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# Mitigation of greenhouse gases emission affected by no-tillage and winter cover crops in a subtropical paddy rice ecosystem

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**ABSTRACT:** Paddy rice production based on traditional soil management emits large amounts of methane ($CH_4$) into the atmosphere. This study assessed the potential of no-tillage (NT) and winter cover crops (WCC) to mitigate net greenhouse gas (GHG) emissions in a subtropical paddy rice ecosystem. A long-term (20-yrs) experiment was evaluated regarding the effect of NT combined with winter fallow or three WCC (ryegrass, white oat, and birdsfoot trefoil) on seasonal $CH_4$-C and nitrous oxide ($N_2O$-N) emissions and on soil organic carbon (SOC) stocks in comparison to conventional tillage (CT) under winter fallow in a Gleysol of Southern Brazil. The changes in SOC were used as a proxy for annual net carbon dioxide ($CO_2$) exchanges in the soil-atmosphere, taking the CT treatment as a reference. The GHG balance (summation of $CH_4$, $N_2O$ and $CO_2$ emissions multiplied by their global warming potential of 34, 298, and 1, respectively) and emissions intensity of GHG emissions were calculated. Across winter managements, NT decreased 25 % of GHG emissions in comparison to CT system. This effect was mainly related to the decrease of seasonal $CH_4$-C emissions (31-113 kg $ha^{-1}$) and by promoting SOC accumulation (0.45-0.65 Mg $ha^{-1}$ $yr^{-1}$) in comparison to CT system, since soil $N_2O$-N emission was not affected by management practices. Increased soil $CH_4$-C emissions offset the positive effect of WCC on SOC accumulation compared with winter fallow. Based on our findings, NT mitigates net GHG emissions in subtropical paddy rice ecosystems, but no additional effect is observed combining NT with WCC.

**Keywords:** nitrous oxide, methane, tillage systems, net balance of GHG, lowland.

## INTRODUCTION

The improvement of agricultural production systems that allow, at the same time, the production of healthy food and mitigation of greenhouse gas (GHG) emissions, is one of the major challenges facing global warming and climate change (Princiotta, 2009; Peters et al., 2013). Agriculture and land-use change contribute to 25 % of total GHG emissions at the global level (Smith et al., 2014). In Brazil, this contribution increased to 51 % due to deforestation and large agricultural area (Brasil, 2016).

Agriculture developed in lowlands, more specifically the irrigated rice, has a particular characteristic of high soil methane ($CH_4$) emissions, which contribute to approximately 18 % of total GHG emissions from agriculture in southern Brazil (Observatório do Clima, 2019). Since soil $CH_4$ fluxes are driven by the balance between methanogenesis and methanotrophy (Le Mer and Roger, 2001), the anoxic soil condition of lowlands favors methanogenesis process and, consequently, $CH_4$ emission. The strong $CH_4$ emissions in the lowlands at this subtropical ecosystem occur by the wide adoption of conventional tillage systems with high soil disturbance by plowing, disking, and leveling, which determine incorporation of weed and crop residues into the soil, providing then C source to the methanogenesis process (Wang et al., 1998; Zschornack et al., 2011; Bayer et al., 2014).

In addition to $CH_4$, losses of SOC under conventional tillage combined with low residues input from winter fallow (Rosa et al., 2011; Ghimire et al., 2012) contribute to net emissions of carbon dioxide ($CO_2$) to the atmosphere in this subtropical ecosystem. Although not emitted significantly as in uplands (Bayer et al., 2014, 2016), nitrous oxide ($N_2O$) emissions in rice fields can be boosted by nitrogen fertilization (Zhang et al., 2015; Islam et al., 2018).

A feasible strategy to GHG mitigation is the adoption of no-tillage (NT) by i) decreasing the $CH_4$ emissions maintaining crop residues on soil surface (Bayer et al., 2014; Hao et al., 2016); ii) retention of atmospheric $CO_2$-C in soil organic matter in the less oxidative environment of NT soil (Nascimento et al., 2009; Rui and Zhang, 2010). The combination of winter cover crops (WCC) with NT can booster the potential of SOC sequestration in NT system (Yagioka et al., 2015; Bayer et al., 2016), despite an increase in soil $CH_4$ emissions can be also expected due to crop residues represent a labile C source to methanogenesis process in soil (Zschornack et al., 2011; Haque et al., 2013; Bayer et al., 2014). Considering legumes as WCC, this impact of legume cover crops on $N_2O$ emissions is partially or totally off-set by SOC sequestration in upland soil (Bayer et al., 2016), despite some studies showed the increase of soil $N_2O$ emission (Zschornack et al., 2011). For lowland soils, the knowledge on the influence of conservation soil management systems comprising NT and WCC on GHG and SOC sequestration is scant, mainly considering subtropical ecosystems.

