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Soil carbon dioxide and nitrous oxide emissions during the growing season from temperate maize-soybean intercrops

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Abstract

The Argentine Pampa is one of the major global regions for the production of maize (*Zea mays* L.) and soybean (*Glycine max* L. [Merr.]), but intense management practices have led to soil degradation and amplified greenhouse-gas (GHG) emissions. This paper presents preliminary data on the effect of maize-soybean intercrops compared with maize and soybean sole crops on the short-term emission rates of CO_2 and N_2O and its relationship to soil moisture or temperature over two field seasons. Soil organic carbon (SOC) concentrations were significantly greater ($p < 0.05$) in the maize sole crop and intercrops, whereas soil bulk density was significantly lower in the intercrops. Soil CO_2 emission rates were significantly greater in the maize sole crop but did not differ significantly for N_2O emissions. Over two field seasons, both trace gases showed a general trend of greater emission rates in the maize sole crop followed by the soybean sole crop and were lowest in the intercrops. Linear regression between soil GHG (CO_2 and N_2O) emission rates and soil temperature or volumetric soil moisture were not significant except in the 1:2 intercrop where a significant relationship was observed between N_2O emissions and soil temperature in the first field season and between N_2O and volumetric soil moisture in the second field season. Our results demonstrated that intercropping in the Argentine Pampa may be a more sustainable agroecosystem land-management practice with respect to GHG emissions.

Key words: Argentine Pampa / complex agroecosystems / global warming / legumes / Pearson-product moment correlation / soil moisture and temperature

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1 Introduction

Intensive agroecosystem management practices have reduced levels of soil organic carbon (SOC) and augmented the emission of greenhouse gases (GHG), which have contributed to global warming. Soil CO_2 and N_2O emissions may be mitigated through improving crop, soil- and fertilizer-management practices (*Adviento-Borbe* et al., 2007), and by the implementation of sustainable agricultural production systems (*Verchot* et al., 2008).

Intercropping, where more than one crop is grown on the same land unit at the same time, may be a more sustainable agricultural production system compared to conventional or sole-crop systems. Although intercropping is not a new land-management concept, especially in tropical regions (*Sharma* and *Behera*, 2009), it is currently gaining recognition in temperate areas (*Oelbermann* and *Echarte*, 2011). This is because intercropping systems have a smaller environmental impact compared to conventional sole-crop agroecosystems (*Li* et al., 2001) and may also be more resilient to local climate change due to their greater structural complexity compared to sole-crop agroecosystems. In the Argentine Pampa, intensive production of maize (*Zea mays* L.) and soybeans (*Glycine max* L. [Merr.]) has led to soil degradation (*Posse* et al., 2010); and as a consequence cereal-legume intercrops were adopted to minimize losses of soil organic matter (SOM). Establishing cereal-legume intercrops may reduce losses of C and N because of an overall increase in agroecosystem complexity and the complementary use of resources in time and space (*Prasad* and *Brook*, 2005). The inclusion of legumes with a ceral such as maize (*Zea mays* L.) regulates the internal N cycle *via* N_2 fixation (*Schipanski*, 2010) and reduces the amount of fertilizer required for crop growth (*Inal* et al., 2007).

To date, most research on intercrop systems has focused on grain yield and grain quality, resource use and competition, nutrient-use efficiency and fertilizer requirements, and weed and erosion control (*Prasad* and *Brook*, 2005; *Waddington* et al., 2007). There is little understanding of the underlying processes involved in the sequestration and stabilization of C and N in temperate intercropping systems, and only a few studies have investigated the effects of cereal-legume inter-

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crops on GHG emissions (*Pappa* et al., 2011). A field experiment was carried out to quantify the short-term GHG emission rates from maize-soybean (*Glycine max* [L.] Merr.) intercrops and maize and soybean sole crops. The objectives of this study were to quantify CO_2 and N_2O emission rates from two differently configured maize-soybean intercrops compared to maize and soybean sole crops, and to correlate CO_2 and N_2O emission rates to soil moisture and temperature over two field seasons. We hypothesized that due to a more effective resource-use efficiency, CO_2 and N_2O emission rates would be lower in the intercrop treatments. This paper presents preliminary results on the initial changes in GHG emissions as a result of intercropping 3 y after this agroecosystem was implemented. It is essential to present preliminary data because it is helpful to draw the first picture on the effect of cereal-legume intercropping on GHG emissions. Such information is crucial as it identifies other agroecosystem management practices effective in the mitigation of GHGs (*Rochette* and *Bertrand*, 2008), and also contributes additional information to the already existing global GHG databases (*Smith* et al., 2007; *Verchot* et al., 2008).

