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Short communication

CO_2 and N_2O flux balance on soybean fields during growth and fallow periods in the Argentine Pampas—A study case

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ABSTRACT

The estimation of the GHG balance of agroecosystems is essential to evaluate the impact of agriculture on the composition of the atmosphere. Cultivated soils may act as a sink or a source of CO_2 and usually emit N_2O. The aim of the present study was to assess the CO_2 and N_2O balances, and to analyze the relationships between N_2O fluxes and environmental variables for two soybean growing seasons and the fallow period between them, in an agricultural field in the Pampas region of Argentina. The fluxes of CO_2 and N_2O were measured by the eddy covariance and the static-chamber methods, respectively. The net ecosystem exchange from sowing to harvest was −2543 and −2307 kg CO_2-C ha^{-1}, for the first and second growing seasons, respectively. The N_2O net balance over the same periods was 1.45 and 0.96 kg N_2O-N ha^{-1}. A multivariate analysis showed that during the growing season the most important variable influencing N_2O emission was % water filled pore space (% WFPS), followed by nitrate content and soil temperature. During fallow, soil temperature was the main control factor, followed by % WPFS. The total balance (including CO_2 and N_2O) showed that the soil gained 753.5 kg Ceq ha^{-1} on average during cultivarion cycle. Taking into account the fallow period, the global balance resulted in a carbon loss of 1328.5 kg Ceq ha^{-1} over about one year. Our results clearly indicate the need to incorporate winter cover crops for improving the production system, as they can provide carbon to the soil and use the available stubble nitrogen from the previous crop.

1. Introduction

Agricultural ecosystems seem to play a major and increasing role in the balance of greenhouse gases (GHG) (Green et al., 2005; Salinger, 2007). Therefore, the estimation of the GHG balance of agroecosystems is essential to evaluate the impact of agriculture on the composition of the atmosphere (Rosenberg et al., 1998). It is important to gather regional-scale data because GHG emissions vary with climate condition, soil type, crop variety and management practices. The principal GHGs emitted from agricultural activities are CO_2 (associated with the balance between photosynthesis and respiration), N_2O (associated with soil nitrogen availability) and CH_4 (associated with flooded areas and livestock). The CO_2 balance is mainly controlled by solar radiation, temperature, phenological stage and vegetation type. N_2O emissions are primarily determined by the activity of soil microbes, carbon and nitrogen availability. Meta-analyses have shown that rates of fertilizer application and soil properties such as organic matter content, texture, drainage and pH, influence emission rates (Bouwman et al., 2002). These factors affect the source of processes of nitrification and denitrification (Dobbie and Smith, 2001), but agricultural management practices are of equal or greater importance (Rees et al., 2013). The multiplicity of factors that affect the balance of GHGs in the croplands may explain, in part, the wide disparity of results in the literature (Hénault et al., 2012).

In Argentina soybean has gained increasing importance since 1970, and currently occupies 60% of the total agricultural land, displacing other crops and activities such as livestock farming. This country is one of the major grain exporters in the world, particularly of soybean, maize and wheat. The objectives of this study were to quantify the CO_2 and N_2O balances in the Rolling Pampa region and to analyze the relationships between N_2O fluxes and environmental variables for two soybean growing seasons plus the winter fallow period between them. This region is the main

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cropland area of Argentina with the longest agricultural history of the country (Hall et al., 1992; Soriano et al., 1991; Viglizzo et al., 2001), and is among the world's most productive areas (Satorre and Slafer, 1999).

2. Materials and methods

2.1. Study site

The study area consisted of two adjacent private agricultural fields (34° 38′ 29.7″ S 59° 28′ 31.7″ W), 110 km west of Buenos Aires City (Argentina). This area is part of the Rolling Pampa region, within the phytogeographic district of the Pampa grasslands (Soriano et al., 1991). The landscape is almost flat (35 m asl) and the soil is classified as typical Argiudoll (Gouin series, INTA-SAGyP, 1990). The soil has a pH of 5.7 and contains 3.50% of mean organic matter, 2.03% of organic carbon and 0.19% of organic nitrogen. Mean annual rainfall is 978 mm and mean annual temperature is 16.5 °C (INTA-Pergamino database, 1967–2004). The fields occupied a total area of 39.6 ha and were managed under no-tillage for at least the last 15 years, with a typical crop rotation of soybean, maize, wheat and oat.