Most GHG studies in agricultural systems focused on one of the three GHG and, thus, they are not conclusive regarding the real impact of management practices on net emissions of GHG. However, a full account of the impact of soil management practices must also include the $N_2O$ and $CH_4$ emission from the soil on GHG emissions, expressed in terms of net GHG emission (Robertson et al., 2000; Mosier et al., 2005; Bayer et al., 2016). That full account can be expressed in terms of GHG emission, which adds up SOC changes and soil $N_2O$ and $CH_4$ emissions, taking into account each gas's respective global warming potential (Mosier et al., 2005). Another useful parameter to measure the impact of soil management systems on GHG emission is the emissions intensity that measures the GHG per unit of grain yield (Mosier et al., 2006).

Our starting hypothesis is that NT and WCC adoption decrease net GHG emissions per area and per unit of yield in subtropical paddy rice ecosystems, possibly related to increased SOC sequestration and mitigation of soil $CH_4$ emission. The main objective of this study was to evaluate the potential of NT and WCC on GHG balance and emissions intensity in paddy rice fields in southern Brazil.

## MATERIALS AND METHODS

### Site description and experiment design and conduction

The study was based on a long-term field experiment (20 years), established in 1996, conducted in Rice Experimental Station of Rio Grandense Rice Institute, in Cachoeirinha, Rio Grande do Sul State, Southern Brazil (29° 55′ 30″ S, 50° 58′ 21″ O, 7 m a.s.l). The climate is humid subtropical and classified as Cfa, according to the Köppen classification system, with a mean annual temperature and precipitation of 19.3 °C and 1434 mm, respectively (Climate data, 2018). The loamy soil is classified as Gleysol (WRB/FAO) (*Gleissolo Háplico Distrófico típico*). The physical and chemical soil properties are described in table 1.

The experiment started in the 1996/97 crop season to evaluate the adaptation and improvements in soil quality with the long-term use of winter cover crops (WCC) associated with no-tillage (NT). Prior to the establishment of this experiment in the area, experiments were carried out with irrigated rice, under conventional tillage and fallow in the autumn-winter period. Irrigated rice (*Oryza sativa* L.) was the summer crop in the whole experiment. Five treatments consisted of different combination of tillage system and cover crops or fallow, as follow: (*i*) conventional tillage (CT) and (*ii*) no-tillage (NT), both combined with winter fallow, and (*iii*-*v*) NT combined with three winter cover crops (WCC) - ryegrass (*Lolium multiflorum* L.), white oat (*Avena sativa* L.), and birdsfoot trefoil (*Lotus corniculatus* L.). The treatments were applied in plots of 5 × 8.8 m, and the distribution of four replicates followed a complete randomized block design. The WCC were sowed in April through surface rice crop residues and grown without irrigation. The seed rates for ryegrass, white oat and birdsfoot trefoil were 80, 20 and 8 kg $ha^{-1}$, respectively. In treatments with fallow, only weeds developed in the plots.

Conventional tillage and NT systems were applied in spring, usually at the end of September. The CT consisted in plowing and disking at 0.25 and 0.07 m, respectively. These operations buried the harvest residues of rice and weeds into soil. In NT system, soil was not disturbed, and rice, weed and WCC residues were maintained on soil surface. In NT system, weeds control and management of WCC were performed by desiccation with glyphosate (Roundup® 3.5 L p.c. $ha^{-1}$) about 30 days before rice sowing.

Every year, the rice crop (cultivar IRGA 424 RI) was sowed at a seed rate of 100 kg $ha^{-1}$ in the first half of October. The mean rates of $P_2O_5$ and $K_2O$ applied at rice sowing were 108 and 68 kg $ha^{-1}$. Nitrogen fertilization rate was applied at 150 kg $ha^{-1}$ split in two times, with 66 % applied in V4 and 34 % in R0 stages (CQFS-RS/SC, 2004; Sosbai, 2016). Weed control was carried out in the pre-emergence rice period using clomazone herbicide (Gamit® 1.2 L $ha^{-1}$) and glyphosate (Roundup® 2.0 L $ha^{-1}$). Post rice emergence, cyhalophope herbicide (Clincher® 1.7 L $ha^{-1}$) and penoxulan (Ricer® 0.25 L $ha^{-1}$) were used. Pest control was carried out with neonicotinoid-pyrethroid

