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Impact of land use during winter on the balance of greenhouse gases

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Abstract

The increase in atmospheric greenhouse gases (GHGs) can be mitigated by capturing CO_2 from the atmosphere and/or by reducing their emissions. Replacing winter intercrop fallow by cover crops (CCs) can sequester carbon and improve nitrogen use efficiency under proper management. We monitored two cycles of a cash crop namely soybean (soy1) and double-cropping soybean (soy2) and their respective post-harvest periods. During the first period, a winter crop (wheat) was used as an alternative to CCs, and in the second period, a chemical fallow treatment (bare soil) was applied. Carbon dioxide and N_2O exchange rates were estimated with turbulent flux measurements and N_2O fluxes with complementary static chambers. During the soy1/wheat sequence, the soil gained 2800 kg C eq/ha, while during the soy2/bare fallow sequence the soil lost 5083 kg C eq/ha. Excluding the carbon exported by harvest, both sequences lost carbon, but the soy2/bare fallow cycle was fivefold higher. The replacement of bare fallow by a winter cover crop like wheat decreases N_2O emissions considerably and converts carbon losses (by respiration) into gains (by fixation in photosynthesis). The replacement of traditional non-harvested cover crops by winter wheat may provide not only similar advantages in terms of soil improvement, preservation, and reduction in nitrogen loss, but also an additional harvest. It will be necessary to adjust the fertilization of this cover crop to prevent excess nitrogen from accumulating in soils.

Keywords: Bare fallow, carbon dioxide (CO_2), eddy covariance, nitrous oxide (N_2O), winter crop

Introduction

There is strong evidence that current climate change is the consequence of increasing greenhouse gases (GHGs) concentration in the atmosphere. Agriculture releases to the atmosphere significant amounts of three of the main GHGs, namely nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4; Paustian *et al*., 2004). Nitrous oxide causes the major impact because of its long lifetime (150 yr) and high calorific value (up to 310 times the atmospheric forcing potential of CO_2 over a 100-yr time horizon). Agricultural lands account for 60% of global N_2O emissions from all sources (e.g. Linquist *et al*., 2012). Nitrous oxide emissions are produced by microbial transformation of N in soils and this process is usually enhanced when available N exceeds plant demands (Henault *et al*., 2012). The intensified use of nitrogen fertilizers has greatly contributed to increase N_2O emissions (Bouwman *et al*., 2002). Taking into account that cultivated areas occupy about 40% of the terrestrial surface (FAO, 2003) and that this proportion is increasing (Green *et al*., 2005), agricultural ecosystems are likely to play a major role in determining the future GHG balance (Salinger, 2007).

The increase in atmospheric GHGs can be mitigated by capturing CO_2 from the atmosphere and/or by reducing their emissions (Hutchinson *et al*., 2007). The balance between inputs and outputs of soil organic carbon exert a key influence on atmospheric CO_2 concentration because soils contain about twice as much carbon as the atmosphere (Amundson, 2001). Existing evidence supports that many, if not most, agricultural soils can sequester carbon under proper management (Lal *et al*., 1998). Appropriate management strategies include to reduce or eliminate soil tillage, reduce bare fallow, crop rotation procedures, crop rotation with forage plants, boost primary production, and enhance the return of organic matter to soil (Paustian *et al*.,

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1997; Follett, 2001; Hutchinson *et al.*, 2007; Lewczuk *et al.*, 2017). Replacement of winter intercrop fallow by cover crops (CCs) is known to decrease nitrate leaching, increase soil fertility, and improve N use efficiency (Veenstra *et al.*, 2007; Restovich *et al.*, 2011).

