Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil Fertility and Plant Nutrition

Straw management effects on global warming potential and yield-scaled greenhouse gas emissions in a subtropical rice ecosystem

Eduardo Lorensi de Souza[(1)], Douglas Adams Weiler[(2)], Cimelio Bayer[(3)], Enio Marchesan[(4)], Bruno Chaves[(4)], Getúlio Elias Pilecco[(4)], Raquel Schmatz[(4)] and Sandro José Giacomini[(4)*]

[(1)] Universidade Estadual do Rio Grande do Sul, Três Passos, Rio Grande do Sul, Brasil.
[(2)] Universidade Federal de Santa Catarina, Centro de Ciências Rurais, Coordenadoria Especial de Ciências Biológicas e Agronômicas, Curitibanos, Santa Catarina, Brasil.
[(3)] Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Departamento de Solos, Porto Alegre, Rio Grande do Suk, Brasil.
[(4)] Universidade Federal de Santa Maria, Centro de Ciências Rurais, Departamento de Solos, Santa Maria, Rio Grande do Sul, Brasil.

*** Corresponding author:**
E-mail: sjgiacomini@ufsm.br

Received: September 30, 2022

Approved: February 23, 2023

How to cite: Souza EL, Weiler DA, Bayer C, Marchesan E, Chaves B, Pileccol GE, Schmatz R, Giacomini SJ. Straw management effects on global warming potential and yield-scaled greenhouse gas emissions in a subtropical rice ecosystem. Rev Bras Cienc Solo. 2023;47nspe:e0220134
https://doi.org/10.36783/18069657rbcs20220134

Editors: Carlos Eduardo Pellegrino Cerri and Maurício Roberto Cherubin.

ABSTRACT: Global warming potential (GWP) of rice paddies depends on straw management. This study evaluated methane (CH_4) and nitrous oxide (N_2O) emissions and soil C stocks to determine GWP and yield-scaled GWP under different strategies and intensities of rice straw management in a subtropical climate. We hypothesized that decreasing soil management intensity and straw incorporation in the soil would reduce GWP. Methane fluxes were substantially higher during the rice growing season than in the off-season, while the opposite was observed for N_2O fluxes. The cumulative emissions of CH_4 during the growing season among the straw management strategies evaluated ranged from 165.8 to 586.0 kg ha^{-1}. Annual CH_4 emissions were lower when soil and straw received some type of management compared to no-tillage. Daily N_2O fluxes ranged from -2.8 to 201.7 g ha^{-1} day^{-1}; cumulative N_2O emissions during the off-season ranged from 455.2 to 2816.5 g ha^{-1}. During the off-season, strategies to reduce N_2O emissions include post-harvest straw incorporation using a disc harrow, winter straw removal, and ryegrass cropping. Soil organic C stocks ranged from 35.96 to 38.36 Mg ha^{-1}. Straw management using a disc harrow reduced soil organic C stocks, with more adverse effects than straw removal. Soil and rice straw management did not affect rice grain yield, with an average of 10.4 Mg ha^{-1}. Methane emissions were the main component of GWP in all straw management systems. The contribution of N_2O emissions to GWP was small and mostly (>85 %) determined by off-season emissions. Yield-scaled GWP ranged from 0.64 to 1.06 Mg CO_2eq Mg^{-1} yield and was lower when soil and straw management systems occurred shortly after the rice harvest. Our results indicate that soil and straw management immediately after rice harvest reduces CH_4 emissions, GWP, and yield-scaled GWP.

Keywords: nitrous oxide, methane, flooded rice, global warming potential, rice straw.

INTRODUCTION

Rice, which is world cultivated on almost 165 M ha (Faostat, 2021), serves as a staple food for more than 3 billion people, and demand for cereal, including rice, is expected to increase in the coming years (Alexandratos and Bruinsma, 2012; Zhu et al., 2018). Flooded rice comprises an area of approximately 93 M ha and is responsible for more than 75 % of the world's rice production (Rao et al., 2017). Areas in which rice is grown under flood irrigation are among the main sources of methane (CH_4) released to the atmosphere (Smith et al., 2014), as the anoxic conditions created by flooding encourage the decomposition of organic material and thus favor methanogenesis (Le Mer and Roger, 2001). Additionally, rice paddies can significantly contribute to nitrous oxide (N_2O) emissions, especially during the rice off-season (Zschornack et al., 2018), a period in which the soil is not flooded and is subjected to wetting and drying cycles that favor the production of N_2O by nitrification and denitrification processes (Congreves et al., 2018). Although rice production currently accounts for only approximately 11 % of total global agricultural GHG emissions (Pachauri et al., 2014), in southern Brazil, CH_4 from rice fields accounts for 20 % of GHG emissions from the agricultural sector (MCTI, 2016). Strategies to mitigate these emissions are crucial to the sustainability of rice production in this subtropical ecosystem (Bayer et al., 2014).

In rice fields, the timing of tillage or straw management has been considered essential to reduce the global warming potential (GWP) resulting from soil CH_4 and N_2O emissions (Sander et al., 2014; Yang et al., 2018). Bayer et al. (2015) showed that anticipation of tillage with straw incorporation into the soil in the autumn, shortly after the rice harvest in the Southern Hemisphere, was effective in reducing seasonal CH_4 emissions by 24 % compared to tillage and incorporation of straw into the soil in spring, just before sowing and soil flooding. According to the authors, with the anticipation of management, straw decomposes under aerobic conditions, producing CO_2 as a final product of microbial respiration, thus decreasing the amount of substrate for methanogenesis during the rice growing season under flood conditions. In Rio Grande do Sul state, the anticipation of tillage with straw incorporation and no-tillage is carried out in approximately 61 % of the area, while conventional tillage is still used in 30 % of the area; pregerminated rice fields occupy 9 % (Sosbai, 2018). An aspect that deserves attention is the combination of different implements and times for carrying out soil preparation and its impacts on the annual emissions of CH_4 and N_2O, encompassing the growing season and off-season periods. Most studies focus on the impact of agricultural practices on GHG emissions during the growing season without considering that off-season emissions can compromise potential environmental benefits in terms of annual emissions (Yang et al., 2018; Zschornack et al., 2018).

Soil tillage and straw management in areas under flooded rice can also affect soil organic C stocks, but the rates at which this occurs are not well-known in subtropical ecosystems. Although the effect of maintaining crop residues on the soil surface in the no-tillage system on the accumulation of C in the soil is recognized (Pandey et al., 2014), rice cropping in a subtropical Gleisol for 10 years in conventional tillage and no-tillage does not promote differences in organic C stocks in the 0.00-0.20 m layer (Nascimento et al., 2009). Little is known about the impacts of soil and straw management (soil surface or incorporation) on the storage of C in subtropical soils subjected to irrigated rice cultivation. Another aspect to be highlighted is that greater stocks of C in the soil can also mean greater emissions of CH_4 in the long term (Liu et al., 2014). Therefore, the benefits of soil and straw management practices on GHG emissions should ideally be evaluated by their global warming potential (GWP), which considers the emissions of the three main GHGs and their respective forcing indices (1 for CO_2, 28 for CH_4 and 265 for N_2O) according to Pachauri et al. (2014), and yield-scaled GWP, which yields the GWP per unit of rice grain yield (Mosier et al., 2006; Bayer et al., 2015).

Although soil CH_4 and N_2O emissions in paddy rice fields have been documented (Bayer et al., 2014, 2015; Moterle et al., 2013; Zschornack et al., 2016), to the best of our knowledge, this study is a pioneering one in assessing the effect of soil and straw management on net soil CO_2 fluxes (using changes in soil C as a proxy) and on seasonal GHG (CH_4 and N_2O) emissions in a subtropical paddy rice ecosystem in southern Brazil. We hypothesized that decreasing soil management intensity and straw incorporation in the soil would decrease the GWP of the field. This study aimed to evaluate the potential of different soil and straw management practices to mitigate GWP and yield-scaled GWP in a subtropical paddy rice field.

MATERIALS AND METHODS

Site and experiment description

The experiment was carried out over two years at the Federal University of Santa Maria, located in Rio Grande do Sul State, southern Brazil (29° 45′ S, 53° 42′ W, approximately 95 m altitude). The climate of the experimental area is humid subtropical, Cfa2 according to Köppen's classification system. The monthly mean air temperature varies from 14 °C for the coldest month (June) to 25 °C for the hottest month (January). The mean annual rainfall is 1,600 mm without a well-defined dry season. Air temperature and rainfall data were obtained from an automated weather station located 500 m from the experimental site. The soil was classified as *Planossolo Háplico* (Santos et al., 2018), corresponding to an Albaqualf (Soil Survey Staff, 2014). The soil layer of the 0.00-0.10 m presented the following physical and chemical properties at the installation of the experiment: 210 g kg^{-1} of sand, 220 g kg^{-1} of clay, 4.7 g kg^{-1} of carbon, pH(H_2O) (1:1 soil:water) 5.9, 16.2 mg dm^{-3} of P, 144 mg dm^{-3} of K, 6.8 $cmol_c$ dm^{-3} of Ca^{2+}, 1.5 $cmol_c$ dm^{-3} of Mg^{2+} and bulk density 1.42 Mg m^{-3}. Prior to the experiment, the site was planted with rice-fallow succession for two years.