**Table 1.** Soil physicochemical characterization before the beginning of the experiment

| Layer | OM | P | K | $CEC_{pH7.0}$ | $pH(H_2O)$ | Clay | Silt | Sand |
|---|---|---|---|---|---|---|---|---|
| m | g $kg^{-1}$ | —— mg $dm^{-3}$ —— | | $cmol_c$ $dm^{-3}$ | | —— g $kg^{-1}$ —— | | |
| 0.00-0.20 | 17 | 14.3 | 41.8 | 7.2 | 5.3 | 170 | 420 | 410 |

OM: organic matter; P: phosphorus by Mehlich-1; K: potassium by Mehlich-1; and $CEC_{pH7.0}$: cation exchange capacity at pH 7.0. Soil $pH(H_2O)$ (1:1).

insecticide (Engeo Pleno® 0.2 L $ha^{-1}$) in R0. Irrigation by flooding started in V4 developing stage of plants just after the first N application, and a water layer of 0.05-0.07 m was maintained until rice maturation, when the water supply was cut.

### Evaluation of biomass addition by cover crops, weeds and rice

Aboveground biomass of WCC and weeds in September (2017) and rice in March (2017/18) at the flowering stage were evaluated by sampling an area of 0.5 $m^2$ per plot at the beginning of the flowering stage. Biomass samples were oven dried (forced air at 50 °C) until constant mass, and the contribution of roots was considered as 30 % of shoot addition by WCC or weeds (Zanatta et al., 2007) and rice (Insalud et al., 2006). Five subsamples were collected per plot.

### Evaluation of rice yield

Rice grain yield evaluation were performed in 2017/2018 crop seasons through a *Wintersteiger* mechanized harvester and were obtained by extrapolating the yield harvested in the useful area of each plot to one hectare and fitting the grain moisture to 130 g $kg^{-1}$.

### Evaluation of $CH_4$ and $N_2O$ fluxes and calculation of seasonal emissions

Air samplings were conducted on a weekly basis during the flooded rice season (spring–summer) using the static closed chamber method (Bayer et al., 2014). Each chamber consisted of an aluminum base 0.60 m long × 0.60 m wide × 0.20 m high and an aluminum top of the same size, totaling a volume of 72 L of air per chamber. The bases were driven 0.05 m deep into the soil before permanent flooding in the rice season and after the rice harvest in the non-rice season and left in the soil throughout the seasons.

Each base had an open bottom and sealable channels on the sides to facilitate the free-flowing of irrigation water in the rice season. The latter was sealed during air sampling events. Each base covered three rows of rice plants. In the rice season, additional 0.20 or 0.30 m aluminum extensors were stacked on the bases as the plants grew taller. The chamber volume was considered in estimating all GHG emissions. Each chamber top had a rubber septum sampling port, a stainless-steel thermometer, and a battery operated fan to circulate and homogenize air within the chamber (Bayer et al., 2014). Chamber closing and initial air sampling were started at 9:00 am and followed by five air samplings 5 min apart (Minamikawa et al., 2012; Bayer et al., 2014). Air samples were withdrawn with polypropylene syringes, transferred to the Biogeochemical Laboratory at UFRGS, and analyzed for $CH_4$ and $N_2O$ on the same day in a gas chromatographer (Shimadzu Corp. 2014) equipped with flame ionization (250 °C) and electron capture (325 °C) detectors. Methane and $N_2O$ fluxes were calculated according to equation 1.

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

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

The flux rate of GHG, as estimated from air samples collected from 9:00 to 11:00 am, was used as a measure of mean daily flux (Costa et al., 2008). Seasonal emissions (rice and non-rice periods) were calculated by trapezoidal interpolation of the daily $CH_4$ and $N_2O$ flux rates throughout each period (Bayer et al., 2014).

### Soil sampling, organic C analysis and calculation of stocks

In September 2015, soil samples of the 0.00-0.025, 0.025-0.05, 0.05-0.075, 0.075-0.10, 0.10-0.15, 0.15-0.20, 0.20-0.30 and 0.30-0.40 m layers were collected before rice sowing the rice (i.e., 18 years after the experiment was started). Trenches were dug manually to allow the assessment of soil bulk density using the volumetric ring method (Blake and Hartge, 1986). In the same layers as those sampled for bulk density assessment, soil samples were collected with a spatula and then air-dried and ground to ≤2 mm in a Marconi 330 grinder.

Approximately 20 g of soil was further ground to ≤0.025 mm in an agate mortar and analyzed for C by dry combustion in a Shimadzu VCSH analyzer. Soil organic carbon stocks were calculated for the whole 0.00-0.40 m profile. The annual rate of soil organic C accumulation was calculated as the ratio of the difference between soil organic C stocks in the treatments and the reference system (CT fallow) and the duration time of the experiment when the soil was sampled (18 years).