In comparison with fallowed soils, CCs reduce water content, soil temperature, and the free nitrogen levels available for soil biota (Tribouillois *et al.*, 2015). These conditions lead to decreased microbiological activity, and therefore emissions are expected to be lower in CCs than in fallowed lands. However, a higher availability of soil carbon from crop residues may favor N_2O emissions (Mitchell *et al.*, 2013). Most studies focused on soil changes induced by the use of CCs during the winter period have aimed at analyzing physical (Restovich *et al.*, 2011; Castiglioni *et al.*, 2016), chemical (Luo *et al.*, 2010; Duval *et al.*, 2016), and biological (Chavarría *et al.*, 2016) properties. The inclusion of legumes (vs. non-legumes) and management of cover crop residue have a high impact on the global GHG balance (Kaye & Quemada, 2017). Typically, CCs are not harvested because they are used to protect the soil surface during winter, providing an extra ecosystem service (Pinto *et al.*, 2017). The use of surplus biomass in biogas systems with adequate reintroduction of biofertilizers could be a solution to be explored.

The general objective of this work is to study the impact of the winter fallow management on the balance of CO_2 and N_2O emissions in agricultural fields. Few investigations have explored the impact of CCs on N_2O emissions (Basche *et al.*, 2014; Guardia *et al.*, 2016) and less research still analyzes the annual balance of both CO_2 and N_2O in this context. The specific objectives were to compare the emissions of CO_2 and N_2O among two soybean growth cycles over field that had different use during the winter period (a winter wheat culture and a winter bare fallow) and to compare the annual sum of CO_2 and N_2O fluxes estimated for both sequences: first soybean (soy1)/wheat cycle versus soybean (soy2)/bare fallow cycle. We tested the hypothesis that the type of soil use in winter (CC or bare fallow) will affect CO_2 and N_2O emissions during this and the following crop growth periods. We predict that the use of winter wheat will increase CO_2 sequestration owing to an increase in photosynthesis rates and a decrease in respiration rates. In addition, N_2O emission will be lower because of the use of available soil nitrogen by the crop. However, the presence of stubble from winter wheat will affect the following crop cycle by increasing CO_2 and N_2O emissions in comparison with bare fallow.

Materials and methods

Study area

The study area is located in the Pampas Region, Province of Buenos Aires (Soriano *et al.*, 1992; Figure 1). Natural vegetation is temperate grasslands. The climate is subhumid with mean temperatures of 23.4 °C in January and 8.2 °C in July. Mean annual temperature is 16.1 °C and mean annual precipitation is 1060.3 mm (National Meteorological Service, historical series 1961–1990). The Pampas Region is one of the most productive areas of the world and responsible for most of the total grain exports in Argentina. In the study area, cattle ranching and agricultural activities coexist without overlapping each other. Typically, there are two crop rotations including continuous soybean/wheat–soybean double cropping/maize and soybean monoculture, alternating with winter fallow with no fixed pattern.

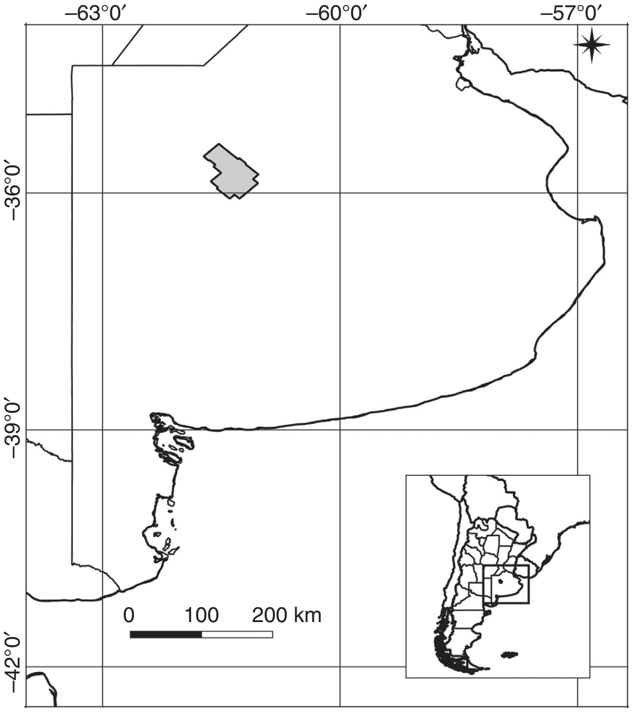

Figure 1 Location of the study site in Buenos Aires Province, in the Pampas region of Argentina.