The field experiment followed a completely randomized block experimental design, with four replicates in 3 × 4 m plots. The treatments consisted of a combination of soil and straw management during rice postharvest (PH) and presowing (PS) periods (Figure 1): 1 - no-tillage (NT); 2 - knife roller in the PH (KR PH); 3 - straw removal (SR); 4 - disc harrow in the PH (DH PH); 5 - NT + ryegrass (*Lolium multiflorum* L.) (NT + R); 6 - DH in the PS (DH PS); 7 – DH PH + DH PS; and 8 – KR PH + DH PS.

The treatments were applied for two consecutive years, right after the rice harvest from the previous season, in April 2010 and March 2011. All rice straw was removed from the

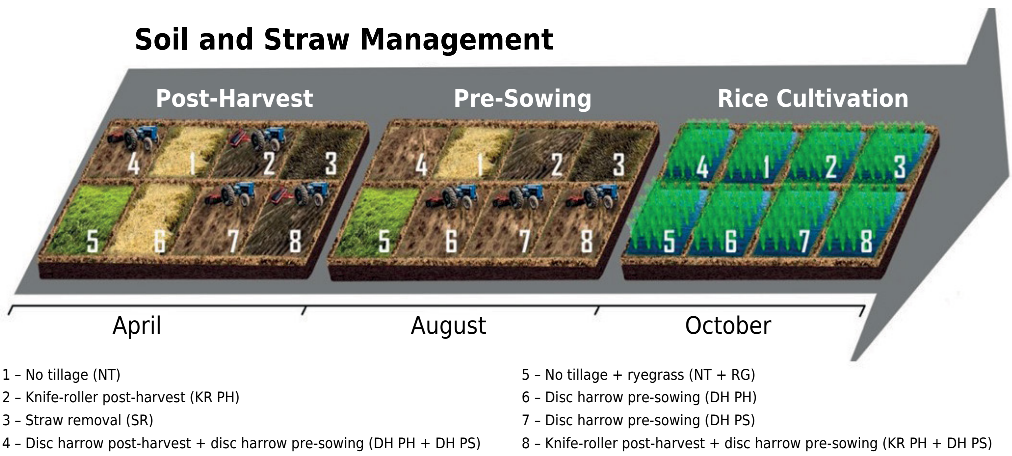

Figure 1. Schematic representation of the soil and straw management systems evaluated regarding greenhouse gas balance for two years (rice season and off-season) in a subtropical ecosystem in southern Brazil. The treatments were applied to the respective plots in the two agricultural years.

plot surface immediately after grain harvest. The amount of rice straw that was returned and distributed on the soil surface of all treatments at the beginning of the experiment was adjusted to 6.5 Mg ha^{-1} in 2010 and 11.3 Mg ha^{-1} in 2011, with the exception of the SR treatment, which retained the plant culms (0.10 m) that were not cut by the harvester. In the NT treatments, the straw was not impacted by handling. In NT+R, ryegrass was sown using 60 kg ha^{-1} of seeds. Ryegrass received only topdressing nitrogen fertilization of 30 kg ha^{-1} at the tillering stage. During ryegrass cultivation, cuts were made, and the residue was removed from the plots to simulate the effect of animal grazing. Straw management using KR treatments was carried out with a knife roller at a water depth of approximately 0.10 m. In the DH treatments, straw management was carried out with a disc harrow in moist soil. The use of the disc harrow in August in the treatments DH PH + DH PS and KR PH + DH PS seeks to improve soil leveling, which is a common practice among rice farmers in southern Brazil. The schedule of operations performed during the two years for soil and straw management systems is summarized in table 1.

The cultivar Puitá Inta-CL was sown in both seasons in October, using 90 kg^{-1} ha^{-1} of seeds. The plant population was adjusted to 250 plants m^{-2}. At the time of sowing, all plots were fertilized at doses equivalent to 300 kg ha^{-1} of the formula N-P_2O_5-K_2O 5-20-20. Nitrogen topdressing was carried out three times: the 1st time- before the flood (50 kg ha^{-1}), four leaves stage; the 2nd time- at the beginning of rice tillering (35 kg ha^{-1}); and the 3rd time- at the beginning of rice panicle differentiation (35 kg ha^{-1}). At sowing, the amount of straw remaining on the soil surface in the NT treatment was 1.5 and 1.1 Mg ha^{-1} in 2010/11 and 2011/12, respectively, and in the NT+R treatment, it was 3.6 and 2.2 Mg ha^{-1}. The soil was flooded 20 days after rice emergence and remained with a 0.10 m water depth during the entire cultivation period. Irrigation was suspended 7 and 5 days before harvest in 2010/11 and 2011/12,

Table 1. Schedule of field operations performed over two years

Field operation	Agricultural year	
	2010/11	2011/12
Soil sampling	04/17//2010	
Straw application on plots	04/17/2010	03/14/2011
Start of gas sampling	04/18/2010	03/15/2011
Straw management with KR in the PH	04/24/2010	03/19/2011
Straw management with DH in the PH	05/03/2010	04/05/2011
Ryegrass sowing in NT + R treatment	05/17/2010	05/07/2011
Nitrogen fertilization on ryegrass in the NT + R treatment	06/16/2010	07/01/2011
Straw management with DH in the PS	08/11/2010	08/18/2011
Ryegrass termination in the treatment NT + R	09/28/2010	10/07/2011
Last gas sampling in the off-season	10/01/2010	10/10/2011
Rice sowing (90 kg ha^{-1} of seeds)	10/22/2010	10/18/2011
Start of gas sampling on the growing season	11/12/2010	11/19/2011
First topdressing N fertilization, four leaves (50 kg ha^{-1})	11/20/2010	11/21/2011
Irrigation start	11/20/2010	11/21/2011
Second topdressing N fertilization (35 kg ha^{-1})	12/22/2010	12/22/2011
Third topdressing N fertilization (35 kg ha^{-1})	01/15/2011	01/11/2012
Irrigation suspension	03/03/2011	03/07/2012
Last gas sampling	03/10/2011	03/08/2012
Harvest	03/10/2011	03/12/2012
Soil sampling		03/12/2012

respectively. In both seasons, the grain yield in each plot was evaluated in a central area equivalent to 2.55 m^2 (10 rows × 1.5 m length), for which the grain yield was expressed at 13 g kg^{-1} of moisture. After the productivity evaluation at each harvest, the self-propelled harvester was passed to harvest the remaining rice plants in the experimental area.

Soil N_2O and CH_4 emissions

Nitrous oxide and CH_4 were measured using the static chamber method (Mosier, 1989) between April 18, 2010, and March 12, 2012. The apparatus consisted of galvanized steel chambers (0.40 × 0.40 × 0.20 m, length × width × height) with a 32 L mean air volume per chamber attached to a metal base. The metal base was inserted into the soil to a depth of 0.12 m, covering two rows of rice plants, and removed only for sowing and harvest operations. Each base had an open bottom channel on the sides to allow water to flow freely, which was sealed before each sampling event. Additional extensors were stacked on the bases as the rice plants grew taller, and the chamber volume was considered in the calculations. Measurements included 64 air sampling events in 2010/11, with 44 and 20 events during the off-season and season, respectively; and 65 air sampling events in 2011/12, with 47 and 18 events during the off-season and season, respectively. The intervals between air samplings varied from 1 to 15 days, depending on the time frame required for straw management, soil tillage, sowing, harvesting and N applications. The flux chambers were simultaneously closed for all treatments, and air samples were manually collected between 9 and 12 a.m. Air samples were collected 0, 8, 16 and 24 min after the chambers were closed. Prior to collection, the air inside the chambers was homogenized for 30 sec using an electrical ventilator attached to the chamber wall, and the internal temperature was measured. The syringes were closed, placed in a refrigerated box and immediately sent to the laboratory for analysis. Air samples in the syringes were analyzed for N_2O and CH_4 concentrations on a gas chromatograph (GC-2014, Shimadzu Corp., Kyoto, Japan) equipped with electron capture (63Ni ECD) and flame ionization (FID) detectors. The GC was equipped with three packed columns (HayeSep Q 80/100) set at 70 °C, N_2 as the carrier gas flowing at 26 mL min^{-1}, an injector with a 1 mL sample loop for direct injection at 250 °C, and ECD and FID detectors at 325 °C and 250 °C, respectively. The air samples were analyzed 24 h after their arrival at the laboratory.

