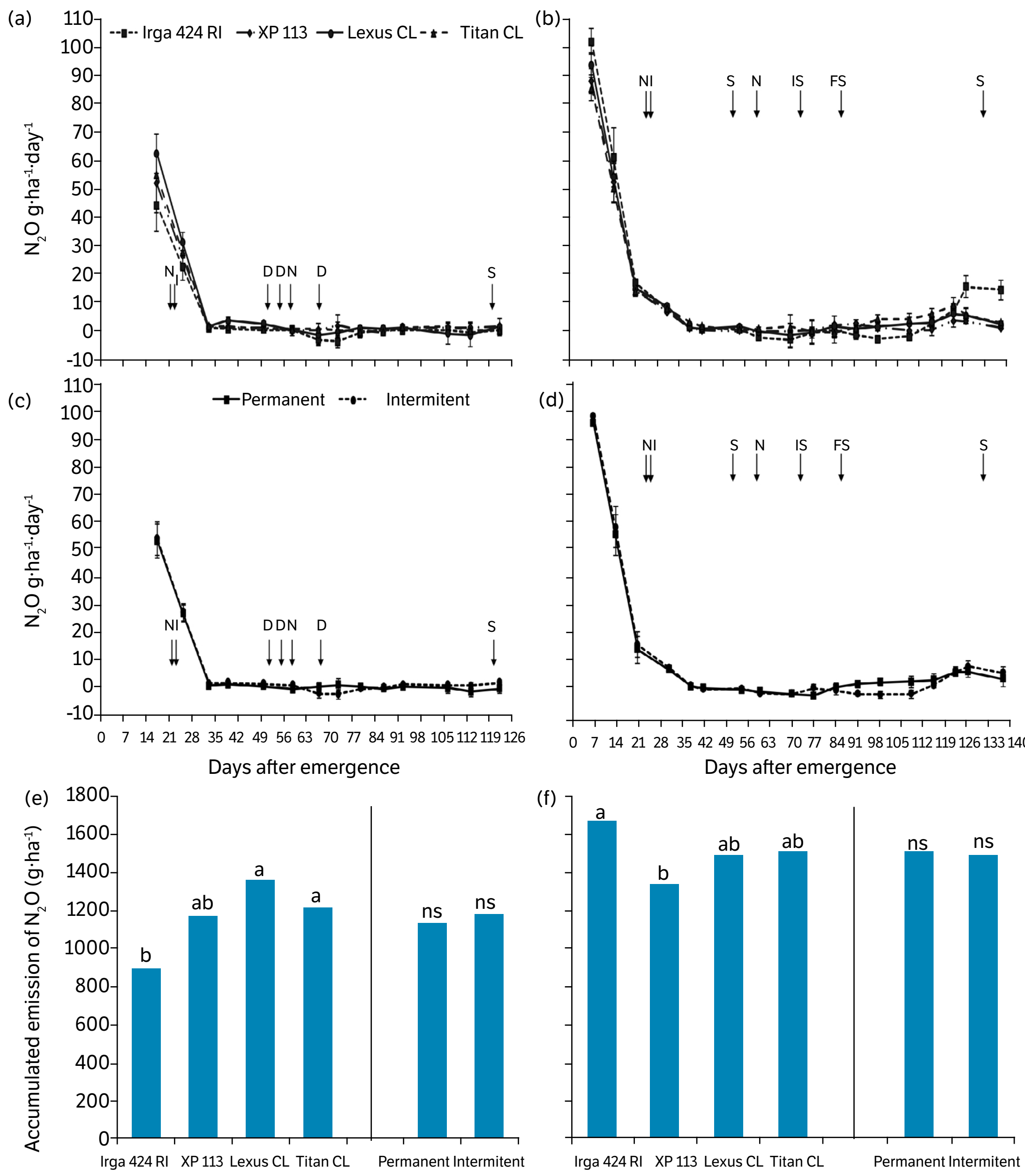

Figure 3. (a, b, d and d) Average daily flow and (e and f) cumulative emission of N_2O in soil under (a and b) rice cultivars and (c and d) management of water in rice cultivation in the (a, c and e) 2016/17 and (b, d and f) 2017/18 crop seasons*.

*The error bars represent the confidence intervals. Equal letters in the bars do not differ from each other by the Tukey's test ($p < 0.05$); N: nitrogen fertilization; I: beginning of irrigation; D: drainage; S: irrigation suppression; IS: irrigation during suppression; FS: end of irrigation suppression.