The study was performed between October 15, 2010 and June 30, 2012. There were two consecutive soybean growing seasons during this period. In the first season, soybean crop was sown on October 16, 2010 and harvested on April 15, 2011. Rows were spaced 40 cm apart and plant density was 38 plants m^{-2}. In winter 2011 both fields remained uncultivated. In the second season one field was sown with maize on September 19, 2011, while the other field was sown with soybean on November 12, 2011. The soybean field was harvested on April 14, 2012. We did not take into account fluxes in the maize field because our objective was to quantify GHG balance of soybean fields. Monthly mean air temperature was similar to historical records, between 9.3 and 23.9 °C. Precipitation was slightly lower than its historical mean in December 2010, October 2011 and early summer 2011/2012 (Fig. 1).

2.2. Measurement of CO_2 fluxes

Fluxes of CO_2 were obtained by the eddy covariance method (Aubinet et al., 2000; Lee et al., 2004; for details of the experimental set-up see Posse et al., 2014) and 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., Lincoln, Nebraska, USA). 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). During the second growing season, when on one field was cultivated soybean and on the adjacent field maize, the CO_2 fluxes on the soybean field were determined by using a methodology proposed by Posse et al. (2014). By convention, positive flux values represent mass transfer into the atmosphere and away from the surface and negative values denote the reverse.

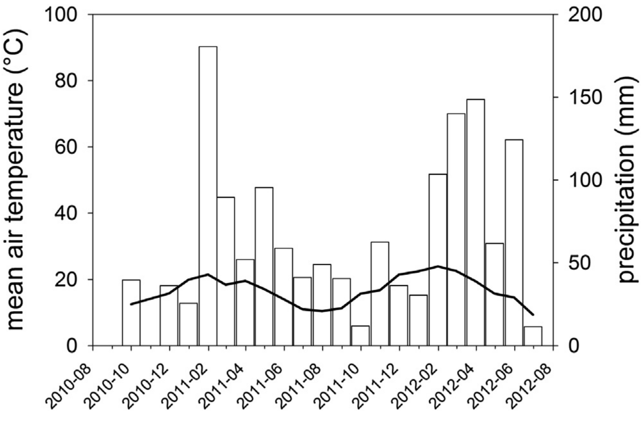

Fig. 1. Mean monthly temperature (lines) and monthly accumulated precipitation (bars) during the study period.

2.3. Static chamber measurements of N_2O fluxes

The N_2O fluxes were determined by the static chamber method using vented static chambers (Parkin and Venterea, 2010; Rochette and Bertrand, 2008) which were randomly placed on each soybean field (four per field). 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. Measurements were carried out from mid December 2010 to June 2012, once a month on average. Measurements have not been carried out between June 30 and November 23, 2011. 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 four different dates, we evaluated whether plant cutting affected N_2O flux rates. We compared the emission rates obtained from chambers including plants with those obtained from chambers without plants, and the results were not significantly different ($p = 0.5155$, data not shown).

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 (Venterea, 2010) because our sampling dates reached the conditions to use this approach.

After gas sampling, two samples of soil from the area enclosed by the chamber were taken at 10 cm depth. One of these samples was used to estimate the soil bulk density (BD) by means of 0.05 m-diameter cylinders (98.17 cm^3), and the gravimetric water content (GWC) by oven-drying at 105 °C for 48 h. The percentage of water-filled pore space (% WFPS) was calculated according to the formula of Parton et al. (2001). The other soil sample was used to determine the NO_3^--N content by the steam distillation method (Bremner, 1965; Keeney and Nelson, 1982). Ammonium content was not determined due to economic constraints. To analyze the relationship between environment conditions and N_2O emission rates we used a decision tree analysis based on the procedure of Morgan and Sonquist (1963). N_2O emission was considered as the dependent variable and NO_3^--N content, % WFPS and soil temperature as the regressor variables (Di Rienzo et al., 2012). The crop growing season and the fallow period were analyzed separately.

The overall balance was calculated on the one hand by summing up daily values of carbon exchange from the eddy covariance method and on the other hand, by calculating a weighted time average between measurements of N_2O from the closed chambers. N_2O values were converted to gram-carbon equivalents taking into account their relative warming potential. For both gases, data from the two growing seasons were averaged and data from the fallow period were then added.

