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Yield-scaled greenhouse gas emissions from flood irrigated rice under long-term conventional tillage and no-till systems in a Humid Subtropical climate

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ABSTRACT

Soils under flooded rice (*Oryza sativa* L.) production are one of the major anthropogenic source of CH_4 emissions, an important greenhouse gas (GHG) with a 25-times larger global warming potential (GWP) than CO_2. No-till systems (NT) systems may be a viable alternative to mitigate GHG emissions in comparison to conventional tillage (CT). The objectives of this study were to evaluate on a field scale the long-term effects of CT and NT systems on soil CH_4 and N_2O emissions, rice yields and yield-scaled emissions during five growing seasons (GS) in Southern Brazil. In addition, a short-term greenhouse experiment was conducted to isolate the effect of winter crop [ryegrass (*Lolium multiflorum* L.)] biomass incorporation on soil CH_4 efflux. Averaged across years, the NT system resulted in 21% lower seasonal CH_4 emissions than the CT system, at 408 and 517 kg CH_4 ha^{-1} GS^{-1}, respectively. No significant effect of tillage system on N_2O emissions was observed. Methane emission was responsible for 96.5% of partial GWP (*p*GWP = $CH_4 \times 25 + N_2O \times 298$), stressing the importance of this GHG for developing low GHGs rice systems. No significant effect of tillage system on rice grain yields (average of 7.8 Mg ha^{-1} GS^{-1}) was detected. Consequently, the NT system resulted in 23% lower yield-scaled *p*GWP, at 1.35 and 1.76 kg CO_2eq kg^{-1} grain for NT and CT treatments, respectively. According to the greenhouse study, the incorporation of ryegrass biomass into the soil resulted in 2.8 times larger cumulative CH_4 emission than the surface application of biomass, at 347.4 and 125.5 g CH_4 m^{-2}, respectively, due to higher dissolved organic carbon (DOC) concentration and reduced soil environment in subsurface soil layers. Our results indicate that biomass incorporation is the main cause of higher CH_4 emissions from conventionally tilled soil and that NT system is a viable alternative to reduce yield-scaled GHG emissions from flooded rice fields.

1. Introduction

Rice (*Oryza sativa* L.) is the staple food of more than half of the world's population (IRRI et al., 2002). In 2012, worldwide rice production covered 163 million ha of cropland (FAOSTAT, 2014). Approximately 80 million ha were managed under continuous flood irrigation, accounting for 75% of the world's rice production (IRRI, 2013). Due to the anoxic soil environment, flood irrigated rice favors the formation of methane (CH_4), representing one of the main sources of anthropogenic CH_4 emission (Le Mer and Roger, 2001). Although nitrous oxide (N_2O) emissions from flooded rice are significantly lower than from aerobic crops (Linquist et al., 2012b), both CH_4 and N_2O need to be considered when developing greenhouse gases (GHGs) mitigation strategies, because strategies that reduce the former usually tend to increase the latter (Hou et al., 2000). Methane and N_2O are important GHGs, exhibiting 25 and 298 times larger global warming potential (GWP) than carbon dioxide (CO_2) in a 100 years horizon, respectively (Intergovernmental Panel on Climate Change (IPCC), 2007). In addition, CH_4 reacts with

Abbreviations: GHG, greenhouse gases; *p*GWP, partial global warming potential; NT, no-till; CT, conventional tillage; DOC, dissolved organic carbon; Eh, redox potential.

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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), while N_2O is the main ozone-depleting substance emitted in the 21st century (Ravishankara et al., 2009).

The concentrations of CH_4 and N_2O in the Earth's atmosphere have been increasing since the Industrial Revolution mainly due to human activities (Intergovernmental Panel on Climate Change (IPCC), 2007). Agricultural soils are among the main anthropogenic source of CH_4 and N_2O (Le Mer and Roger, 2001; van Groenigen et al., 2010). Nitrous oxide is formed by microorganisms predominantly during denitrifier denitrification of NO_3^-, nitrifier nitrification of NH_4^+ (Bremner, 1997), and through nitrifier denitrification of NO_2^- (Kool et al., 2011). In anaerobic soil conditions, denitrifier denitrification is the major pathway of N_2O formation, reducing NO_3^- that accumulated in the soil either through organic matter mineralization during aerobic periods or through N fertilization (Bremner, 1997). Soils under intensive flooded rice cultivation are a particularly important source of CH_4 (Linquist et al., 2012a,b). Methane emissions from soils are affected by a series of complex processes involving methanogenic and methanothrophic microorganisms, presence and type of vegetation, soil physicochemical properties, and climatic factors (Le Mer and Roger, 2001). Rice fields usually exhibit high methanogenic and methanotrophic activities, with the former usually being of greater magnitude, resulting in positive CH_4 emissions. In addition, the presence of rice plants favor the passive transfer of CH_4 to the atmosphere through aerenchima and micropores located within rice leaves (Nouchi et al., 1994).

No-till practices (NT) have been widely used in substitution of conventional tillage (CT) to reduce soil erosion and soil organic matter (SOM) losses, improve soil fertility and structure, and conserve water (Schlesinger, 1999; Six et al., 2002). In lowland flooded rice fields in Southern Brazil, NT systems have been adopted mainly to reduce the number of field operations during the busy rainy spring season, allowing for the sowing of rice at the optimum period.