Soil sampling and analysis

In the off-season, soil samples from the 0.00-0.10 m layer were collected to determine soil moisture and soil inorganic N content. Soil moisture was determined by drying the samples at 105 °C for 48 h. Inorganic N in the soil was extracted by stirring 20 g of moist soil with 80 mL of KCl solution for 30 min. After decanting, the supernatant was collected and kept frozen until analysis. The contents of NH_4^+-N and NO_3^--N were determined by Kjeldahl distillation after sequential additions of MgO and Devarda’s alloy, respectively, and titration with H_2SO_4 0.0025 mol L^{-1} (Keeney and Nelson, 1983). The bulk soil density was determined after the rice harvest using the volumetric ring method (Blake and Hartge, 1986).

After rice harvest, soil samples from the layers o 0.00-0.05, 0.05-0.10 and 0.10-0.20 m were collected at the end of the experiment in April 2012. In each plot, four subsamples were collected, which were air-dried, sieved through a 2 mm mesh and finely ground in a ball mill. The organic C content in the samples was determined by dry combustion in an elemental analyzer (FlashEA 1112, Thermo Electron Corporation, Milan, Italy).

Calculations

Carbon stocks in the 0.00-0.20 m soil layer were calculated using the soil equivalent mass methodology (Ellert and Bettany, 1995), using the soil density of the DH treatment as a reference. The amounts of soil NH_4^+ and NO_3^- (kg ha^{-1}) in the 0.00-0.10 m layer were calculated by multiplying the NH_4^+ and NO_3^- content (mg kg^{-1}) by the soil mass determined from bulk density in each treatment. Total porosity of the soil was estimated considering the bulk density and assuming a particle density of 2.65 kg dm^{-3} (Danielson and Sutherland, 1986). The water-filled pore space (WFPS) in the 0.00-0.10 m soil layer was estimated by dividing the volumetric soil water content by the total porosity (Robertson and Groffman, 2015). Soil CH_4 and N_2O fluxes were calculated using equation 1 as follows:

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

in which: f is the gas production rate (g m^{-2} h^{-1}); $\Delta Q/\Delta t$ is the variation in gas concentration (mol h^{-1}); P is the atmospheric pressure within the chamber (1 atm); V is the chamber volume (L); R is the ideal gas constant (0.08205 atm L mol^{-1} K^{-1}); T is the temperature within the chamber (K); M is the molar gas mass (g mol^{-1}); and A is the basal chamber area (m^{-2}). Cumulative gas emissions were obtained by integrating the daily fluxes between sampling events.

The GWP (Mg CO_2eq ha^{-1}) was calculated considering the annual emissions of N_2O and CH_4 and net CO_2 emissions, according to equation.

$$GWP = (CO_2 + N_2O \times 265 + CH_4 \times 28) + CO_2\ costs \qquad \text{Eq. 2}$$

in which: CO_2 denotes the net annual CO_2 fluxes; N_2O and CH_4 represent the annual fluxes; and 265 and 28 represent their respective forcing indices used for the conversion of N_2O and CH_4 to CO_2 (Pachauri et al., 2014), respectively; and CO_2 costs associated with agricultural operations (sowing, agrochemical and fertilizer applications, irrigation and harvest) and chemical inputs (agrochemicals and fertilizers) were obtained from Lal (2004). The net annual CO_2 fluxes were calculated using the variation in SOC stocks in soil and straw management systems in relation to the reference treatment (DH) as a proxy, according to equation 3.

$$Net\ annual\ CO_2\ fluxes = (SOC_{system} - SOC_{reference}) \times 44/12 \qquad \text{Eq. 3}$$

in which: CO_2 denotes the annual net CO_2 emission in soil of management systems (SOC_{system}) relative to soil in the reference treatment ($SOC_{reference}$) multiplied by a conversion factor of the molecular mass of C to CO_2 (44/12). The reference treatment was DH.

Yield-scaled GWP was calculated by dividing the GWP of each treatment by the respective crop grain yield, according to equation 4.

$$Yield\ scaled\ GWP = \frac{GWP}{grain\ yield} \qquad \text{Eq. 4}$$

Data analysis

The results of seasonal emissions of N_2O and CH_4 in the growing season and off-season, the variations in soil C stocks, the GWP and the yield-scaled GWP were submitted to analysis of variance (ANOVA). Straw management and soil management factors were considered fixed effects, while block and growing season were considered random effects. When the factors were significant at the 5 % level, treatment means were compared using the Scott–Knott test at the 5 % level.

RESULTS

Soil water-filled pore space and inorganic nitrogen

Soil WFPS in the off-season ranged from 49 to 87 % in 2010 and from 43 to 87 % in 2011, with WFPS greater than 60 % in 78 % of samplings (Figures 2a and 2b). In 2011, soil WFPS was evidently greater in the NT treatments than in the other treatments. The NH_4^+-N (Figures 2c and 2d) and NO_3^--N (Figures 2e and 2f) soil contents fluctuated during the off-season; no clear patterns emerged for mineral N levels. With few exceptions, the amount of NH_4^+-N and NO_3^--N in the soil was below 5 kg ha^{-1} in most assessments carried out in 2010 and 2011.

CH_4 emissions

Methane fluxes were low throughout the off-season in the two years evaluated. In this period, CH_4 fluxes ranged from -0.01 to 1.84 kg ha^{-1} day^{-1} in 2010 (Figures 3a and 3b) and from -0.02 to 1.15 kg ha^{-1} day^{-1} in 2011 (Figures 4a and 4b). Although negative fluxes were observed in some evaluations, all treatments represented a source of CH_4 to the

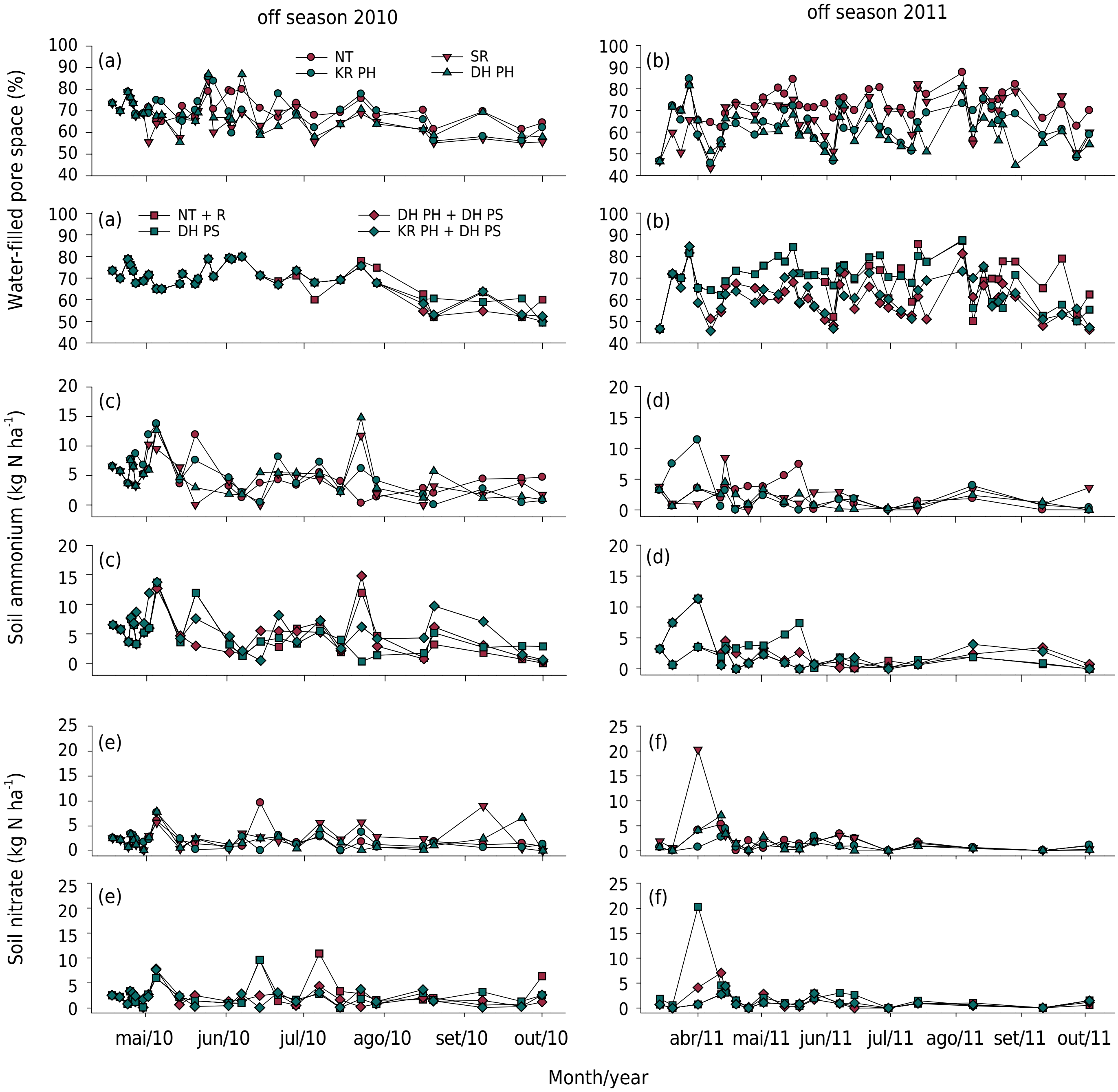

Figure 2. Water-filled pore space (a, b) and N-NH_4^+ (c, d) and N-NO_3^- (e, f) soil content in the 0.00-0.10 m layer during the 2010 and 2011 off-season.

atmosphere during the off-season period (Table 2). Cumulative CH_4 emissions in the off-season differed between treatments only in the first year (Table 2), with the highest and lowest emissions evidenced in the treatments with KR and without soil disturbance (NT and SR), respectively. In the KR and KR+DH treatments, the cumulative CH_4 emissions were significantly higher in the first year than in the second year (Table 2).