3. Results and discussion

The accumulated carbon was −254 (±13) g CO_2-C m^{-2} for the first growing season (182 days between sowing and harvest in 2010/2011) and −220 (±16) g CO_2-C m^{-2} for the second growing season (154 days in 2011/2012) (Fig. 2). Hernandez-Ramirez et al. (2011) reported similar NEE values (−210 g CO_2-C m^{-2} $year^{-1}$) from a no-tillage field in Champaign (USA), while Prueger et al. (2004) recorded a seasonal carbon uptake of between −200 and −300 g CO_2-C m^{-2} in soybean fields from a typical agricultural region in the Midwest of USA. In our study site the farmer did not control weeds after harvest, so the ecosystem also gained some carbon during the winter time of 2011 and 2012 (Fig. 2). Gebremedhin et al. (2012) pointed out the importance of cover crops during winter over a long-term C balance. However, the carbon input was low and of short duration, probably due to the type of weeds colonizing the soil. Our result showed that the fallow period acted globally as a carbon source (170 g CO_2-C m^{-2}). When

Table 1
Carbon equivalent fluxes became from N_2O and CO_2 exchange for two soybean growing seasons and fallow period. The carbon exported through harvest was also added. Negative values indicate ecosystem gains and positive values indicate ecosystem loss.

Period Kg Ceq ha^{-1}	N_2O	CO_2	harvest	Net balance
Soybean (2010–2011)	449	−2543	1391	−703
Soybean (2011–2012)	298	−2307	1205	−804
Soybean average	373.5	−2425	1298	−753.5
Fallow	379	1703		2082
Total	752.5	−722	1298	1328.5

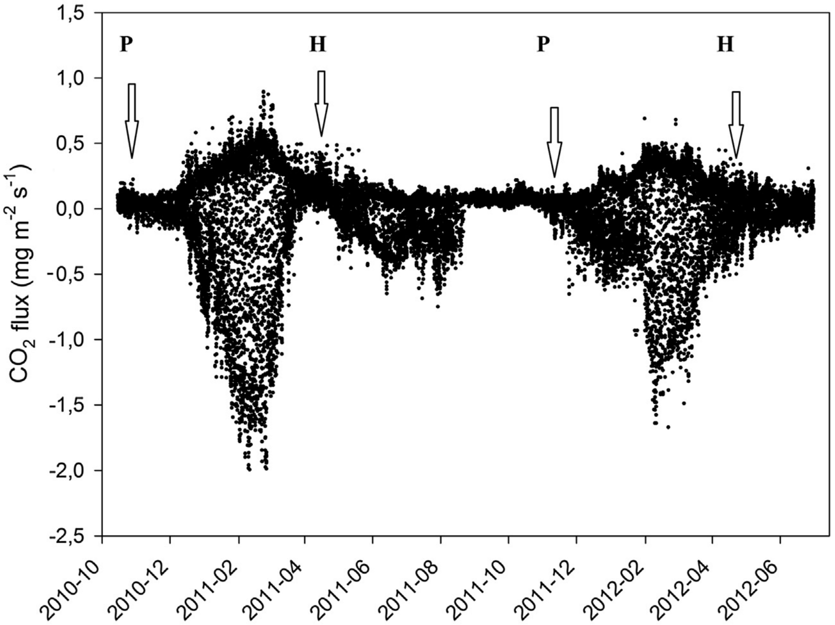

Fig. 2. CO_2 flux time series (gap-filled) measured by the eddy covariance technique in soybean fields near Mercedes, Province of Buenos Aires, Argentina. Arrows indicate dates of planting (P) and harvest (H).