2 Materials and methods

2.1 Site description

The research site was located at the National Institute for Agricultural Technology (INTA) in Balcarce (37°45′ S, 58°18′ W), in the rolling Argentine Pampa. The average annual precipitation was 860 mm, a mean annual temperature of 13.9°C, and the site was located 130 m asl (*Andrade*, 1995). The soil was classified as a Luvic Phaozem (*Mar del Plata* series) (*Studdert* and *Echeverría*, 2000), with a loam soil texture composed of 41.1% sand, 35.8% silt, and 23.1% clay (*Domínguez* et al., 2009). The soil pH was 6.2 to a 120 cm depth (*Oelbermann* and *Echarte*, 2011).

The study was a randomized complete block design (RCBD) with four treatments and three replications per treatment. The treatments were maize (*Zea mays* L.) sole crop, soybean (*Glycine max* L. [Merr.]) sole crop, 1:2 intercrop, and 2:3 intercrop. The 1:2 intercrop consisted of one row of maize and two rows of soybeans, and the 2:3 intercrop consisted of two rows of maize and three rows of soybeans. Since 2007, all crops were sown on the same plots in consecutive years and each treatment plot size was 8.8 m × 12 m. These intercrop configurations and their plant densities were typical of those currently adopted by landowners in this region. Plant density (plants m^{-2}) was 4.3 (1:2 intercrop), 5.3 (2:3 intercrop), 8.0 (maize only), and 29 (soybean only), with a 0.52 m distance between crop rows. The site was under sunflower (*Helianthus annuus* L.) production prior to the initiation of the intercrop study.

Each treatment was mouldboard plowed, and weeds were controlled by N-phosphonomethyl glycine. Crops in each treatment were fertilized with P fertilizer (35 kg P ha^{-1} y^{-1}), and N fertilizer (granular urea) was applied at a rate of 150 kg N ha^{-1} y^{-1} to the maize sole crop and maize only in the intercrops (by hand to the bottom of the maize stems). Fertilizer was applied in November, and soybeans were inoculated with *Bradyrhizobium japonicum*. Maize was seeded in late October and harvested in April; whereas soybeans were seeded in late November and harvested in May. Only the grain or pod was removed, and all other crop residues remained on site. Average steady-state infiltration rates during the 2009/10 growing season were 11.76 mm min^{-1} (1:2 intercrop), 11.52 mm min^{-1} (2:3 intercrop), 9.97 mm min^{-1} (maize sole crop), and 9.41 mm min^{-1} (soybean sole crop).

2.2 Soil chemical and physical characteristics

Soil was sampled (0–10 cm) in February 2009 (Y1) and in 2010 (Y2) using a soil corer (5 cm inner diameter). Two random samples per treatment replicate were extracted and composited into one sample. A 20 g subsample of the composited soil per treatment replicate was oven-dried at 105°C for 48 h to determine bulk density. The remaining soil was air-dried and sieved (2 mm). Soil carbonates were removed by adding 150 mL HCl (0.5 *M*) to 2 g of sieved soil. The mixture was stirred 3 times over a 24 h period, and subsequently washed by pipetting the HCl from the settled soil and adding ultrapure water to the soil. This washing procedure was repeated daily for 4 d after which the soil was dried in an oven at 40°C for 2 d (*Midwood* and *Button*, 1998). The acid-treated soil was ground in a ball mill (Retsch® ZM1, Haan, Germany) and analyzed for C and N (Costech 4010, Cernusco, Italy). Crop-residue biomass data for this site was obtained from the site manager (data on file) and crop-residue C and N inputs (Tab. 1) were obtained from a previous evaluation of crop-residue C and N concentrations from this site (*Vachon* and *Oelbermann*, 2011). Mean values of C and N concentrations of crop-residue biomass in all treatments for maize were 42.2% (C) and 0.66% (N), and 44.8% (C) and 1.4% (N) for soybeans (*Vachon* and *Oelbermann*, 2011).