The study was conducted in a 550 × 550 m-plot (35°37′15″S, 61°19′05″W; 82 m asl) between October 2012 and October 2014. The soil, which belongs to the Hapludoll great group, Mollisol order (INTA-SAGyP, 1990). Table 1 describes its main characteristics to 1 m depth. Prior to the beginning of our study, the plots had been planted with soybean and were harvested at the end of June 2012 and the soil was fallowed until soybean was planted again in early November of that year. We monitored two cycles of soybean (soybean and double-cropping soybean) as cash crop and their respective post-harvest periods. During the first fallow period, we used a winter crop (wheat) as an alternative to CCs, and in the second period, we applied a chemical fallow treatment (bare soil). In the first soybean cycle (soy1), this crop was planted in November 2012 and fertilized at sowing with monoammonium phosphate at 60 kg P/ha, while wheat was fertilized 30 d after sowing with 352 L/ha of 32% UAN.

Table 1 Soil characterization on the study site

Properties	%
Sand	50.0
Loam	35.0
Clay	12.0
Water saturation	39.0
pH	5.7
Organic matter	2.0
Organic carbon	1.19
Organic nitrogen	0.15

Double-cropping soybean was not fertilized at all. The carbon exported was calculated based on crop yields at each harvest using a mean grain carbon content of 511 g C/kg grain (Hernandez-Ramirez *et al*., 2011).

Determination of CO_2 and N_2O fluxes. *Eddy covariance measurements*: Fluxes of CO_2 and N_2O were measured by the eddy covariance method between October 2012 and October 2014. The eddy covariance instruments comprised a fast-response 3-D sonic anemometer (CSAT3; © Campbell Scientific, Logan, UT, USA) for measuring wind speed and sonic temperature, and an open path infrared gas analyzer (IRGA; LI-7500; © Li-Cor Inc., Lincoln, NE, USA) for measuring CO_2 and water vapor concentrations. During the study period, the IRGA was calibrated regularly following standard protocols. The IRGA was oriented vertically and slightly tilted (20° from its vertical axis) to prevent accumulation of rainwater and dew deposition on the sensor surface. The anemometer was oriented eastward (62.5°), based on the predominant wind direction at the study site. Additionally, N_2O concentration was measured using a TDL trace gas analyzer (TGA200; Campbell Scientific Inc.). Data sampling frequency was set at 10 Hz. The three sensors were attached at a height of 2.5 m to an aluminum support structure located near the center of the plot. The sample air was drawn to the TDL analyzer by a vacuum pump (RB0021 model; © Bush, Inc., Virginia Beach, VA, USA). The pump, with a pressure of 54 mbar, was installed at a distance of about 15 m from the support structure. First, the sample air was passed through a diffusive dryer (PD1000; © Perma Pure, Inc., Toms River, NJ, USA) to remove excess water vapor. The flow rate of the air entering the dryer was 18 L/min, from which the sample flow was 15 L/min, and the purge flow was 3 L/min. The sample air leaving the dryer was directed to the TDL analyzer via a 10-m long Teflon tube (inner diameter 4 mm). The pressure inside the sample cell was kept at 55 hPa during the measurement period. The N_2O signal was measured at 1271.077 cm^{-1} laser absorption line and at 723 mA laser direct current. The laser was kept at a constant temperature of 84.4 K using liquid nitrogen tanks. In addition, a reference tank of N_20 (350 ppm) was used as reference at a flux of 10 cm^3/min. The distance between the anemometer and the point where air samples were taken for the TDL analyzer was 20 cm. All data were collected using a data logger (model CR3000; © Campbell Scientific, Inc.).