### Net balance of GHG emissions and emissions intensity

The net balance of GHG emissions for each management system was calculated according to equation 2.

$$\textit{Net balance of GHG} = [N_2O \times 298 + CH_4 \times 34] - \Delta SOC \times 3.67 \qquad \text{Eq. 2}$$

in which: $N_2O$ and $CH_4$ are the seasonal emissions of $N_2O$ and $CH_4$ properly converted into $CO_2$ equivalent ($CO_{2\ eq}$) after considering the global warming potentials (298 for $N_2O$ and 34 for $CH_4$, according to the IPCC (2018); $\Delta SOC$ x 3.67 is the annual change in soil organic carbon (SOC) stock to 0.40 m depth converted to $CO_2$ amounts (Mosier et al., 2005). Emissions intensity was calculated by the ratio between the balance of net GHG emissions (Mg $CO_2$ eq $ha^{-1}$) and the average grain yield of rice (Mg), aiming to infer the intensity of GHG emission per unit of rice grain yield.

### Statistical Analysis

The results were checked for variance normality and homoscedasticity with the Shapiro-Wilk and Oneill & Matthews tests, respectively, and appropriate data transformations were performed when assumptions were violated. Seasonal $CH_4$-C and $N_2O$-N emissions, the balance of GHG, rice grain yield and emissions intensity were submitted to analysis of variance. When significant at the 5 % level, the differences among treatments were subjected to Tukey's post-hoc test at the 5 % significance level. The MIXED procedure was used to compare the effects of soil management in winter on GHG, soil organic C, and rice yield. Statistical procedures used soil winter management as a fixed factor, and blocks and experimental errors as random variables. All analyses were performed with SAS® v. 9.4 (Statistical Analysis System Institute, Cary, NC, USA).

## RESULTS

### Rice grain yield and annual input of biomass

Rice grain yield was not influenced by tillage systems nor by WCC (Table 2), ranging from 8.2 Mg $ha^{-1}$ in CT-fallow to 8.7 Mg $ha^{-1}$ in NT- birdsfoot trefoil (Table 3). A mean rice yield of 8.4 Mg $ha^{-1}$ was attained across soil management systems (Table 3).

Annual biomass input ranged between 10.4 and 16.8 Mg $ha^{-1}$ (Table 3). In the winter, biomass input ranged from 0.7 (CT) to 1.6 Mg $ha^{-1}$ (NT) in the systems under fallow, while in the systems under cover crops the biomass input increased to 5.4 Mg $ha^{-1}$ on average, ranging from 3.9 to 6.8 Mg $ha^{-1}$ (Table 3). The highest biomass input was observed for

**Table 2.** Analysis of variance data (values of calculated F and P of analyzed variables) for seasonal emissions of $CH_4$ and $N_2O$, stock and accumulation rate of soil organic carbon (SOC), net balance of GHG (net GHG), rice yield and emissions intensity in a subtropical Gleysol subjected to flooding rice production in Southern Brazil

| Dependent Variable | F value | Pr > Fc |
|---|---|---|
| Rice Yield | 1.4 *ns* | 0.276 |
| Seasonal $CH_4$-C | 11.9 * | <0.001 |
| Seasonal $N_2O$-N | 0.4 *ns* | 0.776 |
| SOC stock | 5.9 * | <0.001 |
| SOC accumulation rate | 9.2 # | <0.001 |
| Net GHG | 2.8 # | 0.077 |
| Emissions intensity | 5.3 # | 0.010 |

* indicates a significant effect by the Skott-Knott test at 5 % of probability and # indicates a significant effect at 10 % of probability; ns indicates the lack of significant effect.

**Table 3.** Rice grain yield, biomass input by rice, cover crops and weeds in different winter managements (fallow or cover crops) combined with conventional tillage (CT) or no-tillage (NT) in a subtropical Gleysol subjected to flooding rice production in Southern Brazil

| Tillage System | Winter management | Rice | | Weeds / Cover crops | Total |
|---|---|---|---|---|---|
| | | Grain Yield | Biomass | Biomass | Biomass |
| | | Mg $ha^{-1}$ | | | |
| CT | Fallow | 8.2 ± 0.4 ns | 7.7 ± 0.2 | 0.7 ± 0.1 | 10.4 ± 0.4 |
| NT | Fallow | 8.6 ± 0.6 | 10.0 ± 0.3 | 1.6 ± 0.1 | 11.6 ± 0.4 |
| | Ryegrass | 8.5 ± 0.4 | 9.2 ± 0.3 | 5.5 ± 0.3 | 14.8 ± 0.5 |
| | White oat | 8.2 ± 0.8 | 10.0 ± 0.3 | 6.8 ± 1.6 | 16.8 ± 1.4 |
| | B. trefoil | 8.7 ± 0.1 | 9.8 ± 0.3 | 3.9 ± 0.2 | 13.7 ± 0.4 |

ns: not significant by the analysis of variance at 5 % significance level. Values after the ± denote the standard deviation. Dry matter biomass input by rice, weed and cover crops were not statistically analyzed because they are only support data for interpretation of soil organic carbon and greenhouse gases results.

rice, which accounted for 86-93 % of total annual biomass input in fallow systems in CT and NT, and 60-72 % for WCC systems.