During irrigated rice cultivation, CH_4 fluxes were substantially higher than in the off-season. Methane fluxes gradually increased after flooding and reached emission peaks of 18.7 kg ha^{-1} day^{-1} in 2010/11 (Figures 3a and 3b) and 13.3 kg ha^{-1} day^{-1} in 2011/12 (Figures 4a and 4b). The systems in which rice straw was not managed in 2010/11 (NT and NT+R – first crop) showed a greater increase in soil CH_4 fluxes soon after flooding in 2011/12 compared to the other systems. At the end of the season,

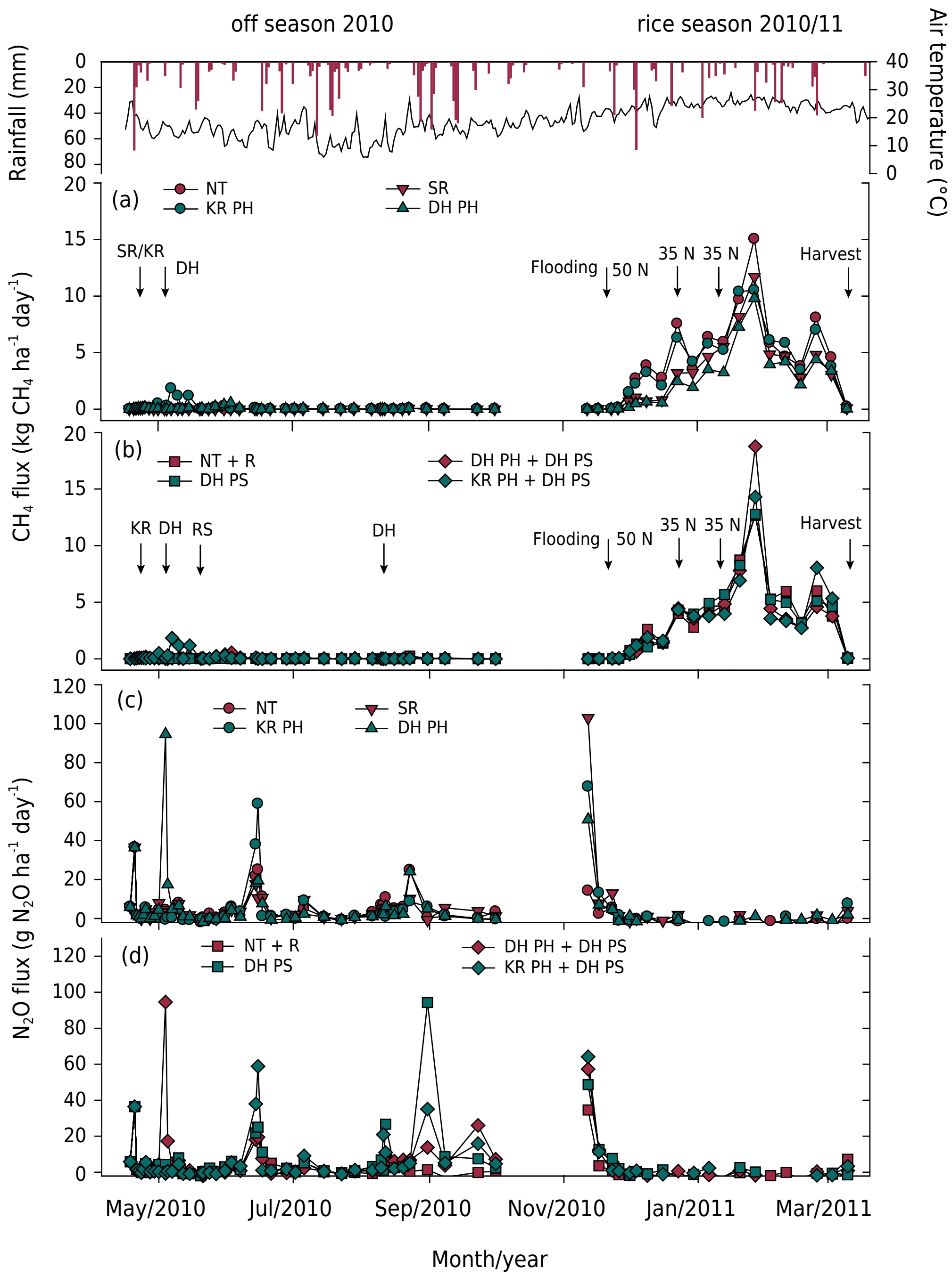

Figure 3. Methane (a, b) and N_2O (c, d) fluxes during the 2010 off-season and 2010/2011 rice season.

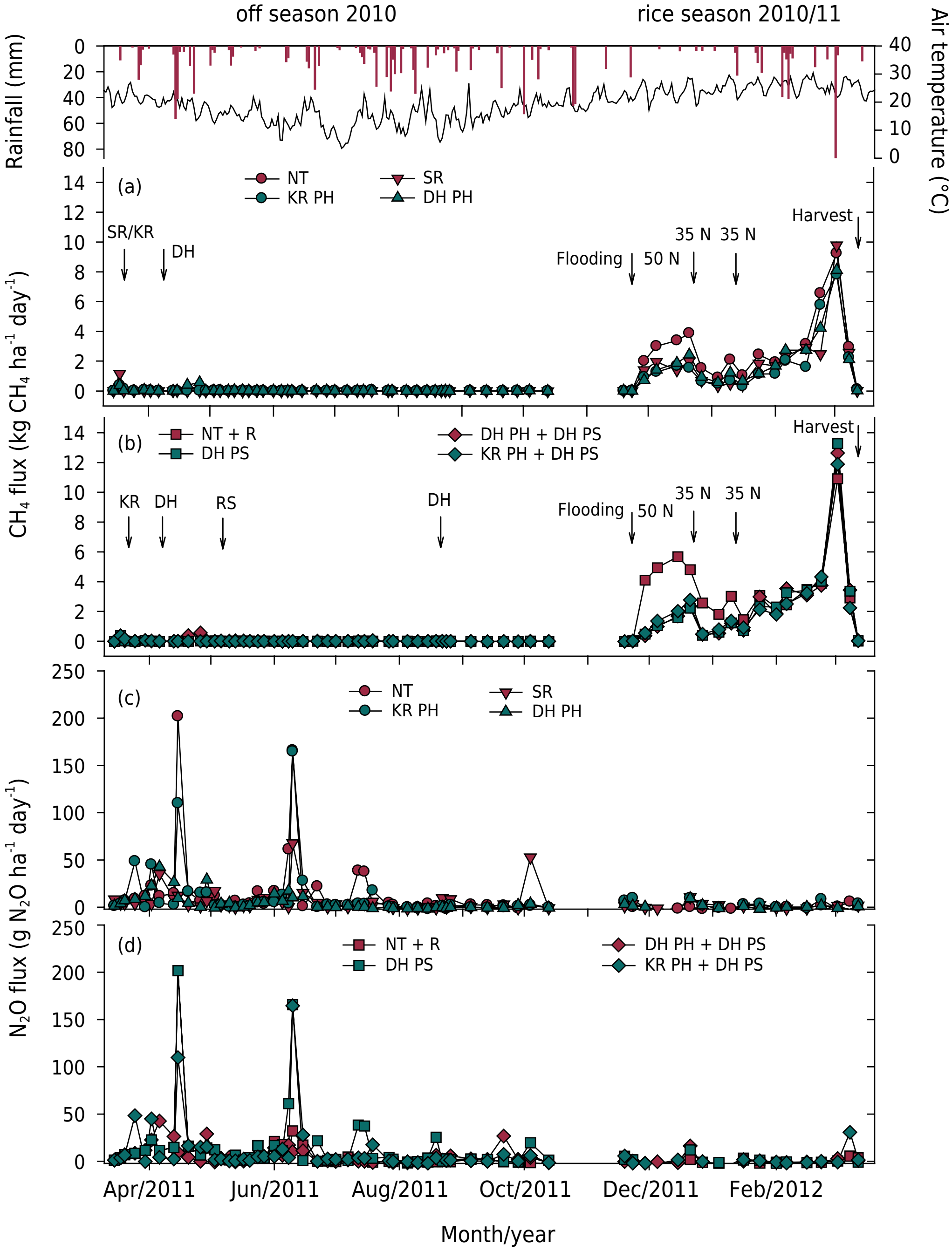

Figure 4. Methane (a, b) and N_2O (c, d) fluxes during the 2011 off-season and 2011/2012 rice season.

after the suspension of water entry into the crop, the daily CH_4 fluxes of all treatments were close to zero.