In the 2016/17 crop season, the cultivars with the lowest total N_2O emissions were IRGA 424 RI and XP 113, however the XP 113 did not differ from Lexus CL and Titan CL. The total emissions in the crop cycle were 887.63; 1,164.39; 1,212.02; and 1,357.18g of $N_2O{\cdot}ha^{-1}$ for the cultivars IRGA 424 RI, XP 113, Titan CL and Lexus CL (Fig. 3e). On the other hand, in the 2017/18 crop season, the IRGA 424 RI cultivar had the highest total N_2O emission (1,665.6 g of $N_2O{\cdot}ha^{-1}$), but did not differ from cultivars Lexus CL (1,489.1 g of $N_2O{\cdot}ha^{-1}$) and Titan CL (1,507.9 g of $N_2O{\cdot}ha^{-1}$), which also did not differ from the cultivar with lower N_2O emission, the XP 113, which emitted the total of 1,336.4 g of $N_2O{\cdot}ha^{-1}$ (Fig. 3f).

As in the results found in the present study, Rector et al. (2018) observed that the weekly flows of N_2O and accumulated emissions were not affected by water management. They also did not observe differences in accumulated emission between conventional and hybrid rice cultivars. In the present study, there was no difference between cultivars XP 113 and IRGA 424 RI in the 2016/17 season, nor among Titan CL, Lexus CL and IRGA 424 RI cultivars in the 2017/18 crop season.

Partial global warming potential, grain yield and pGWP/Y

For the variable pGWP (calculated in CO_2 eq), there were differences related to cultivars and water management in both crop seasons. A mean participation of 96.64 and 94.19% of CH_4 in pGWP for the cultivars and of 96.66 and 95.21% in relation to water management was calculated for the 2016/17 (Fig. 4a) and 2017/18 (Fig. 4b) crop seasons, respectively. A large contribution of CH_4 in GWP related to N_2O was observed in several other works (Bayer et al. 2015; Camargo et al. 2018; Zschornack et al. 2018). These results demonstrate the great importance of CH_4 emitted in rice fields and the need to add mitigating measures for the emission of the gas. The use of cultivars and irrigation water management in the present study has proved to be effective as mitigating measurements of the emission of CH_4 and the pGWP.

The cultivars with lower pGWP were the XP 113 and Titan CL, with the emission of 8,944.78 and 9,402 kg CO_2 eq·ha^{-1}, respectively in the 2016/17 season, and 8,522.69 and 8,400.13 kg CO_2 eq ha^{-1}, respectively, in the 2017/18 crop season. When comparing the average of the cultivars with lower pGWP with the average of the cultivars with the highest pGWP, reduction of 21.60 and 14.41% was observed in pGWP in the 2016/17 and 2017/18 crop seasons, respectively. Regarding irrigation management, a lower pGWP was observed when soil drainage and irrigation intermittence were performed, with values of 12.40 and 11.28% smaller when compared to permanent irrigation.

The pGWP demonstrates how GHGs contribute to global warming and their relationships compared to CO_2. In this way, different managements that are adopted in the production systems can be compared. The pGWP is directly related to emissions of CH_4 and N_2O. Thus, the treatments with higher emission of these gases tend to have greater pGWP. However, as observed in the results of the present study, the CH_4 emissions for the rice crop are more significant for this variable due to the large amount emitted in their cultivation cycle. In addition to concerns about CH_4 emissions in irrigated rice areas, rice productivity also needs to be considered (Tarlera et al. 2016).

The cultivars with higher and lower productivity in the two harvests were XP 113 and IRGA 424 RI, respectively. The cultivars Lexus CL and Titan CL did not differ in relation to grain yield in both crop seasons. The productivity difference is related to the productive characteristics of each cultivar, since all the cultivars were submitted to treatments with the same conditions (Figs. 4c and 4d). In the 2016/17 crop season, there was no difference in productivity due to water management – a result similar to that found by Avila et al. (2015) and Zschornack et al. (2016), both in the southern region of Brazil. In the other hand, Meijide et al. (2017) observed reduction of production with implantation of an intermittent irrigation system in the Mediterranean region, as well as in the results of the 2017/18 crop season. This demonstrates that local and climatic conditions may be determinant for rice yield in systems with intermittent irrigation. However, the effect of irrigation after the period of intermittence may also contribute to the increase of grain yield, as grain yield is determined not only by irrigation regimes, but also by the applied N rates (Avila et al. 2015).