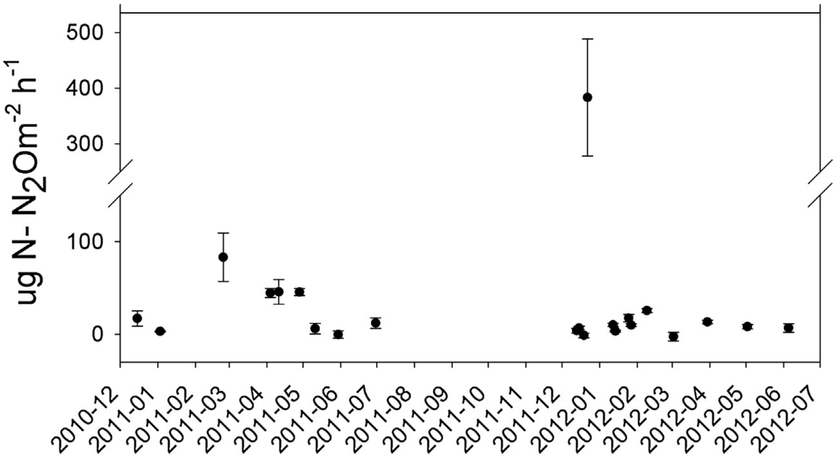

Fig. 3. Mean flux values (µg N_2O-N m^{-2} h^{-1}) and the corresponding standard deviation obtained from soybean fields during two growing seasons and the first two months after harvest. Different letters indicate significant differences (Generalized linear mixed models and Tukey's test $p < 0.05$).

considering the entire study period (including the average of both growing seasons and the fallow period), the agricultural system gained 67 g CO_2-C m^{-2}. However, since grains are exported from agricultural fields at harvest, grain C removal should be considered when calculating the real carbon balance. We estimated a carbon extraction via grain of 139 g CO_2-C m^{-2} for 2010/2011 and 120 g CO_2-C m^{-2} for 2011/2012. When subtracting the harvested biomass, carbon balance analysis indicated that the system lost carbon (Table 1). The same was found by Gong et al. (2015), when analysed a set of data comprising different tillage and maize varieties from different climate zones. They took into account the harvested grain carbon in the global carbon balance and foundthat the balance was negative in nine over twelve sites.

N_2O emissions showed a high variability, as previously reported for other agricultural areas. Mean N_2O emission ranged between 2.45 μg N_2O-N m^{-2} h^{-1} in March 2012 and 383.2 μg N_2O-N m^2 h^{-1} in December 2011 (Fig. 3). The time-weighted averaged emission values for 2010–2011 and 2011–2012 growing seasons were 33 and 43.97 μg N_2O-N m^{-2} h^{-1}, respectively. Between growing seasons, the mean emission was 6.6 μg N_2O-N m^{-2} h^{-1}. Soil temperature was similar for both growing seasons, with 14 °C in winter and 25 °C in summer (Fig. 4a). Water-filled pore space (% WFPS) ranged between 5 and 54% (Fig. 4b). Soil nitrate content was highly variable, ranging between 28 ppm and 391 ppm (Fig. 4c). These values range would indicate that the prevailing process was nitrification (Skiba and Smith, 2000). The total mean emission obtained by us is lower than those recorded in Ontario, Canada, where Wagner-Riddle et al. (1997) reported 67.35 μg N_2O-N m^{-2} h^{-1}, and Drury et al. (2008) reported 157.50 μg N_2O-N m^{-2} h^{-1}. This was probably due to the thaw, high temperatures and high soil humidity conditions in Ontario, having a direct effect on the increase in emission values. In China, mean values in soybean fields with different fertilization treatments ranged between 5 and 28.8 μg N_2O-N m^{-2} h^{-1} and reachied 242 μg N_2O-N m^{-2} h^{-1} after fertilization, thus showing the great impact of nitrogen fertilization on emission values (Chen et al., 2002). In Argentina, soybeans cultivation is done without using nitrogen fertilization. However a remarkable N_2O-N emission peak of 383 μg m^{-2} per hour was recorded on December 22, 2011, during the active growth phase of soybean (Fig. 3). On this date, both % WFPS and soil temperature showed usual values, so the peak could not be explain with environmetal variables measured. Episodic N_2O emissions are usually recorded by continuous measurement systems, i.e. automatic chambers or the eddy covariance method. Modelling of episodic emissions is however difficult to achieve because they do not show a significant relationship with any environmental variable (Molodovskaya et al., 2012). It is necessary to intensify field measurements and to enhance the understanding of the relationship among emission rates, environmental variables and agricultural practices.