The cumulative emissions of CH_4 among the straw management strategies evaluated ranged from 334.5 to 586.0 kg CH_4 ha^{-1} in 2010/11 and from 165.8 to 346.5 kg CH_4 ha^{-1} in 2011/12. The treatment with straw incorporation with a disc harrow immediately following rice harvest showed the lowest CH_4 emissions in 2010/11 but did not differ from the other treatments in 2011/12. However, it did differ from those without straw management. In the two evaluated seasons, the cumulative CH_4 emissions in the NT and NT+R treatments without straw management were higher than in the treatments with some management type (KR, DH and SR). The CH_4 emissions drove the total annual emissions of each management during the growing season, which represented more than 95 % of the annual emissions. In all treatments, the accumulated emissions of CH_4 were higher in the 2010/11 season than in the 2011/12 season.

N_2O emissions

The N_2O fluxes ranged from -2.63 to 94.55 g ha^{-1} day^{-1} in 2010 (Figures 3c and 3d) and from -2.80 to 201.70 g ha^{-1} day^{-1} in the 2011 off-season (Figures 4c and 4d). Several N_2O emission peaks were observed during soil wetting and drying cycles in both off-season periods. Soil N_2O cumulative emissions differed between treatments only in the second year during the off-season. Off-season N_2O emissions were higher in 2011 than in 2010, except for the DH and DH+DH treatments (Table 2). In the 2010 off-season, straw management after harvest did not affect soil N_2O emissions. In the 2011 off-season, cumulative N_2O emissions were reduced in three ways: straw incorporation after rice harvest using a disc harrow, straw removal, and ryegrass cultivation. Most N_2O emitted to the atmosphere came from the off-season in the two years evaluated.

In 2010/11, the highest N_2O fluxes were observed a few days before the soil was flooded. In the second year (2011/12), soil N_2O fluxes were close to zero throughout the period. Negative cumulative N_2O emissions observed during the harvest period indicated N_2O consumption by the soil (Table 2). On average, across treatments, cumulative N_2O emissions in 2011/12 were 175 % higher than those in 2010/11.

Soil carbon stocks

At the end of the two rice seasons, the soil C organic stocks (0.00-0.20 m) varied from 35.96 Mg ha^{-1} in the DH+DH treatment to 38.36 Mg ha^{-1} in the NT+R treatment

Table 2. Cumulative N_2O and CH_4 emissions in the off-season and rice-growing season

Treatments	N_2O		CH_4		N_2O	CH_4
	off season	season	off season	season	annual	
	g ha^{-1}		kg ha^{-1}		g ha^{-1}	kg ha^{-1}
Year 1						
NT	678.8*	-134.5	2.2 c	586.0 a*	544.3*	588.1 a*
KR PH	565.3*	105.8	21.7 a*	414.6 b*	671.1*	436.3 b*
SR	648.0*	116.6	1.3 c	466.6 b*	764.6*	467.8 b*
DH PH	716.4	26.7	6.7 b	334.5 c*	743.0	341.1 c*
NT+R	455.2*	-136.6	1.8 c	530.0 a*	318.6*	531.8 a*
DH PS	1511.0*	47.5	2.1 b	464.4 b*	1558.5*	466.5 b*
DH PH + DH PS	1086.9	-1.7	7.0 b	459.6 b*	1085.2	466.6 b*
KR PH + DH PS	1052.6*	-62.3	21.6 a*	451.1 b*	990.3*	472.7 b*
Year 2						
NT	2577.2 a	-43.4	1.8	276.5 b	2533.8 a	278.3 b
KR PH	2427.5 a	48.8	1.8	165.8 c	2476.3 a	167.6 c
SR	1638.1 b	44.1	1.9	175.7 c	1682.2 b	177.6 c
DH PH	1027.4 b	-2.8	5.9	187.3 c	1024.6 b	193.1 c
NT+R	1536.9 b	-133.1	1.1	346.5 a	1403.9 b	347.6 a
DH PS	2816.5 a	-137.4	1.6	213.1 c	2679.1 a	214.7 c
DH PH + DH PS	1357.1 b	-31.5	5.7	212.1 c	1325.6 b	217.8 c
KR PH + DH PS	2524.9 a	56.2	1.3	209.0 c	2581.1 a	210.3 c

Means followed by the same letter are not statistically different within each year, according to Scott-Knott test (α<0.05). * indicates that differences between years are statistically significant according to Scott-Knott test (α<0.05). NT: no tillage; NT + R: no tillage + ryegrass; KR PH: knife-roller post-harvest; DH PH: disc harrow post-harvest; SR: straw removal; DH PS: disc harrow pre-sowing; DH PH + DH PS: disc harrow post-harvest + disc harrow pre-sowing; KR PH + DH PS: knife-roller post-harvest + disc harrow pre-sowing.

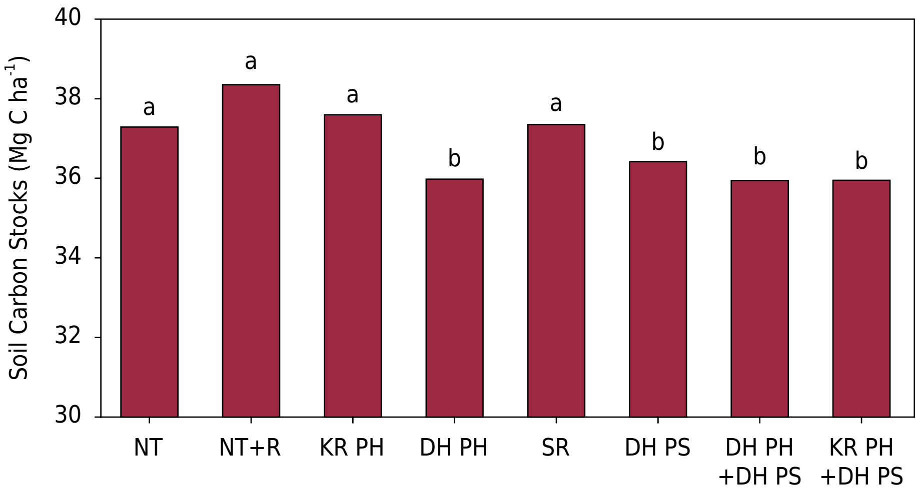

Figure 5. Carbon stocks in the 0.00-0.20 m soil layer in different straw management systems.

(Figure 5). Soil C stocks in all treatments with the use of a disc harrow for straw management were lower than those in treatments without the use of a disc harrow. Straw removal had a less adverse effect on soil C stocks than straw management operations involving disc harrows. Furthermore, straw removal did not affect C stocks compared to the NT treatment. Though not significantly different from the NT, KR and SR treatments, in absolute terms, the C stock tended to be higher in the NT+R treatment soil.

Compared to the disc harrow reference system (DH), the annual rates of change in soil organic C stocks ranged from -0.01 Mg ha^{-1} yr^{-1} in the DH+DH and KR+DH treatments to 1.19 Mg in the NT+R treatment.

Rice grain yield, GWP and yield-scaled GWP

Rice grain yield was not affected by soil and rice straw management systems or by year (Table 3). The average yield was 10.4 Mg ha^{-1} in both seasons. Straw management in autumn, right after rice harvest, reduced the GWP of the systems in relation to spring management, just before rice sowing. The highest GWP was observed in the treatment without straw management after harvest and in the treatments with two soil operations just before rice seeding. Methane emissions were the main component of the GWP in all straw management systems. The contribution of N_2O emissions to GWP was small and mostly (>85 %) determined by emissions in the off-season. In straw management systems without the use of disc harrows, the increase in soil C stocks neutralized part of the CH_4 and N_2O emissions, reducing GWP. The yield-scaled GWP ranged from 0.64 to 1.06 Mg CO_2eq Mg^{-1} yield and was lower in soil and straw management systems shortly after rice harvest compared to management applied in spring (Table 3).

