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Mitigating greenhouse gas emissions from a subtropical Ultisol by using long-term no-tillage in combination with legume cover crops

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ABSTRACT

Greenhouse gas (GHG) emissions can be partially mitigated with conservation agriculture. In this study, we assessed the effects of conventional tillage (CT) and no-tillage (NT), as well as five NT cover crop-based cropping systems, on yield-scaled GHG emissions in two long-term experiments (18 and 19 years) on a subtropical Paleudult. Air samples collected in static closed chambers were used to measure nitrous oxide (N_2O) and methane (CH_4) fluxes. The annual rate of change in soil organic C from the beginning of the experiments was used as proxy for net CO_2 flux. Cumulative annual emissions of the three GHG and the CO_2 costs of agricultural inputs and operations were taken in full account when estimating the global warming potential (GWP). Under legume cover crops, NT soil exhibited increased N_2O emissions relative to CT soil (531 vs 217 kg CO_2eq ha^{-1} yr^{-1}); however, emissions of this gas from NT soil were fully offset by CO_2 retention in soil organic matter (−2063 to −3940 kg CO_2 ha^{-1} yr^{-1}). Soil CH_4 fluxes were very low with all management systems (−1.5 to 30.5 kg CO_2eq ha^{-1} yr^{-1}). NT soil under legume cover crops behaved as a net sink for GHG (GWP ranged from −971 to −2818 kg CO_2eq ha^{-1} yr^{-1}); by contrast, CT soil and NT soil with a low biomass input were net sources of GHG (GWP ranged from 857 to 2133 kg CO_2eq ha^{-1} yr^{-1}). The legume cover crops increased maize yield and further reduced yield-scaled GHG emissions. This result suggests that conservation management practices involving no-till in combination with legume cover crops provide an effective approach to sustainable low-C footprint food production in subtropical regions.

1. Introduction

Agriculture plays a major role in regulating the exchange of greenhouse gases (GHG) between soils and the atmosphere in most tropical and subtropical countries (Mosier et al., 2006). In Brazil, the agriculture sector contributes 36%, 84% and 94% of the overall emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), respectively (MCTI, 2013). Based on these figures, adopting mitigation strategies in this sector in Brazil might be highly useful with a view to curbing the country's overall annual emission (1.25 Pg CO_2 eq) according to MCTI (2013).

Land clearing followed by conventional tillage (CT) generally turns soil into a net GHG source (Mosier et al., 2006, 2005; Robertson et al., 2000), mainly as the result of increased carbon (C) losses by effect of microbial oxidation (Amado et al., 2006; Bayer et al., 2006a,b). An even direr scenario is observed when CT is compounded with low-biomass input cropping systems or fallow periods, especially under the warm, humid conditions of the tropics and subtropics (De Bona et al., 2008; Zanatta et al., 2007).

Conservation agriculture might be useful to mitigate GHG emissions (Mosier et al., 2006; Robertson et al., 2000; Six et al., 2004), especially in soils under no-tillage (NT), which is known to provide a more favorable C balance than CT (Amado et al., 2006; Bayer et al., 2006a; Bayer et al., 2006b; Conceição et al., 2013).

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However, the effectiveness of NT in "sequestering" atmospheric CO_2 into soil relies heavily on an effective crop biomass input (Bayer et al., 2006a; Dieckow et al., 2005), high-input legume cover crops typically resulting in the highest sequestration rates (Bayer et al., 2006a; Jantalia et al., 2007).

Tillage and cropping systems also affect N_2O and CH_4 fluxes from agricultural soils. Thus, increased N_2O fluxes have usually been related to increased concentrations of mineral N derived from synthetic or organic fertilizers (Garcia-Ruiz and Baggs, 2007; Mosier et al., 2006), legume residues (Baggs et al., 2006; Gomes et al., 2009; Millar and Baggs, 2005) or soil compaction under NT (Ball et al., 1999). Because these practices affect both nitrogen (N) and oxygen (O) availability, they may boost N_2O production by nitrification and/or denitrification (Baggs et al., 2006; Mosier et al., 2004; Yamulki and Jarvis, 2002).

The CH_4 oxidation capacity of undisturbed freely drained soils is dramatically reduced by agricultural use (Hütsch, 1998, 2001; Robertson et al., 2000). Also, restoring their ability to oxidize CH_4 by using conservation management systems seems to be a slow process (Bayer et al., 2012; Jacinthe and Lal 2005; Jacinthe and Lal 2006) that can be hampered by yield-supportive N fertilization once high ammonium levels have decreased the ability of methane monooxygenase to oxidize CH_4 (Baggs and Blum 2004; Bayer et al., 2012).

Although N_2O and CH_4 have lower fluxes than CO_2, each molecule of these gases has a warming potential over a 100-year time frame 296 and 23 times, respectively, higher than that of CO_2 (IPCC, 2013). Therefore, assessing the overall impact of GHG on radiative forcing requires considering not only CO_2 absorption from and emission to the atmosphere, which can be estimated from changes in soil C, but also the impact of soil use and management systems on CH_4 and N_2O fluxes (Robertson et al., 2000) in addition to the hidden CO_2 equivalent costs from fuel consumption and the manufacturing of agronomic inputs (lime, fertilizer, pesticides, irrigation).