The EC fluxes were calculated as the average covariance between the vertical wind velocity and the CO_2 and N_2O concentrations over 30 min computed with standard procedures (Aubinet *et al*., 2012), such as 30-min. block averaging, de-spiking, two-dimensional rotation for anemometer tilt correction, and frequency response correction, using the EddyPro software (Li-Cor Inc.). Invalid data (e.g. night-time fluxes under non-turbulent conditions) were removed and gap filling was carried out applying the methodology of Reichstein *et al*. (2005) for the CO_2 data and the daily average of subsequent days (10-day window) for missing data of N_2O. Additionally, a radiometer (photosynthetically active radiation (© Cavadevices) was used to estimated global radiation. The footprint model (Hsieh *et al*. 2000) shows the area from which 80% of the flux was obtained within 300 m from the tower.

Static chamber measurements of N_2O fluxes: The N_2O fluxes were also determined by the static chamber method using vented static chambers (Rochette & Bertrand, 2008), which were placed randomly on the study site. Measurements were carried out about once a month from October 2012 to October 2014, with a total of 22 sampling dates. On each of these dates, we used 12 chambers. The chambers, covered with a reflective insulation, were 37 cm long, 25.5 cm wide, and 14 cm high. Since we aimed at characterizing the entire ecosystem, plants (with their roots) had to be included in the study area. Therefore, we placed each chamber on a row also covering half of each side inter-row. After each sampling, the anchors were replaced into other sites of the field for the next measurement. When plant height exceeded that of the chambers, the stems were cut to less than 2 cm above the soil before installing the chamber on the anchor. On each sampling date, three 10 mL-air samples were collected at 15-min intervals (0, 15, 30 min) between 09.00 and 12.00 a.m. for all dates. Air temperature and soil temperature at 10 cm depth were recorded during each sampling date. As soon as possible, the N_2O concentration was measured using a gas chromatograph (Agilent Technologies 6890N) equipped with a 63 Ni electron capture detector (HP-Plot Molesieve, 30 m × 530 μm × 25 μm). The carrier gas was nitrogen (N_2). The injector, oven, and detector temperatures were 100, 150, and 300 °C, respectively. Nitrous oxide fluxes were calculated by the linear regression method (Parkin & Venterea, 2010) because our sampling dates reached the conditions to use this approach.

Data analysis

We compared the cumulative N_2O emissions among the first and second soybean cycles, winter wheat, and winter bare fallow. The cumulative N_2O emissions were obtained by calculating a weighted average for each land use of interest, with the number of days between sampling dates as the weights. For bare fallow, we considered the time period from the harvest of the second soybean cycle to the sowing of the next crop in October 2014. These same periods were considered to calculate the cumulative fluxes of N_2O and CO_2, which were estimated with the Eddy covariance method (EMC). To complete the temporal series, daily gaps were filled with the daily average (Mishurov & Kiely, 2011). Finally, we compared the cumulative emission values (CO_2 and N_2O by ECM and N_2O by the static chamber method) among land use types, and compared the impact of land use types on gas emissions between the annual sequences: first soybean/wheat cycle vs double crop soybean/bare fallow cycle.

Results

Mean annual air temperature was 16.12 °C for 2013 and 16.8 °C for 2014, similar to the average historical value (16.1 °C, National Meteorological Service). Maximum temperatures were around 30 °C from December to March and minimum temperatures around 7 °C from June to August. Precipitation was higher in the second year (1102 mm in 2014) than in the first one (709 mm in 2013) and slightly higher than the average historical value (1060.3 mm, National Meteorological Service; Figure 2a). Cumulative precipitation was 495 mm for the first soybean cycle, 321 mm for winter wheat, 492 mm for the second soybean cycle, and 291 mm for bare fallow.

Eddy covariance measurements

As expected, the dynamics of the CO_2 flux estimated by the ECM was associated with changes in crop phenology. We followed the atmospheric criterion where negative values indicate carbon sequestration by the ecosystem when the fraction of carbon consumed by photosynthesis is higher than that produced by respiration. In contrast, positive values indicate loss of carbon by the ecosystem and are recorded during crop maturation/senescence and fallow. Maximum values of carbon gain reflect the period of maximum growth of each crop (Figure 2b). The N_2O emissions estimated by the ECM were highly variable without any discernible pattern associated with crop phenology. Daily N_2O emission rates ranged between −0.12 and 0.48 kg N_N_2O/ha/day (Figure 2b).