The effects of NT systems on GHG emissions are variable and conflicting. In aerobic soil conditions, some have reported lower emissions (Cole et al., 1997; Ellert and Janzen, 1999; Gregorich et al., 2008; Mosier et al., 2006), while others reported higher emissions (Ball et al., 1999; Burford et al., 1981), or no differences between NT and CT systems (Lemke et al., 1998). Several authors have determined GHG emissions from flooded rice systems (Deng et al., 2012; Linquist et al., 2012a,b; Moterle et al., 2013; Nouchi et al., 1994); however, only a few have evaluated the effect of NT system on GHG emissions (Ahmad et al., 2009; Harada et al., 2007; Pandey et al., 2012). Generally, higher CH_4 emissions have been observed in CT compared to NT systems (Ma et al., 2013). However, the effects of NT on yield-scaled GHG emissions have been largely overlooked. Different tillage systems can affect both GHG emissions and yields. Since there is an ever-growing demand for agricultural products, reductions in GHG emission with concomitant reductions in yield may only displace food production and associated GHG emissions to a different area (Venterea et al., 2011). Expressing GHG emissions on a yield basis can account for both impacts (van Groenigen et al., 2010).

Most of the available GHG emission data deal with short-term conversion to NT system (Jian-She et al., 2011; Li et al., 2011). Since there is a time-dependent effect of NT system on GHG emissions (Six et al., 2004; van Kessel et al., 2013), it is imperative to evaluate the long-term effect of NT on yield-scaled GHG emissions in flooded rice systems. Furthermore, the incorporation of biomass into the soil may be the main mechanisms through which CT systems can affect CH_4 emissions, requiring studies designed specifically to isolate the effect of biomass incorporation from all other factors governing CH_4 emissions. This study was carried out at a long-term field experiment to determine soil CH_4 and N_2O emissions, partial GWP (*p*GWP), rice grain yields, and yield-scaled *p*GWP across five growing seasons under CT and NT systems. In addition, a short-term greenhouse experiment was conducted to assess the effect of winter biomass management (incorporation vs. surface application) on soil CH_4 emissions.

2. Materials and methods

2.1. Field experiment

2.1.1. Site description and field management practices

The experiment was conducted at the Research Station of the Riograndense Rice Institute (IRGA) at Cachoeirinha city (29.9°S; 51.1°W), Rio Grande do Sul State, Southern Brazil. According to the updated Koppen–Geiger classification (Peel et al., 2007), Cachoeirinha is located in a Humid Subtropical climate (Cfa), exhibiting warm summers (mean temperature of 25 °C), cool winters (mean temperature of 15 °C), and mean 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 Table 1.

The field study was conducted on an ongoing long-term experiment, established in 1994 as a randomized complete block design with three replications, to evaluate the effects of CT and NT systems on rice yields and irrigation requirements. Each plot measures 28 by 40 m and is separated from the other plots by levees. Since the beginning of the experiment, rice has been drill seeded and grown during the summer season under flood irrigation, while a self-reseeding ryegrass (*Lolium multiflorum* L.) is grown during the winter months as a cover crop without irrigation. A glyphosate-based herbicide (3 L ha^{-1}) is applied on the ryegrass in the spring followed by machine chopping of the standing biomass in both tillage treatments. The CT treatment consists of one ploughing-disc operation and two leveling-disc operations before rice seeding, whereas no soil tillage is employed in the NT treatment and rice is seeded through winter crop residues.

The present study was conducted during the rice growing seasons of 2002/2003, 2003/2004, 2007/2008, 2009/2010, and 2011/2012, referred to from now on as GS-1, GS-2, GS-3, GS-4, and GS-5, respectively. The rice cultivar IRGA422CL was drill seeded in the GS-1, GS-2, GS-3, while the cultivar Puitá INTA-CL was drill seeded in GS-4 and GS-5. Nitrogen, P, and K were applied at rice seeding (Table 2). Additional top-dress N fertilizer was applied at four-leaf, eight-leaf, and panicle differentiation rice developmental stages. The fields were flooded approximately 20 days after rice seeding, kept with constant flood (10 cm water layer), and drained 10 days before rice harvesting. After harvest, the rice straw was kept

Table 1
Particle size distribution and main chemical characteristics of a Haplic Gleysoil (0–10 and 10–20 cm) subjected to conventional tillage and no-till system in Southern Brazil since 1994. Soil samples were collected in August 2003.

Soil property	Conventional tillage		No-till	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Clay (g kg^{-1})	260	280	230	270
pH (H_2O)	5.2	5.0	5.2	4.8
Phosphorus (mg L^{-1})	17.0	10.9	27.0	6.1
Potassium (mg L^{-1})	81.0	37.0	92.7	37.0
Soil organic matter (g L^{-1})	23	17	29	13
C/N ratio	8	12	10	15
Cation exchange capacity (cmolc L^{-1})	6.3	6.9	6.5	5.7
Base saturation (%)	45.0	52.0	47.0	45.0
Aluminum saturation (%)	8.4	7.7	8.8	12.8