According to Sass and Cicerone (2002), under a common set of climatic and agricultural conditions, lower CH4 emissions are observed from plots containing rice plants with a higher number of grain-filled spikelets. This indicates that those closest to their potential yield limit emit less CH4 into the atmosphere, thus resulting in a lower index of pGWP/Y. For the calculation of pGWP per unit of yield (pGWP/Y), it was considered the result of the productivity and the emission of CO_2eq (CH_4+N_2O).

In relation to the pGWP/Y index, the cultivar XP 113 (0.65 and 0.66 kg CO_2 eq. kg·rice^{-1} in the 2016/17 and 2017/18 crop seasons, respectively) had presented the best results. This occurred because the lower this index is, the lower the pGWP/Y and consequently greater the mitigation carried out for this cultivar in relation to the other ones. However, in the 2017/18 crop season, the cultivar XP 113 did not differ from the cultivar Titan CL (0.69 kg CO_2 eq. kg·rice^{-1}). When comparing the cultivars Lexus CL (0.99 and 0.87 kg CO_2 eq. kg·rice^{-1}) and IRGA 424 RI (1.01 and 0.89 kg CO_2 eq. kg·rice^{-1}) in the respective 2016/17 and 2017/18 crop seasons, which were the cultivars with the highest pGWP/Y indexes and greater pGWP due to greater productive potential, the cultivar Lexus CL did not differ from IRGA 424 RI. Therefore, the use of pGWP/Y can serve as an aid tool to make a decision about the adoption of a particular management practice.