A WET-2 sensor (Delta-T Devices, Cambridge, UK) was used to quantify soil moisture (% volume) and temperature (°C) to a 10 cm depth. Measurements of soil moisture and temperature were taken at the same time, and in the same location, as GHGs. Ambient temperature and precipitation data (30 y mean) was obtained from a weather station, operated by the University of Mar del Plata, located adjacent to our study site.

2.3 Greenhouse-gas emission rates

Greenhouse-gas chambers were constructed from PVC piping (25 cm height, 10 cm radius) (*Parkin* et al., 2004; *Rochette* and *Bertrand*, 2008). Two sampling chambers per replicate in each treatment (*n* = 6) were placed randomly in the soil (10 cm depth) between crop rows, and between maize and soybean rows in the intercrops. The chambers were closed with an insulated (6 mm polyolefin foam [Borealis, Port Murray, USA]) and ventilated (10 cm long, 6 mm inner diameter clear PVC tube [Fisher Scientific, Mississauga, Canada]) PVC cap with a sampling port.

Table 1: Annual aboveground (shoots and leaves) crop-residue biomass, biomass C and N input (g m^{-2} y^{-1}) from maize and soybeans in a maize and soybean sole crop and in two differently configured intercropping systems in Balcarce, Argentina for the 2008/09 and 2009/10 field seasons ($n = 3$). Biomass data on file at INTA. Mean values of C and N concentrations of crop-residue biomass in all treatments for maize were 42.2% (C) and 0.66% (N), and 44.8% (C) and 1.4% (N) for soybeans (*Vachon* and *Oelbermann*, 2011).

			Soybean sole crop	**Maize sole crop**	**1:2 intercrop**	**2:3 intercrop**
Biomass	2008/09	soybean	681		170	177
		maize		2187	1306	1496
		total	**681**	**2187**	**1476**	**1673**
	2009/10	soybean	569		355	358
		maize		2593	1363	1597
		total	**596**	**2593**	**1718**	**1955**
Carbon	2008/09	soybean	305		76	79
		maize		923	551	631
		total	**305**	**923**	**627**	**710**
	2009/10	soybean	355		159	160
		maize		1094	575	674
		total	**255**	**1094**	**734**	**834**
Nitrogen	2008/09	soybean	10		2	2
		maize		14	9	10
		total	**10**	**14**	**11**	**12**
	2009/10	soybean	8		5	5
		maize		14	9	11
		total	**8**	**14**	**14**	**16**

Gases were measured biweekly (Parkin, pers. com., 2006) from December to February in 2008/09 (Y1) and 2009/10 (Y2). This short-term measurement phase corresponded to the maximum biomass accumulation of crops, where soil was not yet completely covered, and to the beginning of crop senescence at the latter part of the sampling regime. During sampling, the chambers were capped for 30 min and samples were extracted from the headspace with an air-tight 5 mL syringe at time 0 ($t = 0$), 15 ($t = 15$), and 30 min ($t = 30$), and transferred into 3 mL evacuated vials (Labco Ltd., High Wycombe, UK). Gas samples were analyzed on an Agilent 6890N (Santa Clara, California, USA) gas chromatograph, and a gas standard (100 ppm CO_2 and 10 ppm N_2O) was injected at a 10-sample interval.