### Seasonal $CH_4$ and $N_2O$ emissions

Seasonal $CH_4$-C emissions were affected by management systems (Figure 1) and ranged from 359 to 472 kg $ha^{-1}$ (Figure 1). Greater $CH_4$-C emission was observed in CT with winter fallow compared to NT with winter fallow (74 kg $CH_4$-C $ha^{-1}$ of difference) (Figure 1a). Under NT, seasonal soil $CH_4$-C emission was similar comparing WCC and fallow, with exception of white oat that presented a seasonal soil $CH_4$-C emission slightly higher (441 kg $ha^{-1}$) in comparison to the others WCC (366 kg $ha^{-1}$, on average) (Figure 1a). Seasonal soil $N_2O$-N emissions ranged from 0.25 to 0.87 kg $ha^{-1}$, and were not influenced by tillage and WCC (Tables 2 and 3; Figure 1b).

### Soil organic C stocks and annual accumulation rates

Soil organic C content was influenced by the management systems (Table 2), mainly in the surface soil layers (0.00-0.025 and 0.025-0.05 m), where NT and WCC favored greater SOC content than CT and winter fallow (Figure 2a). Considering 0.00-0.40 m layer, lower SOC stocks were observed in CT (47.0 Mg $ha^{-1}$) than NT (53.3 Mg $ha^{-1}$), both combined with winter fallow (Figure 2b). Under NT, the increase in biomass input by WCC did not promote an increase in SOC stocks compared to winter fallow. Compared to CT, NT combined with fallow and WCC presented annual accumulation rates of SOC ranging from 0.45 to 0.65 Mg $ha^{-1}$ $yr^{-1}$ (Table 4).

### Net balance of GHG and emissions intensity

Net balance and emissions intensity GWP were influenced by soil tillage and WCC in the long term (Table 2). Considering the three main GHG ($CO_2$, $CH_4$ and $N_2O$) emitted from the rice field, total GHG emissions ranged from 14.8 (Ryegrass-NT) to 21.7 (Fallow-CT) Mg $CO_2$ eq ha$^{-1}$ among soil management systems (Table 4). In comparison to the traditional management system (CT combined with winter fallow), NT adoption decreased GHG emissions by 5.2 Mg $CO_2$ eq ha$^{-1}$ when combined with winter fallow, and by 3.7-6.8 Mg $CO_2$ eq ha$^{-1}$ when combined with WCC (Table 4).

Emissions intensity was higher in CT (2.6 Mg $CO_2$ eq Mg$^{-1}$ grain rice) than in NT (1.9 Mg $CO_2$ eq Mg$^{-1}$ grain rice), both combined with winter fallow. No effect of WCC was observed on emissions intensity in NT soil, ranging between 1.8 and 2.2 Mg $CO_2$ eq Mg$^{-1}$ grain rice (Table 4).

