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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

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ABSTRACT

In southern Brazil, flood irrigated rice is grown during the summer, while a self-reseeding ryegrass is grown during the winter months without irrigation. Soil tillage operations that incorporate the rice and ryegrass residues into the soil are performed only in the spring season, which may increase methanogenesis due to higher substrate availability in reduced subsurface soil layers. It was hypothesized that anticipating the soil tillage from spring to the fall season reduces yield-scaled greenhouse gas emissions during the summer rice season due to lower availability of C compounds to methanogenic bacteria in subsurface soil layers. A seven-year study was conducted to determine soil methane (CH_4) and nitrous oxide (N_2O) emissions, partial global warming potential [pGWP = (CH_4*25) + (N_2O*298)], rice yields, and yield-scaled pGWP emissions (yield-scaled pGWP = pGWP/yield) from flood irrigated rice under spring and fall tillage treatments. No significant effect of tillage treatments on soil N_2O emissions and rice yields was detected. When averaged across treatments and growing seasons (GSs), rice yield was 7.9 Mg ha^{-1} GS^{-1}, whereas cumulative N_2O emissions were 3.65 kg N_2O ha^{-1} GS^{-1}. Soil CH_4 emissions were responsible for 91.5% of pGWP. The spring tillage treatment resulted in an earlier and larger first peak of CH_4 efflux, likely due to higher labile C availability originated from the rice and ryegrass biomass decomposition in subsurface soil layers. In contrast, in the fall tillage treatment the easily decomposable compounds of the rice residue was utilized during the winter months, which combined with the ryegrass biomass kept on the soil surface resulted in lower labile C availability in subsurface soil layers. The fall tillage treatment significantly reduced cumulative CH_4,pGWP and yield-scaled pGWP emissions by 24, 21, and 25%, respectively. Averaged across GSs, CH_4, pGWP and yield-scaled pGWP emissions for the fall and spring tillage treatments were 316 and 417 kg CH_4 ha^{-1} GS^{-1}, 8.6 and 10.9 Mg CO_2eq ha^{-1} GS^{-1}, and 1.06 and 1.41 kg CO_2eq kg^{-1} grain, respectively. Our results indicate that shifting soil tillage operations from spring to fall can successfully mitigate yield-scaled pGWP emissions from regional flooded rice fields.

1. Introduction

Flood irrigated rice occupied approximately 80 million ha in 2012, accounting for 75% of worldwide rice production (IRRI, 2013). Intensive flood irrigated rice production is one of the main sources of anthropogenic methane (CH_4) due to the anoxic soil environment (Le Mer and Roger, 2011). Nitrous oxide (N_2O) emissions during flood irrigated rice cultivation are significantly smaller than aerobic crops (Linquist et al., 2012). However, since management practices may have distinct impacts on CH_4 and N_2O emissions (Hou et al., 2000), both greenhouse gases (GHGs) need to be considered when developing GHGs mitigation strategies. Methane and N_2O are important GHGs, exhibiting 25 and 298 times larger global warming potential (GWP)

Abbreviations: GHG, greenhouse gases; CH_4, methane; N_2O, nitrous oxide; CO_2, carbon dioxide; GS, growing season; pGWP, partial global warming potential.

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than carbon dioxide (CO_2) in a 100 years horizon, respectively (IPCC, 2013). In addition, CH_4 may react with hydroxyl radicals in the troposphere, reducing its ability to eliminate chloro-fluor carbons and leading to the production of other GHGs (Cicerone and Oremland, 1988; Le Mer and Roger, 2001), whereas N_2O is the main ozone-depleting substance emitted in the 21st century (Ravishankara et al., 2009).

Methane emission from soils encloses a series of complex processes involving methanogenic and methanotrophic microorganisms, presence and type of vegetation, soil physicochemical properties, and climatic factors (Le Mer and Roger, 2001; Ponnanperuma, 1972). Rice fields exhibit greater methanogenic than methanotrophic activity, resulting in an efflux of CH_4 from soil, which transfer to the atmosphere is facilitated by the aerenchyma and micropores located on rice leaves (Nouchi et al., 1994). Nitrous oxide is formed by microorganisms predominantly during denitrifier denitrification of NO_3^-, nitrifier nitrification of NH_4^+ (Bremner, 1997), and nitrifier denitrification of NO_2^- (Kool et al., 2011). In flood irrigated rice systems, denitrifier denitrification is the major pathway of N_2O formation, reducing NO_3^- that accumulated in the soil from organic matter mineralization (Bremner, 1997).

Methane mitigation strategies from rice fields have focused on controlling either CH_4 production, oxidation, or transport processes (Yagi et al., 1997). Methane production is dependent on dissolved organic carbon (DOC) availability and highly reduced soil conditions (Bossio et al., 1999 Yagi et al., 1997). Therefore, reducing substrate (DOC) availability, delaying the onset of low redox potential (Eh), or increasing Eh to aerobic levels can reduce CH_4 formation (Patrick & Jugsujinda, 1992; Ponnanperuma, 1972). Several soil and water management strategies have successfully reduced CH_4 emissions from rice fields, such as no-till systems (Bayer et al., 2014), straw management (Bossio et al., 1999), and intermittent irrigation regimes (Yagi and Minami, 1990; Sass et al., 1991). However, some of these strategies may have undesirable effects, such as higher N_2O emissions, lower rice yields, increased production costs, and air pollution (Yagi et al., 1997).