CO_2 and N_2O emission rates were quantified according to *Hutchinson* and *Mosier* (1981):

$$([C_1 - C_0] / [C_2 - C_1]), \tag{1}$$

where C_0, C_1, and C_2 are the chamber headspace gas concentrations (ppmv) at $t = 0$, $t = 15$, and $t = 30$. If the outcome of Eq. 1 was > 1, linear regression was used to calculate the slope of the concentration *vs.* time. However, if Eq. 1 yielded a value of < 1, then linear regression is not appropriate. Instead the build-up of gas concentration in the chamber headspace is curvelinear with time, and as such the following equation was used (*Hutchinson* and *Mosier*, 1981):

$$f_0 = V (C_1 - C_0)^2 / (A\, t_1\, [2C_1 - C_2 - C_0]) \cdot \ln([C_1 - C_0] / [C_2 - C_1]), \tag{2}$$

where f_0 was the quantity gas produced (µL m^{-2} min^{-1}); V is the chamber headspace volume (L); A was the soil surface area (m^2); t_1 was the time interval between gas-sampling points (min). The value of the slope from the linear regression analysis was substituted for f_0 in the ideal gas law equation. Data for atmospheric temperature and pressure used in the ideal gas law equation were obtained from the INTA meteorological station, located adjacent to the study site. Resulting values (µmol m^{-2} min^{-1}) were converted to µg CO_2 m^{-2} h^{-1} and µg N_2O m^{-2} h^{-1}.

2.4 Statistical analysis

All data were examined for homogeneity of variance and normality and were found to have normal distributions.

Differences between treatments for soil characteristics and GHG emission rates were analyzed using the univariate general linear model (ANOVA) in SPSS (SPSS Science Inc., 1989). Significant differences were further analyzed using Turkey's multiple comparison test (*Steel*, 1997). A paired t-test was used to compare differences in GHG emission rates between sampling years (Y1 and Y2) within treatments. For each treatment, linear regression analysis was used to determine the relationship between CO_2 or N_2O emission rates and soil temperature or volumetric soil moisture. For all statistical analyses, the threshold probability level was $p < 0.05$.

3 Results

3.1 Soil chemical and physical characteristics

The two field season means (Y1 and Y2) of soil physical and chemical characteristics were significantly different between treatments (Tab. 2). Soil bulk density was significantly lower in the intercrops; and SOC concentration (g kg^{-1}) was significantly greater in the maize sole crop and intercrops (Tab. 2). Soil temperature and moisture varied within each field season and between the two field seasons. Both soil moisture and temperature followed a similar pattern to that of the ambient temperature and precipitation (Fig. 1). Soil moisture was highest in December of Y1 and in February of Y2 (Fig. 1). This