According to the sum of CO_2 and N_2O fluxes estimated by the ECM, the system showed carbon gain during the soy1/wheat sequence (Figure 3) owing to carbon uptake from CO_2. In contrast, carbon uptake from CO_2 fixation was very small compared with the losses of N_2O during soy2-winter fallow. Emissions of CO_2 and N_2O contributed with similar amounts of carbon equivalents during bare fallow (Figure 3). The sum of CO_2 and N_2O fluxes resulted in a carbon gain of 2800 kg C eq./ha during the soy1 cycle/wheat cycle and a carbon loss of 5083 kg C eq./ha during the soy2/bare fallow cycle (Figure 4). If we exclude C exported by harvest, there were losses of C during both sequences, but these were fivefold higher when the cycle included the long bare fallow (1207 vs. 6258 kg C eq./ha, for the first and second cycles, respectively).

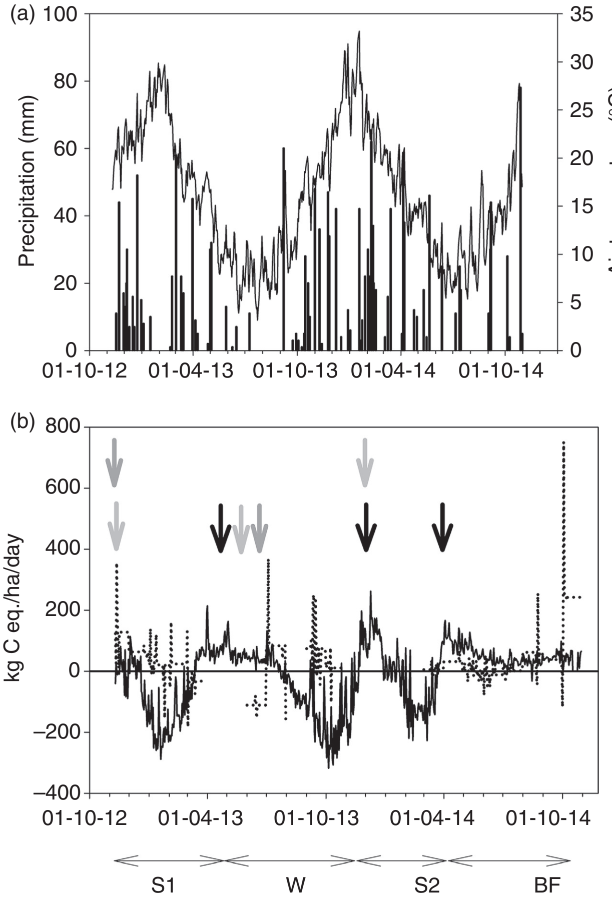

Figure 2 Environmental, management, and flux data during the study period. (a) Daily rainfall (bars, in mm) and mean daily air temperature (continuous line) over October 2012 – October 2014; (b) Daily CO_2 (continuous line) and N_2O (dotted line) fluxes estimated with the Eddy covariance method (expressed as kg C eq./ha/day). ↓: sowing; ↓ fertilization; ↓ harvest.

Static chamber measurements of N_2O fluxes

Instantaneous rates ranged between 4 and 37 mg N_N_2O/m^2/h. Winter bare fallow yielded the highest cumulative N_2O emission (1.62 kg N_N_2O/ha) in comparison with the rest of

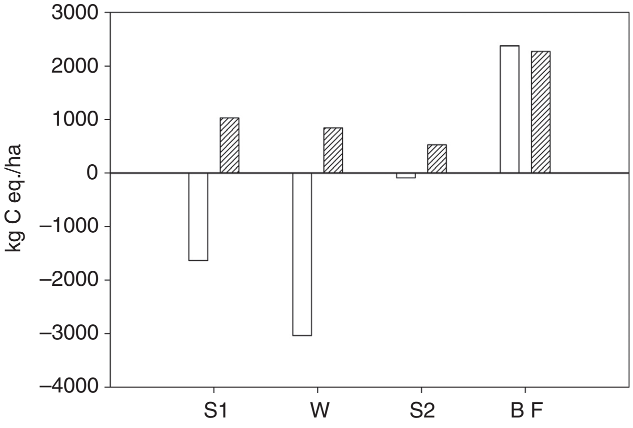

Figure 3 Cumulative CO_2 flux (white bar) and N_2O (dark bar), expressed as kg C eq./ha, for the studied land use types. BF, bare fallow; S1, soy 1; S2, soy 2; W, wheat.