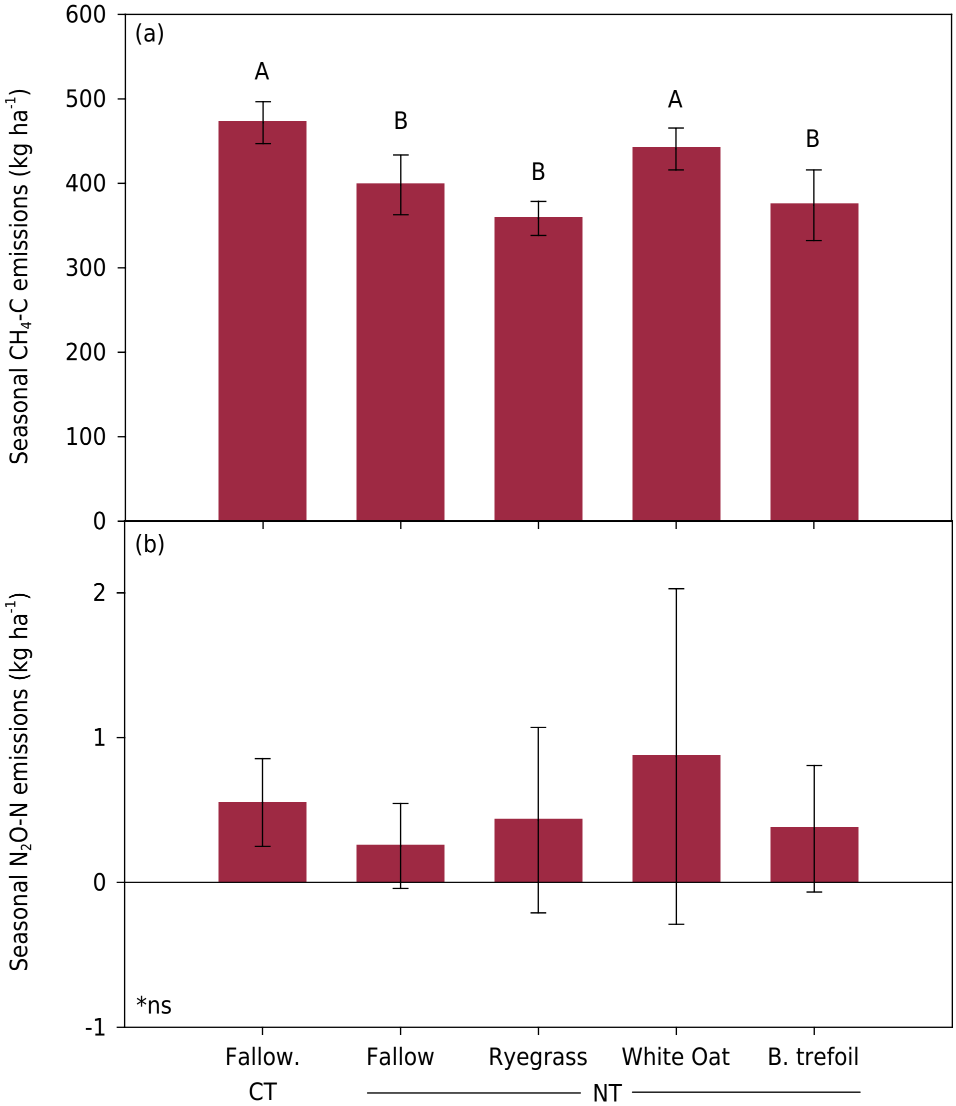


**Figure 1.** Seasonal emissions of (a) methane ($CH_4$) and (b) nitrous oxide ($N_2O$) in a subtropical Gleysol subjected to different soil winter management (fallow or cover crops) combined with conventional tillage (CT) or no-tillage (NT) in Southern Brazil. Vertical lines denote the mean standard deviation. Different letters on the bars indicate a significant difference between treatments by the Test of Skott-Knott at 5 % level. ns: no significant.

**Table 4.** Seasonal methane ($CH_4$) and nitrous oxide ($N_2O$) emissions, annual accumulation rate of SOC, net balance of GHG (net GHG) and emissions intensity in a flooded rice field on a Gleysol subjected to winter managements (fallow or cover crops) combined with conventional tillage (CT) and no-tillage (NT) in Southern Brazil

| Tillage System | Winter management | $CH_4$ | $N_2O$ | SOC | Net GHG | Emissions intensity |
|---|---|---|---|---|---|---|
| | | Mg $CO_2$ eq $ha^{-1}$ $ano^{-1}$ | | | | Mg $CO_2$ eq $Mg^{-1}$ grain |
| CT | Fallow | 21.4 a | 0.3 a | 0.0 b | 21.7 a | 2.6 a |
| NT | Fallow | 18.1 b | 0.1 a | 1.7 a | 16.5 b | 1.9 b |
| | Ryegrass | 16.3 b | 0.2 a | 1.6 a | 14.8 c | 1.8 b |
| | White oat | 20.0 a | 0.4 a | 2.4 a | 18.0 b | 2.2 b |
| | B. trefoil | 17.0 b | 0.2 a | 1.7 a | 15.4 c | 1.8 b |

Different letters in the colunm indicate a significant difference between means of the treatment by Skott-Knott at 5 % level.

## DISCUSSION

The positive impact of NT system reduced between 15 and 28 % of soil $CH_4$ emissions in comparison to the traditional CT combined with winter fallow, which is in agreement with previous studies that reported a decrease from 21 % in Southern Brazil (Bayer et al., 2014) and from 22 to 27 % in China (Zhang et al., 2015; Zhao et al., 2016). This lower $CH_4$ emission in NT has been likely attributed to the no residues incorporation into the soil. These residues are a source of labile C readily available for methanogenic microorganisms that are highly active in subsurface soil layers compared to surface layers (Wang et al., 1993; Silva et al., 2011; Zschornack et al., 2011). The WCC, when associated with NT, increased the $CH_4$ emission with fallow, since an expressive biomass input was observed (3.9-6.8 vs. 1.6 Mg $ha^{-1}$).