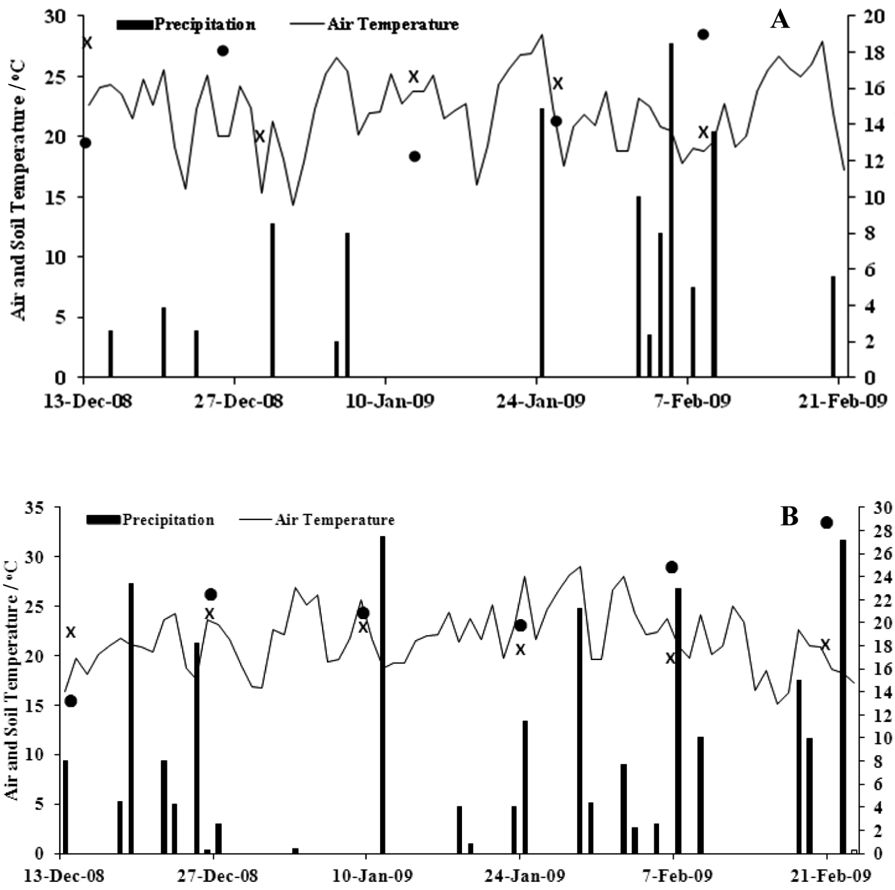

Figure 1: Mean air and soil (0–10 cm) temperature (X [°C]), and ambient precipitation (mm) and soil moisture (● [%vol]) of soybean and maize sole crop and intercrops ($n = 6$) over two field seasons. A) Y1: December 2008 to February 2009; B) Y2: December 2009 to February 2010 in the Argentine Pampa.

Table 2: Soil chemical and physical characteristics (mean of two field seasons) to a 10 cm depth in soybean and maize sole crops, and 1:2 and 2:3 intercrops in the Argentine Pampas, Balcarce, Argentina. Standard errors are given in parentheses ($n = 3$). Values followed by the same lowercase letter for each soil characteristic and comparing differences between treatments are not statistically different ($p < 0.05$).

	Soybean sole crop	Maize sole crop	1:2 intercrop	2:3 intercrop
Bulk density / g cm^{-3}	1.20 (0.1)^{a}	1.20 (0.1)^{a}	1.17 (0.1)^{b}	1.17 (0.1)^{b}
SOC / g kg^{-1}	23.76 (0.1)^{a}	24.58 (0.1)^{b}	24.46 (0.2)^{b}	24.41 (0.3)^{b}
TN / g kg^{-1}	2.26 (0.1)^{a}	2.28 (0.1)^{a}	2.27 (0.1)^{a}	2.29 (0.1)^{a}
C : N ratio	10.68 (0.2)^{a}	10.79 (0.1)^{a}	10.81 (0.3)^{a}	10.67 (0.2)^{a}
SOC stock / g m^{-2}	2898 (29.8)^{a}	2999 (22.0)^{b}	2861 (17.1)^{b}	2856 (9.0)^{b}
Soil TN stock / g m^{-2}	275 (2.7)^{a}	278 (3.5)^{a}	266 (6.8)^{b}	268 (4.5)^{b}