DISCUSSION

Effects of soil and straw management on soil carbon stocks

The soil C stocks in the 0.00-0.20 m layer observed in our study are in agreement with values reported in other locations in subtropical climates, which range from 35.9 to 41.4 Mg ha^{-1} (Nascimento et al. al., 2009; Huang et al., 2016; Yang et al., 2018). After two years, SOC stocks were lower in treatments using disc harrows and higher in treatments without soil tillage. In addition, our results suggest that the implement used for straw management (disc harrow or knife roller) has a greater effect on soil C stocks than the tillage time. Pandey et al. (2014) showed that soil C losses are proportional

Table 3. Cumulative N_2O and CH_4 emissions, variation in C stocks (Δ soil C), operating costs, estimated global warming potential (GWP) and yield-scaled GWP

Treatments	N_2O	CH_4	Δ soil C	Operational costs	GWP	Annual Yield[1]	AnnualYield-scaled GWP
	Mg CO_2 ha^{-1}					Mg ha^{-1}	
NT	0.81 a	24.22 a	-4.82 a	0.66	20.87 a	10.9	1.04 a
KR PH	0.83 a	16.32 c	-5.95 a	0.74	11.94 c	10.7	0.64 c
SR	0.65 b	18.05 b	-5.05 a	0.66	14.31 c	9.8	0.82 b
DH PH	0.47 b	14.79 c	0.00 b	0.74	16.00 b	10.6	0.83 b
NT+R	0.45 b	24.59 a	-8.72 a	0.80	17.12 b	9.9	0.94 a
DH PS	1.12 a	19.50 b	-1.63 b	0.74	19.74 a	10.1	1.05 a
DH PH + DH PS	0.64 b	19.00 b	0.10 b	0.83	20.56 a	10.8	1.03 a
KR PH + DH PS	0.95 a	18.55 b	0.09 b	0.83	20.41 a	10.4	1.06 a

[1] Average of two growing seasons. Means followed by the same letter are not statistically different within each year according to Scott-Knott test (α<0.05). * indicates that differences between years are statistically significant according to Scott-Knott test (α<0.05). NT: no tillage; NT + R: no tillage + ryegrass; KR PH: knife-roller post-harvest; DH PH: disc harrow post-harvest; SR: straw removal; DH PS: disc harrow pre-sowing; DH PH + DH PS: disc harrow post-harvest + disc harrow pre-sowing; KR PH + DH PS: knife-roller post-harvest + disc harrow pre-sowing.

to the intensity and frequency of soil tillage and that even the recalcitrant fraction of soil C cannot be considered inert to long-term biodegradation. Soil tillage significantly reduces the stability and proportion of macroaggregates, which are broken down into microaggregates or individual particles, thus indicating that tillage reduces the structural quality of soils (Jiang et al., 2011). Liu et al. (2021) suggest that paddy soils that have been continuously tilled for many years have depleted soil carbon stocks because tillage reduces the physical and chemical protection of C from microbial attacks through organo-mineral associations and increases soil C losses associated with erosion.

On the other hand, some studies have not observed differences in soil C stocks in different tillage systems in irrigated rice production systems (Nascimento et al., 2009; Huang et al., 2016). Nascimento et al. (2009) observed a higher stock of C in the surface layer of the soil under no-tillage, which suggests that physical protection has little effect on the stabilization of C in flooded soils and, therefore, the tillage systems do not differ in terms of C stocks. However, Tang et al. (2020) observed a higher mass of large aggregates and SOC content in superficial soil layers (0.00-0.05 m) under no-tillage than conventional tillage.

Soil C stocks were higher in the treatment with straw removal than those with soil tillage using disc harrows (usual management). These findings indicate that the breakdown of aggregates affecting soil structure under frequent harrowing is more detrimental to soil C stocks than the removal of rice straw, but this conclusion has to be viewed with caution. Pampolino et al. (2008) suggest that residues from roots and algae that proliferate in aquatic environments may be sufficient to maintain C and N stocks in soils that remain flooded for most of the year.

Effects of straw management on N_2O emissions

The off-season showed several peaks of N_2O emissions, as observed in other studies (Zhang et al., 2016a; Yang et al., 2018). During the off-season, as a result of irrigation suppression, the topsoil is exposed to several cycles of wetting and drying, driven by rainfall and evapotranspiration. Some studies have shown that soil wetting and drying cycles increase substrate availability for nitrification and denitrification (Borken and Matzner, 2009; Guo et al., 2014). In addition, rewetting reduces soil oxygen availability, resulting in N_2O and N_2 emissions; if flooding is prolonged, these gases remain trapped in the soil and are released as the soil dries (Congreves et al., 2018).

The peaks of N_2O emissions observed during the off-season represented more than 85 % of annual emissions. Zschornack et al. (2018) reinforce the need to include assessments of N_2O emissions during the rice crop off-season, a period that accounted for up to 90 % of annual N_2O emissions. According to the authors, strategies to mitigate N_2O emissions should be focused on in this period. Our results indicate that incorporating straw with disc harrows, cultivating ryegrass in winter, and removing straw after the rice harvest are potential strategies to reduce N_2O emissions in the off-season because they possibly restrict substrate availability for nitrification and denitrification. Some studies have suggested that N immobilization caused by rice straw incorporation with a high C/N ratio (Yang et al., 2018) and that N uptake by a winter crop (Bayer et al., 2015) contributes to reducing available N in the soil and, consequently, N_2O emissions in rice paddies. Removal of rice straw reduces the availability of organic C in the soil, which can influence denitrification under anaerobic conditions during the off-season. Wu et al. (2018) compared the effect of straw on N_2O fluxes in two irrigation regimes and observed that straw removal reduced annual N_2O emissions, especially in the system where the soil does not remain flooded throughout the period. On the other hand, other studies have found that straw removal can increase soil N_2O emissions, as it serves as a substrate for microbial growth, possibly generating strong competition for NH_4^+ between different groups of microorganisms (Sander et al., 2014; Zhang et al., 2017).

During the growing season, N_2O fluxes were mostly low. Several studies report this same pattern of N_2O emissions during the period of soil flooding (Sander et al., 2014; Wu et al., 2018; Zschornack et al., 2018). Soil flooding can reduce N_2O emissions in two ways: first, it restricts nitrification, which, in addition to being one of the processes responsible for N_2O emissions, also provides NO_3^- as a substrate for denitrification; second, the low availability of O_2 in the soil establishes conditions that favor the final reduction of N_2O to N_2 (Chapuis-Lardy et al., 2007). In some samplings, N_2O influxes were observed, suggesting that soil acted as an N_2O sink during the growing season. Several other studies have also observed influxes of N_2O during soil flooding (Bayer et al., 2014; Wu et al., 2018; Zschornack et al., 2018), which can be attributed to the intensely reduced soil redox potential. Cumulative N_2O emissions throughout the years evaluated, though especially the second year, were similar to those in other studies carried out in the Philippines (Sander et al., 2014), China (Zou et al., 2005) and India (Tirol-Padre et al., 2016) but slightly higher than those in other studies (Ahmad et al., 2009; Zhang et al., 2016; Wu et al., 2018).

Effects of straw management on CH_4 emissions

The results of our study confirm our hypothesis that rice straw management shortly after harvest decreased soil CH_4 fluxes in the subsequent growing season. Soil CH_4 fluxes gradually increased after soil flooding in all treatments due to changes in soil redox potential (Zschornack et al., 2016; Bertora et al., 2018). Soil flooding induces an intense soil redox potential reduction, and once other final electron acceptors, such as Fe^{3+}, Mn^{4+}, SO_4^{2-} and NO_3^-, have been consumed, the environment becomes favorable for CH_4 production (Kögel-Knabner et al., 2010); in addition, the presence of crop residues further reduces the soil redox potential and provides a substrate for methanogenesis (Bertora et al., 2018). As the flooding period and the development of rice plants advance, conditions become even more favorable for the production and emission of CH_4. Several studies indicate maximum peaks of CH_4 emission observed in the reproductive stages of the crop cycle (Bhattacharyya et al., 2012; Bayer et al., 2015; Zhang et al., 2017). According to Le Mer and Roger (2001), in this period, CH_4 fluxes are related to the increase in root exudation and organic matter inputs due to root exfoliation and plant senescence. The maximum CH_4 emission rates during rice cultivation observed in our study ranged from 9 to 18.7 kg CH_4 ha^{-1} day^{-1} and are in agreement with the CH_4 emission rates reported in other studies carried out in the same region (Bayer et al., 2015; Camargo et al., 2018; Zschornack et al., 2018).

Without management, the maintenance of rice and/or ryegrass crop residues on the soil surface did not reduce CH_4 emissions during the rice crop. These results disagree with other studies that report lower CH_4 emissions in no-tillage, which is attributed to the maintenance of plant residues on the soil surface compared to their incorporation into the soil by tillage (Ahmad et al., 2009; Bayer et al., 2014). In our study, the absence of tillage and the maintenance of straw on the soil surface possibly reduced straw decomposition during the winter. The daily CH_4 fluxes partially support this hypothesis during the season. In treatments without crop residue management, the first peak of CH_4 emissions was observed in the first air sampling after soil flooding, which can be attributed to the decomposition of easily mineralizable organic matter (Le Mer and Roger, 2001). This effect was even more evident when ryegrass was cultivated during winter, increasing the amount of substrate for methanogenesis at the time of soil flooding in spring/summer.