Despite the wide range of soil $N_2O$-N emissions (0.25-0.86 kg $ha^{-1}$) among soil management systems, the observed difference in seasonal $N_2O$ emissions was not statistically significant ($p>0.05$) and cannot be attributed to the management systems (Table 2). The magnitude of $N_2O$ emissions is similar to that observed in previous studies conducted in paddy rice fields (Bayer et al., 2014; Zschornack et al., 2018), which have been attributed to the temporal and spatial variability that add up to the complex combination of the several soil variables encompassed in soil $N_2O$ production (Hénault et al., 2012).

No-tillage increased SOC stocks in this lowland soil, a similar tendency observed in previous studies in Southern Brazil (Nascimento et al., 2009; Rosa et al., 2011; Carlos et al., 2022), and other countries such as Uruguay (Terra et al., 2006) and China (Rui and Zhang, 2010). The annual accumulation rates of SOC observed in this study (0.45 to 0.65 Mg $ha^{-1}$) were similar to those observed in upland soils considering the time of NT adoption, clay content and soil depth (Bayer et al., 2006; Zanatta et al., 2007; Veloso et al., 2018). Even though these results suggest a similar impact of no soil disturbance on soil organic matter stabilization in lowland and upland soils, the importance of mechanisms encompassed on SOC stabilization may differ. In lowland soils cultivated with irrigated rice, flooding weakens and favors the disruption of aggregates, with a lower impact of NT on the physical protection of SOC (Nascimento et al., 2009). However, this effect must be partially off-set by the higher magnitude of organo-mineral interactions in flooded soils (Hanke and Dick, 2017). On the other hand, WCC had no effect on SOC stocks in NT soil, despite the higher annual biomass input compared to winter fallow. Annual variability of winter biomass production can help to explain this lack of effect of WCC on SOC stocks, since we have evaluated the residue input during only one year.

The GHG balance in rice production systems is represented by the net GHG, which is the sum of seasonal $CH_4$ and $N_2O$ emissions and $CO_2$ emissions for which annual net change in SOC was used as a proxy (Piva et al., 2012). Across winter managements, NT system had lower net GHG than CT combined with winter fallow. These results were mainly