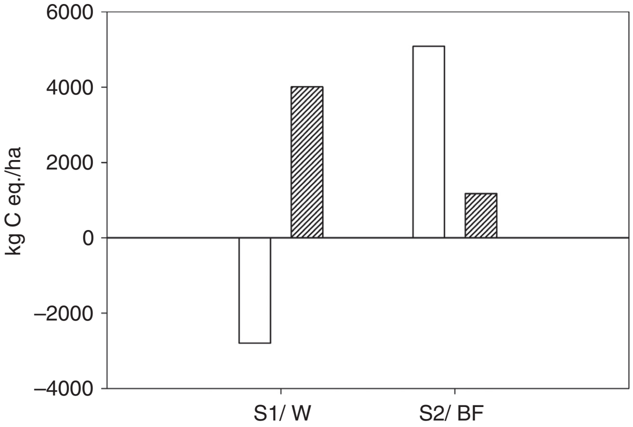

Figure 4 Cumulative CO_2 plus N_2O flux (white bar), expressed as kg C eq./ha, and the carbon exported from the system by harvest (dark bar), expressed in the same unit, during the two studied sequences: S1/W: soybean 1/wheat; S2/BF: soybean 2/bare fallow.

the monitored periods (e.g. 0.69 kg N_N_2O/ha during winter wheat). In comparing cumulative N_2O fluxes between soybean cycles, values were higher for soy1 (1.11 kg N_N_2O/ha) than for soy2 (0.50 kg N_N_2O/ha), which preceded winter wheat. In regard to the two sequences studied, N_2O loss was 1.79 kg N_N_2O/ha during the soy1/wheat cycle and 2.12 kg N_N_2O/ha^{-1} during soy2/bare fallow cycle. The linear regression showed that the values of N_2O emissions estimated by the ECM were fourfold higher than those estimated by the static chamber method. This difference may be due in part to the lower spatial and temporal representation of the data coming from the chambers with respect to the data obtained using the turbulent flow method (Wang *et al.*, 2010). Episodic high flux events can easily be missed when using a method that does not measure continuously (Podgrajsek *et al.*, 2014). Also, the location in the field of each individual chamber confers a different weight to each within the footprint of the tower. Molodovskaya *et al.*, 2011 managed the nitrous fluxes calculated by weighting each flow coming from the chambers according to source area function, to decrease the differences. Therefore, the different spatial scales make the comparison very complex. Despite these differences, we found a significant correlation ($P = 0.0023$) between the N2O cumulative fluxes and the types of land use of interest.

Discussion

Agroecosystems are particularly vulnerable to the detrimental effects of climate change, such as an increase in crop pests, changes in rainfall patterns, and increase in the frequency of extreme events (droughts, heavy rains, and severe heat waves). The intensification of crop rotations leads to higher productivity and efficiency of resource use (Matson *et al.*, 1997; Altieri, 1999; Andrade *et al.*, 2015), while monocultural practices create unfavorable soil conditions (Castiglioni *et al.*, 2013; Novelli *et al.*, 2013). On this basis, the implementation of crop rotation should be supported by government policies (Lin, 2011). Despite this evidence of long-term improvement in terms of agroecosystem sustainability, some studies from the United States indicate a decrease in crop diversification and rotation over time (Aguilar *et al.*, 2015). A similar situation has occurred in the Pampas Region of Argentina, where a single summer crop followed by a long-term fallow (Pinto *et al.*, 2017) covers a large proportion of the surface area. To reduce bare fallow periods, winter cover crops have emerged as a promising alternative for preserving soil quality. In recent years, many studies have focused on GHG emissions owing to land use changes (Kaye & Quemada, 2017; Sanz-Cobena *et al.*, 2017). Cover crops are also being promoted as a new source of biomass for energy purposes increasing the active photosynthesis over land on a year by year basis. This extra biomass can also be used as a source of biogas, using the digest of this cover crop as a source of energy, while increasing the organic matter in the soil (Witing *et al.*, 2018).