On the other hand, removing or incorporating straw in the soil soon after the rice harvest possibly reduced the amount of C available for anaerobic decomposition and, consequently, the CH_4 fluxes. In agreement with these results, Bertora et al. (2018) also demonstrated that both early management and straw removal are effective strategies to reduce CH_4 emissions in rice fields because they reduce substrate availability for methanogenesis. When soil is drained during the off-season, straw management soon after harvest allows straw decomposition to be carried out under aerobic conditions, reducing substrate availability for methanogenesis in the rice growing season (Bayer et al., 2015; Bertora et al., 2018). In this sense, Sander et al. (2014) recommend draining the area in the off-season as a strategy to reduce CH_4 emissions during the growing season.

The CH_4 emissions observed during the rice growing season corresponded to more than 95 % of the annual emissions. Cumulative emissions of CH_4 were similar to studies carried out in Asia (Ahmad et al., 2009; Sander et al., 2014) and slightly higher than those observed by Tirol-Padre et al. (2016). Although our results indicate a small increase in CH_4 fluxes during the off-season when crop residues were managed with a knife roller in the first year, this trend was not repeated in the second year, and CH_4 emissions in the off-season were close to zero. Several other studies have indicated that the rice growing season period is mainly responsible for CH_4 emissions (Zhang et al., 2016a; Yang et al., 2018; Zschornack et al., 2018). Thus, management strategies aimed at reducing CH_4 emissions should be focused on the rice growing season.

Effects of straw management on GWP and yield-scaled GWP

The annual GWP ranged from 6.0 to 10.4 Mg CO_2 eq ha^{-1} yr^{-1} between soil and straw management systems, which are close to the values observed in other studies carried out in subtropical climate regions (Bayer et al., 2014, 2015; Zhang et al., 2016b; Zschornack et al., 2018). Methane emissions were the main determinant of GWP in all management systems but were partially neutralized by soil C sequestration in treatments where the soil was not tilled. In a meta-analysis study, Liu et al. (2014) showed that flooded soils are effective in increasing C stocks, but this increase can also lead to higher CH_4 emissions and GWP. Our results suggest that straw removal might be a strategy to reduce the GWP of systems in the short term, but it is necessary to evaluate the effects of straw removal on soil C stocks in the long term. Furthermore, as noted by Bertora et al. (2018), the costs involved in removing straw as well as the nutrient cycling promoted by straw, make this practice unattractive. According to the authors, similar results regarding GWP can be obtained by increasing the temporal distance between straw management and soil flooding. In fact, our results demonstrate that the anticipation of straw management is an effective strategy to reduce GWP.

According to Sosbai (2018), in 61 % of areas cultivated with rice in the state of Rio Grande do Sul, straw management is carried out immediately after harvest, while 30 % of the areas are managed with conventional tillage. Based on our GWP estimates and considering that 30 % of the cultivated area corresponds to 300,000 ha^{-1}, managing straw immediately after the rice harvest could generate a C-saving of 561 Gg CO_2 eq yr^{-1}. Managing the straw using a knife-roller right after rice harvest could have even greater benefits. The low GWP of this system is a result of the combination of low CH_4 emissions and increased soil C stocks. Thus, our results suggest that management practices with reduced soil disturbance that allow aerobic straw decomposition during the winter period and that promotes increases in soil C stocks are the most suitable to reduce the GWP of rice paddies. However, long-term studies should assess the possibility of soil C saturation and reduced ability to neutralize CH_4 emissions. Yield-scaled GWP was directly related to GWP since the grain yield did not differ between the straw management systems. Thus, the anticipation of straw management reduces GHG emissions per Mg of grain produced, that is, it makes the system more efficient.

CONCLUSIONS

Soil tillage with a disc harrow to incorporate rice straw, regardless of the time of year, reduces soil C stocks. However, different straw management strategies do not affect rice grain yield. The off-season period is responsible for most annual N_2O emissions, while CH_4 emissions occur mostly during the rice growing season. Straw incorporation using a disc harrow, straw removal, or ryegrass cropping in the winter are strategies to reduce N_2O emissions in the off-season. Straw management immediately after rice harvest efficiently reduces CH_4 emissions during the rice growing season and, consequently, reduces GWP and yield-scaled GWP.

ACKNOWLEDGMENTS

This study was funded by the National Institute of Science and Technology for a Low Carbon Agriculture (INCT-Low Carbon Agriculture) sponsored by CNPq (406635/2022-6) and Technological and Inovation Network for a Low Carbon Agriculture in South Brazil supported by FAPERGS (22/2551-0000392-3). We are also greatful to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

AUTHOR CONTRIBUTIONS

Conceptualization: Eduardo Lorensi de Souza (equal), Enio Marchesan (supporting) and Sandro José Giacomini (equal).

Data curation: Bruno Chaves (supporting), Eduardo Lorensi de Souza (equal), Enio Marchesan (supporting), Getúlio Elias Pilecco (supporting) and Raquel Schmatz (supporting).

Formal analysis: Douglas Adams Weiler (equal), Eduardo Lorensi de Souza (equal) and Sandro José Giacomini (equal).

Funding acquisition: Sandro José Giacomini (lead).

Investigation: Bruno Chaves (supporting), Eduardo Lorensi de Souza (equal), Getúlio Elias Pilecco (supporting) and Raquel Schmatz (supporting).

Methodology: Bruno Chaves (supporting), Cimelio Bayer (supporting), Eduardo Lorensi de Souza (equal), Getúlio Elias Pilecco (supporting), Raquel Schmatz (supporting) and Sandro José Giacomini (equal).

Project administration: Sandro José Giacomini (lead).

Resources: Enio Marchesan (supporting) and Sandro José Giacomini (lead).

Writing – original draft: Douglas Adams Weiler (equal), Eduardo Lorensi de Souza (equal) and Sandro José Giacomini (equal).

Writing – review & editing: Cimelio Bayer (supporting), Douglas Adams Weiler (equal), Eduardo Lorensi de Souza (equal) and Sandro José Giacomini (equal).

REFERENCES

Ahmad S, Li C, Dai G, Zhan M, Wang J, Pan S, Cao C. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. Soil Till Res. 2009;106:54-61. https://doi.org/10.1016/j.still.2009.09.005

Alexandratos N, Bruinsma J. World agriculture towards 2030/2050: The 2012 revision. Rome: FAO; 2012. (ESA Working paper, 12-03). Available from: https://www.fao.org/3/ap106e/ap106e.pdf

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

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

Bertora C, Cucu MA, Lerda C, Peyron M, Bardi L, Gorra R, Sacco D, Celi L, Said-Pullicino D. Dissolved organic carbon cycling, methane emissions and related microbial populations in temperate rice paddies with contrasting straw and water management. Agr Ecosyst Environ. 2018;265:292-306. https://doi.org/10.1016/j.agee.2018.06.004

Bhattacharyya P, Roy KS, Neogi S, Adhya TK, Rao KS, Manna MC. Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. Soil Till Res. 2012;124:119-30. https://doi.org/10.1016/j.still.2012.05.015

Blake GR, Hartge KH. Bulk density. In: Klute A, editor. Methods of soil analysis: Part 1 Physical and mineralogical methods. Madison: SSSA; 1986. p. 363-75. https://doi.org/10.2136/sssabookser5.1.2ed.c14

Borken W, Matzner E. Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. Global Change Biol. 2009;15:808-24. https://doi.org/10.1111/j.1365-2486.2008.01681.x

Camargo ES, Pedroso GM, Minamikawa K, Shiratori Y, Bayer C. Intercontinental comparison of greenhouse gas emissions from irrigated rice fields under feasible water management practices: Brazil and Japan. Soil Sci Plant Nutr. 2018;64:59-67. https://doi.org/10.1080/00380768.2017.1415660

Chapuis-Lardy L, Wrage N, Metay A, Chotte JL, Bernoux M. Soils, a sink for N_2O? A review. Global Change Biol. 2007;13:1-17. https://doi.org/10.1111/j.1365-2486.2006.01280.x

Congreves KA, Wagner-Riddle C, Si BC, Clough TJ. Nitrous oxide emissions and biogeochemical responses to soil freezing-thawing and drying-wetting. Soil Biol Biochem. 2018;117:5-15. https://doi.org/10.1016/j.soilbio.2017.10.040

Danielson RE, Sutherland PL. Porosity. In: Klute A, editor. Methods of soil analysis: Part 1 Physical and mineralogical methods. Madison: SSSA; 1986. p. 443-61. https://doi.org/10.2136/sssabookser5.1.2ed.c18

Ellert B, Bettany J. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can J Soil Sci. 1995;75:529-38. https://doi.org/10.4141/cjss95-075

Food and Agriculture Organization of the United Nations - Faostat. Statistics Division [internet]. Rome: FAO; 2021. Available from: https://www.fao.org/statistics/en/.