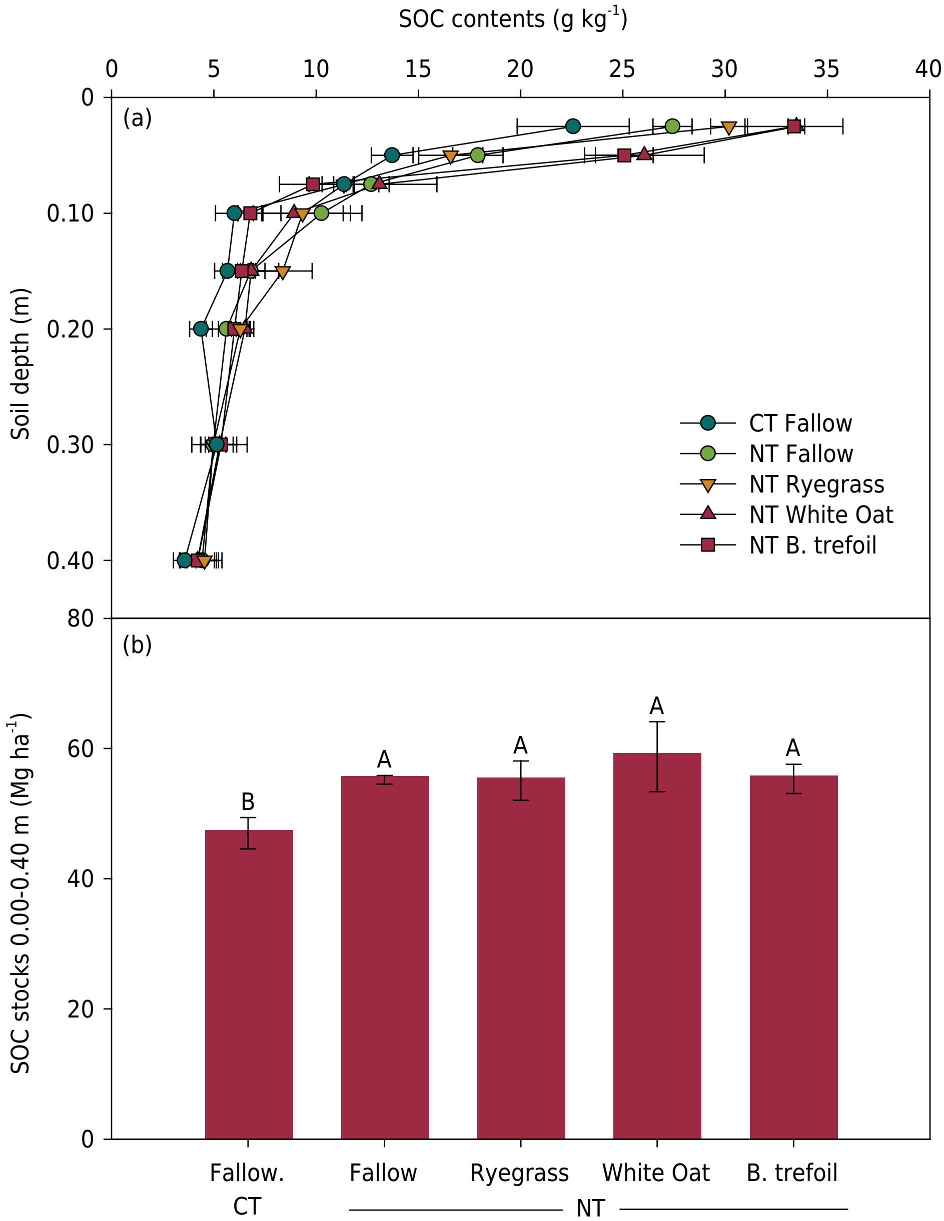


**Figura 2.** Soil organic C (SOC) contents in soil profile (a) and stocks at 0.00-0.40 m soil layer (b) of a Gleysol subjected to different soil winter managements (fallow or cover crops) combined with conventional tillage (CT) or no-tillage (NT) in southern Brazil. Vertical lines denote the standard deviation. Different letters on the bars indicate a significant difference between treatments by the Test of Skott-Knott at 5 % level. ns: no significant.

related to the decrease of seasonal soil $CH_4$-C emissions and also to the atmospheric $CO_2$-C sequestration in soil organic matter. The $CH_4$-C was the stronger component of net GHG, representing more than 85 % of total GHG emissions, which is widely reported for flooded rice fields (Kim et al., 2012; Bayer et al., 2014, 2015). Across winter cropping systems, SOC accumulation in NT soil was responsible by 12 % of GHG mitigation in comparison to CT soil.

The lack of effect of NT and WCC on rice grain yield has been observed in other studies based on field experiments in Southern Brazil (Bayer et al., 2014; Zschornack et al., 2016) and in other regions of the world (Bijay-Singh et al., 2008; Huang et al., 2015). This is due to the supply of all the demanded nutrients for the crop by fertilization summed to flooding conditions, which reduces the redox potential of the soil and contributes to increasing the content of most nutrients in the soil solution (Sousa et al., 2021), not reflecting the impact of soil management. This is a different result than that observed in uplands, where water availability for crops has been the main variable related to the increase of crop yields in rainfed no-till cropping systems (Franchini et al., 2012).

Higher emissions intensity under CT with winter fallow than under NT combined with winter cover crops indicated that NT could decrease 26 % of GHG emissions for each 1 Mg of grain rice produced. This result reinforces the NT as a potential tool to increase the sustainability of irrigated rice production in subtropical ecosystems. In general, WCC did not affect net balance of GHG and emissions intensity in NT soil, which is associated to the fact that although favoring SOC sequestration by increasing crop residues input, net GHG and emissions intensity was offset by also favoring $CH_4$-C emissions. This effect was clearly observed in the system with white oat, where the increase of SOC stock was compensated by the high $CH_4$-C emissions, compromising the effect of mitigation of NT.

This study observed the importance of adopting no-tillage as a soil management strategy that aims to increase SOC stocks and reduce the intensity of $CO_2$ equivalent emissions, being an important alternative for the production of irrigated rice in subtropical ecosystems like the south of Brazil.

## CONCLUSIONS

No-tillage mitigates net GHG emissions compared with conventional tillage in lowland soils cultivated with flooded rice, which is mainly associated with decreased soil $CH_4$-C emissions and increased SOC sequestration. The decrease of $CH_4$-C emissions in no-tillage soils is also related to the maintenance of crop residues on soil surface with consequent lower exposure of labile C to the anaerobic environment favoring the reduction of the emission of this potent GHG. Winter cover crops have no clear impact on the net balance of GHG emissions and emissions intensity in NT soil, possibly because the soil C sequestration due to higher aboveground biomass was partially offset by increased $CH_4$-C emissions.

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## APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.01.030.

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