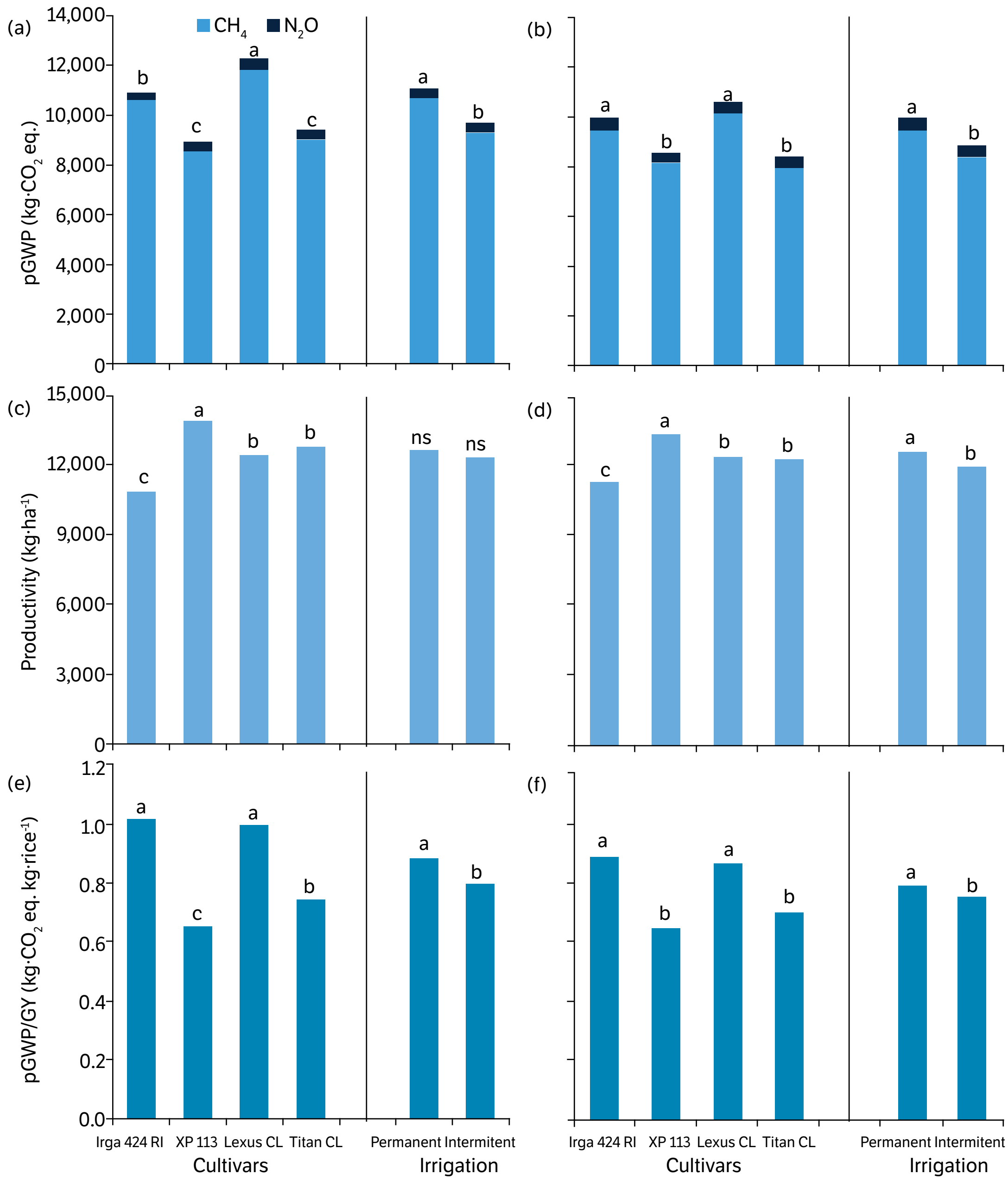

Figure 4. (a and b) Partial global warming potential, (c and d) productivity, and (e and f) index partial global warming potential per unit of yield (pGWP/Y) of rice cultivars and water management in rice cultivation during the (a, c and e) 2016/17 and (b, d e f) 2017/18 crop seasons in Santa Maria, RS, Brazil*.

*Equal letters in the bars do not differ from each other by the Tukey's test ($p < 0.05$); nsnot significant.

There are reports in the literature of reduction of pGWP by mass of grains produced when using hybrid cultivars in relation to conventional cultivars, such as the studies conducted in China (Ma et al. 2010) and in the United States (Rogers et al. 2014). Smartt et al. (2016), who observed mean reduction of 44% of pGWP/Y when comparing a hybrid cultivar with two conventional cultivars in the present study of the 2016/17 crop season, found a 36%-reduction in pGWP/Y of the hybrid cultivar XP113 when compared to the cultivar IRGA 424 RI (Fig. 4e). In the 2017/18 crop season, there was reduction of 24.51% of pGWP/Y of the means of the hybrid cultivars XP 113 and Titan CL when compared to the cultivar IRGA 424 RI (Fig. 4f).

Regarding the irrigation management of both harvests, there was reduction of pGWP/Y when irrigation was intermittent in the rice crop. This fact was observed because there was reduction in CH4 emission when irrigation intermittence was carried out in the two crop seasons. However, even with intermittent irrigation management reducing grain yield in the 2017/18 crop season, the pGWP/Y for this treatment remained below the management of permanent irrigation. The use of pGWP/Y as a parameter for mitigation assessments serves to identify management practices that, even with the emission of large amounts of GHG, result in higher productivity and can be considered as a mitigation of the same (Kim et al. 2013). According to the results presented, it is observed that genetic material and irrigation management are factors that influence pGWP/Y. However, other soil managements are also effective in mitigating pGWP/Y (Bayer et al. 2015; Zschornack et al. 2018) in irrigated rice crops. It can be emphasized that local characteristics such as climate, soil and technological level can also influence this variable.

CONCLUSION

The XP 113 hybrid emits less methane and nitrous oxide, besides presenting higher grain yield, which ensures, together with the cultivar Titan CL, lower pGWP and lower index pGWP/Y.

Intermittent irrigation, combined with low rainfall, negatively affects rice grain yield, but results in lower methane emission, pGWP and pGWP/Y. In this sense, more precise criteria should be met to evaluate the degree of burst. There was no difference in nitrous oxide emission as a function of irrigation management.

AUTHORS' CONTRIBUTION

Conceptualization: Nunes, J. A. S.; Marchesan, E.; **Methodology:** Nunes, J. A. S.; Marchesan, E.; Giacomini, S. J.; Grohs, M.; **Investigation:** Nunes, J. A. S.; Grohs, M.; Taschetto, A. M.; Fortuna, C. R.; Soares, C. F.; Fleck, A. G.; Donato, G.; **Writing – Original Draft:** Nunes, J. A. S.; **Writing – Review and Editing:** Nunes, J. A. S.; Marchesan, E.; **Funding Acquisition:** Nunes, J. A. S.; Marchesan, E.; **Resources:** Marchesan, E.; Giacomini, S. J.; **Supervision:** Marchesan, E.; Giacomini, S. J.

DATA AVAILABILITY STATEMENT

All dataset were generated and analyzed in the current study..

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