The overall balance of CO_2, CH_4 and N_2O fluxes across the soil–atmosphere interface represents the net global warming potential (GWP) of a crop production system (Mosier et al., 2006, 2005; Robertson et al., 2000; Sainju et al., 2014) on a per hectare basis. Recently, however, GWP has been referred to food yield in so called "yield-scaled GWP", which has been proposed as an index for evaluating the efficiency per unit food yield of agricultural practices in decreasing GHG emissions (Venterea et al., 2011; Bayer et al., 2014; Sainju et al., 2014).

The impact of cover crops and no-tillage on soil GHG emissions has to date been inadequately assessed in tropical and subtropical regions. In this study, we hypothesized that no-till in combination with a legume cover crop would reduce yield-scaled GWP relative to conventional tillage and grass cover crops as a result of increased N_2O emissions from soil under legumes being fully offset by even more markedly increased atmospheric CO_2 retention into organic matter. The primary aim of this study, conducted in two long-term experiments on a subtropical Paleudult in Southern Brazil, was to assess the potential of conservation tillage and cropping systems for mitigating GHG emissions while preserving sustainable production of food relative to the soil management systems traditionally used in the region.

2. Material and methods

2.1. Long-term experiments

This study was based on two adjacent long-term experiments performed at the Experimental Agronomic Station of the Federal University of Rio Grande do Sul, Southern Brazil. Table 1 shows selected details about the study including site location, climate, soil, experimental conditions and treatments. At the time the experiments were established, the soil, which was previously native grassland, was physically degraded by effect of rotary tillage and low crop biomass inputs over the previous two decades.

Table 1
Selected characteristics of the experimental site, soil and treatments in the two long-term experiments.

Characteristic	Experiment I	Experiment II
County	Eldorado do Sul, RS	
Geographic coordinates	30°06′34″ S, 51°40′38″ W	
Mean annual air temperature (°C)	19.4	
Mean annual rainfall (mm)	1440	
Altitude (m)	96	
Soil type	Typic Paleudult	
Soil texture in 0–20 cm layer	Sandy clay loam	
Clay (g kg^{-1})	220	
Silt (g kg^{-1})	240	
Sand (g kg^{-1})	540	
Establishment year	1983	1985
Sampling year		
Soil sampling	19th (2002)	18th (2003)
Gas sampling	20th (2003)	18th (2003)
Studied tillage systems[a]	NT	CT NT
Studied cropping systems[b]	O + V/M + C L + M P + M	O/M V/M

[a] NT no-tillage with glyphosate desiccation prior to maize planting; CT conventional tillage with plowing and two diskings prior to maize planting. Experiment I, only under NT.
[b] O oat (*Avena strigosa* Schreb.) and V-vetch (*Vicia sativa* L.) were winter cover crops; M maize (*Zea mays* L.) was the cash crop; C cowpea (*Vigna unguiculata* [L.] Walp.), L lablab (*Lablab purpureum* (L.) Sweet) and P pigeon pea (*Cajanus cajan* L. Millsp.) were summer cover crops, intercropped with maize.

Experiment I, established in 1983, involved ten no-till (NT) cropping systems distributed in a randomized complete block design with three replicates. All experimental plots were 5 × 16 m. Only three of the systems were examined in this study, namely: pigeon pea + maize (P + M) and lablab + maize (L + M) as examples of summer intercropping of a legume cover crop and maize; and oat + vetch/maize + cowpea (O + V/M + C), a grass plus legume cover crop in winter followed by a legume cover crop intercropped with maize in summer. The maize used was a cash crop. The scientific names of the species used are *Cajanus cajan* (L.) Millsp. (pigeon pea), *Lablab purpureum* (L.) Sweet (lab-lab), *Vigna unguiculata* (L.) Walp (cowpea), *Avena strigosa* Schreb (oat), *Vicia sativa* (L.) (vetch) and *Zea mays* (L.) (maize).

Experiment II, established in 1985, consisted of a combination of three tillage systems and three cropping systems distributed in a split-plot randomized complete block design with three replicates. Tillage system was used as the main plot (15 × 20 m) and cropping system as the subplot (5 × 20 m). Only two tillage systems and another two cropping systems in the experiment were examined here, namely: conventional tillage (CT) and no-tillage NT, each combined with oat/maize (O/M), to represent a grass cover crop; and with vetch/maize (V/M) to represent winter legume cover crop. The criteria used for treatment selection was to assess the effects of different levels of soil disturbance and incorporation of crop residues into the soil (CT and NT), and also to span a wide range of C and N biomass addition with the summer and winter cover crops.

Oat, vetch and their combination were sown with a NT drill in early fall (April), following harvesting of the previous maize crop in March and spreading of its aboveground residue with a knife roller. The seed rate for both oat and vetch when sown individually was