The effect of cover crops on GHGs may change according to the cash crop or intercrop period. Therefore, the entire cycle should be considered when estimating the effect of winter crops on the global gas balance. Some meta-analyses show that intercropped cover crops (particularly legumes) increase N_2O emissions (Basche *et al.*, 2014; Guardia *et al.*, 2016). In our study, N_2O emissions were lower during the winter wheat than during winter fallow (Figure 3). Although wheat is not capable of fixing nitrogen as legumes do, it is fertilized with inorganic nitrogen. N_2O emissions during the cash crop season are usually lower when it is preceded by a winter cover crop than by a winter bare fallow (Basche *et al*., 2014). Although we did not monitor different sequences over time, the two soybean cycles studied were influenced by the previous land use in winter: the first soybean cycle was preceded by fallow and the second one by wheat. Cumulative N_2O emissions were similar during both cycles, but they were slightly higher for the first soybean cycle, in agreement with the results of Basche *et al*. (2014). In regard to the effect of the different land use types on CO_2 balance, our results showed that winter crop has more beneficial effects on agroecosystem functioning than does winter bare fallow because the former acts as a carbon sink and the latter as a carbon source.

The sum of CO_2 and N_2O cumulative emissions reached a maximum value during winter fallow (Figure 3). On the other hand, wheat accounted for the highest CO_2 gain and lowest N_2O emission, which was probably associated with the low winter temperatures. The remarkably lower carbon gain during the double-cropping soybean cycle in comparison with the first soybean cycle would have been related to the lower rainfall (492 vs. 1063 mm, respectively) and to the positive CO_2 balance recorded during the first phase (Figure 2b). CO_2 emissions lasted for about one month, possibly owing to the residues of the preceding winter wheat (Drury *et al*., 2007). The respiration from decomposing crop residues induces CO_2 loss, which cannot be compensated by the photosynthetic activity of growing soybean until canopy closure. Some authors have assumed that N_2O emissions are influenced by the preceding land use (Wagner-Riddle *et al*., 1997; Flessa *et al*., 2002).

In this work, we compared the two most widely used methods for N_2O flux measurement: chambers and turbulent fluxes. The absolute values of N_2O emission differed between both methods. The differences in the spatial and temporal scale between both methods resulted in that using the EMC the fluxes were four times greater than the one estimated by the cameras for all types of land use (Wang *et al*., 2012). Although both methods are considered valid for the estimation of N_2O emissions, they exhibit important differences in spatial-temporal resolution that may affect the results.

Conclusions

The replacement of crop residues by a winter cover crop like wheat decreases N_2O emissions considerably and converts carbon losses (by respiration) into gains (by fixation in photosynthesis). However, it may affect the GHG balance of the following crop cycle by increasing soil residues subjected to decomposition. Taking into account both CO_2 and N_2O, soybean following fallow gained carbon while soybean following the winter crop lost carbon. Notwithstanding this, the sum of CO_2 and N_2O fluxes obtained in the cash crop/fallow sequence were higher than those in the cash crop/wheat sequence because of the high values estimated during fallow (Figure 4). As replacement of winter intercrop fallow by cover crops is known to improve physical properties, increase organic matter, and decrease erosion, the replacement of traditional non-harvested cover crops by winter wheat may provide not only similar advantages in terms of soil improvement, but also an additional biomass harvest. Since wheat usually requires the addition of nitrogen fertilizers, it will be necessary to adjust the doses to prevent excess nitrogen from accumulating in soils that could be source of N_2O emissions.

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