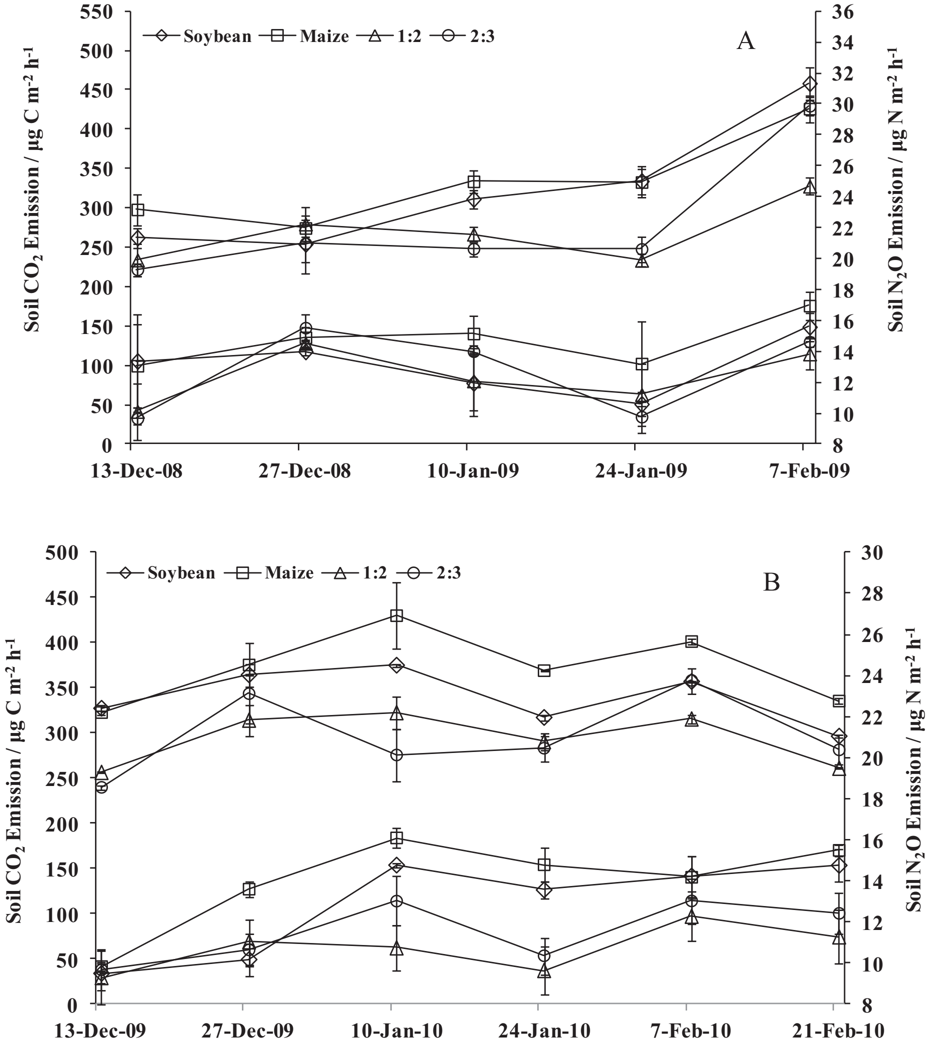

Figure 2: Soil CO_2 (µg C m^{-2} h^{-1}) and N_2O (µg N m^{-2} h^{-1}) (lower set of lines) emission rates from soybean and maize sole crop and intercrops ($n = 6$) over two field seasons. A) Y1: December 2008 to February 2009; B) Y2: December 2009 to February 2010 in the Argentine Pampa. Vertical bars represent standard errors.

study included a dry (Y1) and a wet (Y2) growing season showing variable measurements in ambient air temperature and precipitation, which also reflected a similar variation in soil temperature and soil moisture. Soil moisture was lower in Y1 due to a lower amount of precipitation, which was 171 mm below the 30 y average from December to February.

3.2 Carbon dioxide and nitrous oxide emission rates

In Y2, the mean CO_2 emission rates over the entire sampling period were significantly lower in the intercrcrops ([299 ± 7] µg C m^{-2} h^{-1} [1:2 intercrop], [300 ± 13] µg C m^{-2} h^{-1} [2:3 intercrop]) compared to the sole crops ([384 ± 7] µg C m^{-2} h^{-1} [soybean sole crop], [380 ± 11] µg C m^{-2} h^{-1} [maize sole crop]) (Fig. 2). When comparing differences in CO_2 emission rates between treatments (mean of both field seasons over the entire sampling period), a lower emission was observed in both intercrop systems. For example, CO_2 emission rates were (354 ± 14) and (357 ± 13) µg C m^{-2} h^{-1} in the soybean and maize sole crops respectively, whereas that in the intercrops was (284 ± 10) µg C m^{-2} h^{-1} (1:2 intercrop) and (290 ± 17) µg C m^{-2} h^{-1} (2:3 intercrop). Intraannual variation in CO_2 emission rates (December to February) were observed in Y1 and Y2 for all treatments (Fig. 2) but were not significantly correlated to soil temperature (°C) and moisture (% volume).

When comparing differences in N_2O emission rates between treatments (mean of both field seasons over the entire sampling peirod) lower emissions were observed in the intercrop systems (Fig. 2). For example, N_2O emission rates were (13.5 ± 0.8) and (14.0 ± 0.7) µg N m^{-2} h^{-1} in the soybean and maize sole crops, respectively, whereas that in the intercrops was (11.5 ± 0.8) and (12.0 ± 0.8) µg N m^{-2} h^{-1} in the 1:2 and 2:3 intercrops, respectively. N_2O emissions varied over the growing season in Y1 and Y2 and were only significantly correlated to soil temperature (Y1; $r^2 = 0.866$) and soil moisture (Y2; $r^2 = 0.700$) in the 1:2 intercrop.