Guo X, Drury CF, Yang X, Daniel Reynolds W, Fan R. The extent of soil drying and rewetting affects nitrous oxide emissions, denitrification, and nitrogen mineralization. Soil Sci Soc Am J. 2014;78:194-204. https://doi.org/10.2136/sssaj2013.06.0219

Huang M, Zhou X, Cao F, Zou Y. Long-term effect of no-tillage on soil organic carbon and nitrogen in an irrigated rice-based cropping system. Paddy Water Environ. 2016;14:367-71. https://doi.org/10.1007/s10333-015-0506-y

Jiang X, Hu Y, Bedell JH, Xie D, Wright AL. Soil organic carbon and nutrient content in aggregate-size fractions of a subtropical rice soil under variable tillage. Soil Use Manage. 2011;27:28-35. https://doi.org/10.1111/j.1475-2743.2010.00308.x

Keeney DR, Nelson DW. Nitrogen - Inorganic forms. In: Page AL, editor. Methods of soil analysis: Part 2 Chemical and microbiological properties. Madison: SSSA; 1983. p. 643-98. https://doi.org/10.2136/sssabookser5.3.c38

Kögel-Knabner I, Amelung W, Cao Z, Fiedler S, Frenzel P, Jahn R, Kalbitz K, Kölbl A, Schloter M. Biogeochemistry of paddy soils. Geoderma. 2010;157:1-14. https://doi.org/10.1016/j.geoderma.2010.03.009

Lal R. Carbon emission from farm operations. Environ Int. 2004;30:981-90. https://doi.org/10.1016/j.envint.2004.03.005

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

Liu C, Lu M, Cui J, Li B, Fang C. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Global Change Biol. 2014;20:1366-81. https://doi.org/10.1111/gcb.12517

Liu Y, Ge T, van Groenigen KJ, Yang Y, Wang P, Cheng K, Zhu Z, Wang J, Li Y, Guggenberger G, Sardans J, Penuelas J, Wu J, Kuzyakov Y. Rice paddy soils are a quantitatively important carbon store according to a global synthesis. Commun Earth Environ. 2021;2:154. https://doi.org/10.1038/s43247-021-00229-0

Ministério da Ciência, Tecnologia e Inovaçã - MCTI. Estimativas anuais de emissões de gases de efeito estufa no Brasil. 3. ed. Brasília, DF: MCTI; 2016.

Mosier AR. Chamber and isotope techniques. In: Andreae MO, Schimel DS, editors. Exchange of traces gases between terrestrial ecosystems and the atmosphere. Berlim: Wiley; 1989. p. 175-87.

Mosier AR, Halvorson AD, Reule CA, Liu XJ. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. J Environ Qual. 2006;35:1584-98. https://doi.org/10.2134/jeq2005.0232

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

Nascimento PC, Bayer C, Silva Netto LF, Vian AC, Vieiro F, Macedo VRM, Marcolin E. Sistemas de manejo e a matéria orgânica de solo de várzea com cultivo de arroz. Rev Bras Cienc Solo. 2009;33:1821-7. https://doi.org/10.1590/S0100-06832009000600030

Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P, Dubash NK, Edenhofer O, Elgizouli I, Field CB, Forster P, Friedlingstein P, Fuglestvedt J, Gomez-Echeverri L, Hallegatte S, Hegerl G, Howden M, Jiang K, Jimenez Cisneroz B, Kattsov V, Lee H, Mach KJ, Marotzke J, Mastrandrea MD, Meyer L, Minx J, Mulugetta Y, O'Brien K, Oppenheimer M, Pereira JJ, Pichs-Madruga R, Plattner GK, Pörtner HO, Power SB, Preston B, Ravindranath NH, Reisinger A, Riahi K, Rusticucci M, Scholes R, Seyboth K, Sokona Y, Stavins R, Stocker TF, Tschakert P , van Vuuren D, van Ypserle JP. Global. Climate Change 2014: Sysnthesis report. Contribution of Working Groups I, II and II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: Intergovernmental Panel on Climate Change - IPCC; 2014.

Pampolino MF, Laureles EV, Gines HC, Buresh RJ. Soil carbon and nitrogen changes in long-term continuous lowland rice cropping. Soil Sci Soc Am J. 2008;72:798-807. https://doi.org/10.2136/sssaj2006.0334

Pandey D, Agrawal M, Bohra JS, Adhya TK, Bhattacharyya P. Recalcitrant and labile carbon pools in a sub-humid tropical soil under different tillage combinations: A case study of rice–wheat system. Soil Till Res. 2014;143:116-22. https://doi.org/10.1016/j.still.2014.06.001

Rao AN, Wani SP, Ramesha MS, Ladha JK. Rice production systems. In: Chauhan BS, Jabran K, Mahajan G, editors. Rice production worldwide. New York: Springer Cham; 2017. p. 185-205. https://doi.org/10.1007/978-3-319-47516-5_8

Robertson GP, Groffman P. Nitrogen transformations. In: Paul EA, editor. Soil microbiology, ecology and biochemistry. 4th ed. Amsterdan: Elsevier; 2015. p. 421-46.

Sander BO, Samson M, Buresh RJ. Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. Geoderma. 2014;235-236:355-62. https://doi.org/10.1016/j.geoderma.2014.07.020

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.

Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, Haberl H, Harper R, House J, Jafari M, Masera O, Mbow C, Ravindranath NH, Rice CW, Robledo Abad C, Romanovskaya A, Sperling F, Tubiello F. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, USA: Cambridge University Press; 2014.

Sociedade Sul-Brasileira de Arroz Irrigado - Sosbai. Arroz irrigado: Recomendações técnicas da pesquisa para o sul do Brasil. In: XXXII Reunião técnica da cultura do arroz irrigado, 08 a 10 de agosto de 2018; Farroupilha, RS. Cachoerinha: Instituto Rio Grandense do Arroz IRGA; 2018. Available from: https://www.sosbai.com.br/uploads/documentos/recomendacoes-tecnicas-da-pesquisa-para-o-sul-do-brasil_906.pdf

Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2014.

Tang H, Xiao X, Li C, Tang W, Pan X, Cheng K, Guo L, Wang K, Li W, Sun G. Impact of tillage pratices on soil aggregation and humic substances under double-cropping paddy filed. Agron J. 2020;112:624-32. https://doi.org/10.1002/agj2.20051

Tirol-Padre A, Rai M, Kumar V, Gathala M, Sharma PC, Sharma S, Nagar RK, Deshwal S, Singh LK, Jat HS, Sharma DK, Wassman R, Ladha J. Quantifying changes to the global warming potential of rice wheat systems with the adoption of conservation agriculture in northwestern India. Agr Ecosyst Environ. 2016;219:125-37. https://doi.org/10.1016/j.agee.2015.12.020

Wu X, Wang W, Xie X, Hou H, Yin C. Response of N_2O emission to straw retention under two contrasting paddy water conditions: a field experiment over rice–rice-fallow rotation. Paddy Water Environ. 2018;16:199-205. https://doi.org/10.1007/s10333-017-0621-z

Yang Y, Huang Q, Yu H, Song K, Ma J, Xu H, Zhang G. Winter tillage with the incorporation of stubble reduces the net global warming potential and greenhouse gas intensity of double-cropping rice fields. Soil Till Res. 2018;183:19-27. https://doi.org/10.1016/j.still.2018.05.005

Zhang G, Yu H, Fan X, Yang Y, Ma J, Xu H. Drainage and tillage practices in the winter fallow season mitigate CH_4 and N_2O emissions from a double-rice field in China. Atmos Chem Phys. 2016a;16:11853-66. https://doi.org/10.5194/acp-16-11853-2016

Zhang J, Hang X, Lamine SM, Jiang Y, Afreh D, Qian H, Feng X, Zheng C, Deng A, Song Z, Zhang W. Interactive effects of straw incorporation and tillage on crop yield and greenhouse gas emissions in double rice cropping system. Agr Ecosyst Environ. 2017;250:37-43. https://doi.org/10.1016/j.agee.2017.07.034

Zhang ZS, Chen J, Liu TQ, Cao CG, Li CF. Effects of nitrogen fertilizer sources and tillage practices on greenhouse gas emissions in paddy fields of central China. Atmos Environ. 2016b;144:274-81. https://doi.org/10.1016/j.atmosenv.2016.09.003

Zhu C, Kobayashi K, Loladze I, Zhu J, Jiang Q, Xu X. Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. Sci Adv. 2018;4:eaaq1012. https://doi.org/10.1126/sciadv.aaq1012

Zou J, Huang Y, Jiang J. A 3-year measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. Global Biogeochem Cy. 2005;2:GB2021. https://doi.org/10.1029/2004GB002401

Zschornack T, Rosa CM, Pedroso GM, Marcolin E, Silva PRF, Bayer C. Mitigation of yield-scaled greenhouse gas emissions in subtropical paddy rice under alternative irrigation systems. Nutr Cycl Agroecosyst. 2016;105:61-73. https://doi.org/10.1007/s10705-016-9775-0

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