In southern Brazil, rice is grown during the summer under flood irrigation, while a self-reseeding ryegrass (*Lolium multiflorum* L.) is grown during the winter season as a cover crop without irrigation. The conventional farming practices consist of soil tillage operations in spring before rice seeding, incorporating into the soil both the rice biomass from the previous season and the ryegrass biomass that accumulated during the winter. No soil tillage is performed after rice harvesting. However, spring biomass incorporation often results in an early-season peak in CH_4 emissions due to an increase in substrate (DOC) availability (Schutz et al., 1989) and a decrease in Eh values (Patrick and Jugsujinda, 1992). Shifting the soil tillage operations and incorporation of rice residues from spring to fall season may speed up biomass decomposition during the winter under aerobic conditions, consequently decreasing the amount of easily decomposable compounds and DOC availability during the rice growing season. In addition, under a fall tillage system, the ryegrass biomass would remain in the oxidized soil surface during the rice growing season due to the absence of a spring soil tillage, which may further reduce substrate availability in anaerobic soil layers, as has been shown in no-till systems in the same region (Bayer et al., 2014). Therefore, shifting the soil tillage operations from spring to fall season may alter the C cycling in the rice–ryegrass agroecosystem, resulting in lower methanogenesis and CH_4 emissions during the rice growing season. However, even though rice biomass decomposition may not result in high N mineralization rates due to high C/N ratios, the fall soil tillage may increase soil N_2O emissions due to higher pre-flood soil NO_3^- concentrations in relation to spring soil tillage, due to the decomposition and mineralization of rice residues during the winter.

In addition to GHGs emission, it is important to evaluate the effects of fall tillage on rice yields, because management strategies that reduce yields will only displace food production and associated GHGs emissions to a different location (Venterea et al., 2011). Therefore, it is imperative to account for the effect of fall soil tillage on GHGs and rice yields to identify the tillage system with the lower partial global warming potential (*p*GWP) and yield-scaled *p*GWP to account for both impacts (van Groenigen et al., 2010). Our study was conducted across seven growing seasons with the objective of determining soil CH_4 and N_2O emissions, *p*GWP emissions, rice grain yields, and yield-scaled *p*GWP emissions under spring tillage and fall tillage systems in the humid subtropical climate of southern Brazil>.

2. Materials and methods

2.1. Site description and crop management practices

The experiment was conducted at the Research Station of the Rio Grandense Rice Institute (IRGA) at Cachoeirinha city (29.9°S; 51.1°W), located in a humid subtropical climate (Cfa) (Peel et al., 2007). The site exhibits warm summers (average of 25 °C), cool winters (average of 15 °C), and annual precipitation of 1350 mm evenly distributed throughout the year. The soil at the experiment is classified as a loamy Haplic Gleysoil (US Soil Taxonomy Entisol). Particle size distribution and main chemical characteristics are presented in the Table 1.

The present study was conducted on an experiment laid out as a randomized complete block design with four replications designed to evaluate the effects of spring and fall tillage systems on rice yields and soil properties. Each plot measured 28 by 40 m. Rice was drill seeded and grown during the summer season under flood irrigation, while a self-reseeding ryegrass was grown during the winter months as a cover crop without irrigation. A glyphosate-based herbicide (3 l ha^{-1}) was applied on the ryegrass in the spring followed by machine chopping of the standing biomass for both tillage treatments. The soil tillage operations were completely identical in both treatments, consisting of one ploughing-disc and two leveling-disc operations to the depth of 20 cm. However, in the spring tillage treatment the soil tillage was performed in the spring season before rice seeding, whereas in the fall tillage treatment the soil tillage was performed in the fall season after the rice harvesting. On average, the soil tillage operations were performed within 20 days after rice harvesting in the fall tillage treatment, and 7 days before rice seeding in the spring tillage treatment (Table 2). No additional soil tillage operations were performed.

Greenhouse gas fluxes were determined during seven rice growing seasons (GSs) in 2004/05, 2005/06, 2006/07, 2007/08, 2009/10, 2011/12, and 2012/13, referred to from now on as GS-1, GS-2, GS-3, GS-4, GS-5, GS-6, and GS-7, respectively. The rice

Table 1
Particle size distribution and main chemical characteristics of a Haplic Gleysoil (0–20 cm) subjected to spring and fall tillage systems in southern Brazil. Soil samples were collected in August 2004.

Soil property	Spring tillage	Fall tillage
Clay (g kg^{-1})	160	190
pH (H_2O)	5.6	5.3
Phosphorus (mg L^{-1})	18	23.7
Potassium (mg L^{-1})	65	64
Soil organic matter (g L^{-1})	17	17
Cation exchange capacity (cmolc L^{-1})	6.2	6.2
Base saturation (%)	72	55.8
Aluminum saturation (%)	0	0