4 Discussion

Soil physical and chemical characteristics were similar to those reported by others from the same region of the Argentine Pampa (*Studdert* and *Echeverría*, 2000; *Aparicio* and *Costa*, 2007; *Domínguez* et al., 2009). Although measureable differences in the SOC and N (g m^{-2}) stocks were not observed between treatments at this time, and it is expected that within the short term (≥ 5 y), measurable differences in the SOC and N stocks will occur between treatments. For example, *Alvarez* et al. (1998) reported a measurable difference in the SOC stock after 5 y, whereas *Studdert* and *Echeverría* (2000) noted changes after 11 y in this region of the Argentine Pampa.

Soil CO_2 and N_2O emission rates for all treatments fell within the range of values reported in other agroecosystems in the temperate zone (*Omonode* et al., 2007; *Ellert* and *Janzen*, 2008; *Pappa* et al., 2011). Values of CO_2 and N_2O emission rates from the sole crops, observed in our study, were similar to those reported by others (*Rastogi* et al., 2002; *Baggs* et al., 2006; *Posse* et al., 2010). Limited data is available on GHG emission rates from temperate cereal-legume intercropping systems, and no data exists for maize-soybean intercropping systems. In Scotland, *Pappa* et al. (2011) observed that N_2O production rates from cereal-legume intercrops were either greater or lower compared to sole crops; noting that the type of legume cultivar and previous crop-rotation regimes influenced emissions. When comparing CO_2 emission rates from agroecosystems with an annual maize-soybean rotation, emissions were similar to those of our intercrop systems. *Omonode* et al. (2007) found a 16% lower CO_2 emission in a maize-soybean rotation in Indiana compared to a maize sole crop, and attributed such differences to crop-residue quality. Greater root biomass and rhizodeposition in the maize sole crop in our study, compared to the soybean sole crop, may have also led to a higher CO_2 emission rate (*Sehy* et al., 2008).

West and *Post* (2002) evaluated the relationship between soil CO_2 emission rates and crop-residue input. They found that maize sole crops had a greater input of C from crop residues compared to a maize-soybean rotation, and observed a lower CO_2 emission rate in the treatment with crop rotation. These results corresponded to those of our study, including those of N_2O, showing that the treatment with the greatest crop-residue input (maize sole crop) had the greatest GHG emission rate (Tab. 1). This suggested that there may be an interaction that reduces the amount of CO_2 produced from the soil when maize and soybean are grown in rotation or as an intercrop, but no such interaction occurs in either maize or soybean sole crop (*West* and *Post*, 2002). *Cardoso* et al. (2007) suggested there may be a beneficial effect when legumes are intercropped with nonlegumes; where the nonleguminous crop may absorb N that is excreted from the leguminous root system (*Hauggaard-Nielsen* and *Jensen*, 2001).

Crop-residue biomass N was greatest in the maize sole crop and intercrops, however, N_2O emission rates, although not statistically different between treatments, were lower in the intercrops. In our study, the greater N_2O emission rates from the maize sole crop compared to the intercrops may be due to differences in the source (*Eichner*, 1990), the amount (*Drury* et al., 2008) and availability of N (*Jarecki* et al., 2008). However, *Mosier* et al. (1996) suggested that soil management and cropping systems may have a greater impact on N_2O emissions than the source of mineral N. Additionally, many of the key factors that increase N_2O emissions (soil temperature, moisture, pH, osmotic stress, and C and N availability) may be controlled by management practices such as site-specific N-fertilizer application. In our study, site-specific application of N fertilizers, where only maize and maize in the intercrops received N fertilizer, may be a better management option than sole cropping to help curb N_2O emissions.

5 Conclusions

Our study is unique because it is the first of its kind to evaluate soil CO_2 and N_2O emissions from a temperate maize-soybean intercrop system, thus addressing a current gap in the literature. Our results demonstrated that intercropping may be a more sustainable agroecosystem land-management practice with respect to GHG emission.

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