The complex relationships between N_2O emissions and other variables are more difficult to describe under field than under laboratory conditions. We used a decision tree analysis to rank the importance of environmental variables for N_2O emissions. In spite of having low values of % WFPS (taking into account the values considered associated to high emission rates), the analysis identified % WFPS as the most important variable, followed by NO_3^--N content and soil temperature depending on the value of % WFPS (Fig. 5a). This result reveals the relevance of soil water availability in N_2O emissions, as already pointed out by other authors (Groffman, 1991; Linn and Doran, 1984), although denitrification is not the prevailing process. For the fallow period, the main variable was soil temperature, followed by % WFPS (Fig. 5b), probably because the fallow period occurred during winter.

The global balance showed that the ecosystem acted on average as a carbon sink with −1127 kg C ha^{-1} from CO_2 (−2425 kg Ceq ha^{-1} from photosinthesis and respiration balance and 1298 kg Ceq ha^{-1} lost by harvest), but lost 373 kg Ceq ha^{-1} via N_2O emissions (Table 1). Therefore, the total balance (including CO_2 and N_2O) showed that the soil gained 753.5 kg Ceq ha^{-1} on average during cultivarion cycle. Taking into account the fallow period, when the net balance indicates only lost of carbon (2082 kg Ceq ha^{-1}) the global balance resulted in a carbon loss of 1328.5 kg Ceq ha^{-1} over about one year. It is worthwhile to note the negative impact of the fallow period on the carbon balance. Our results clearly indicate the need to incorporate winter cover crops for improving the production system, as they can provide carbon to the soil and use the available stubble nitrogen from the previous crop.

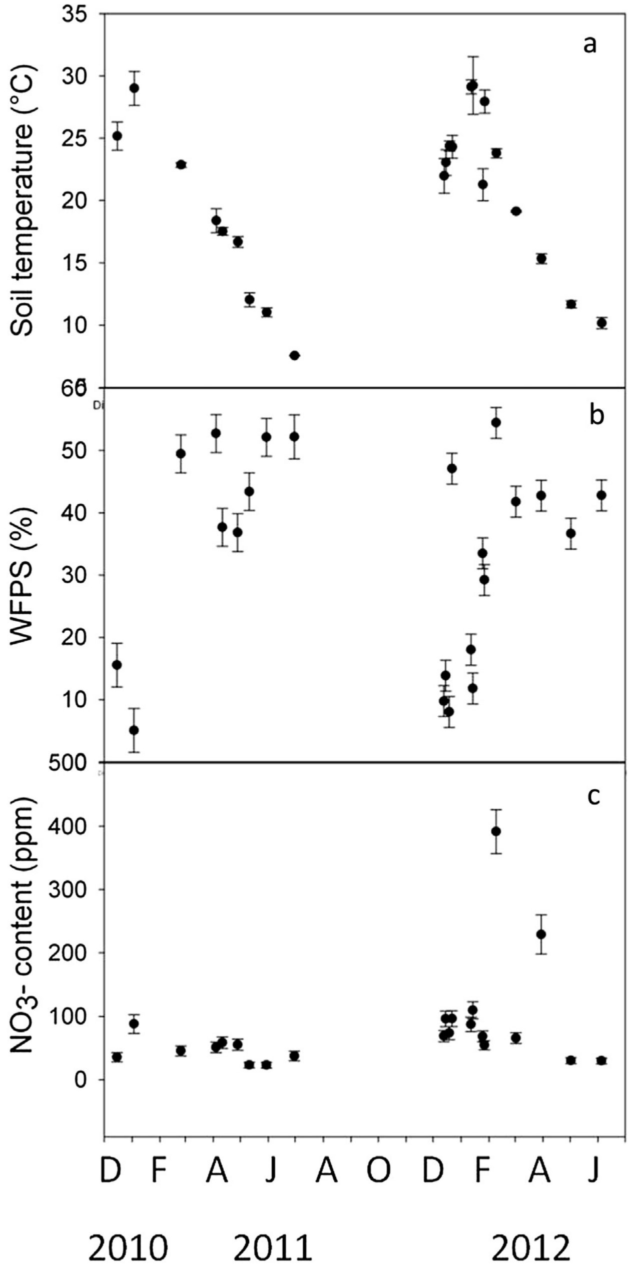

Fig. 4. Mean values of a) mean soil temperature; b) % WFPS and c) NO_3-N soil content and the corresponding standard deviation obtained from soybean fields during two growing seasons and the first two months after harvest.

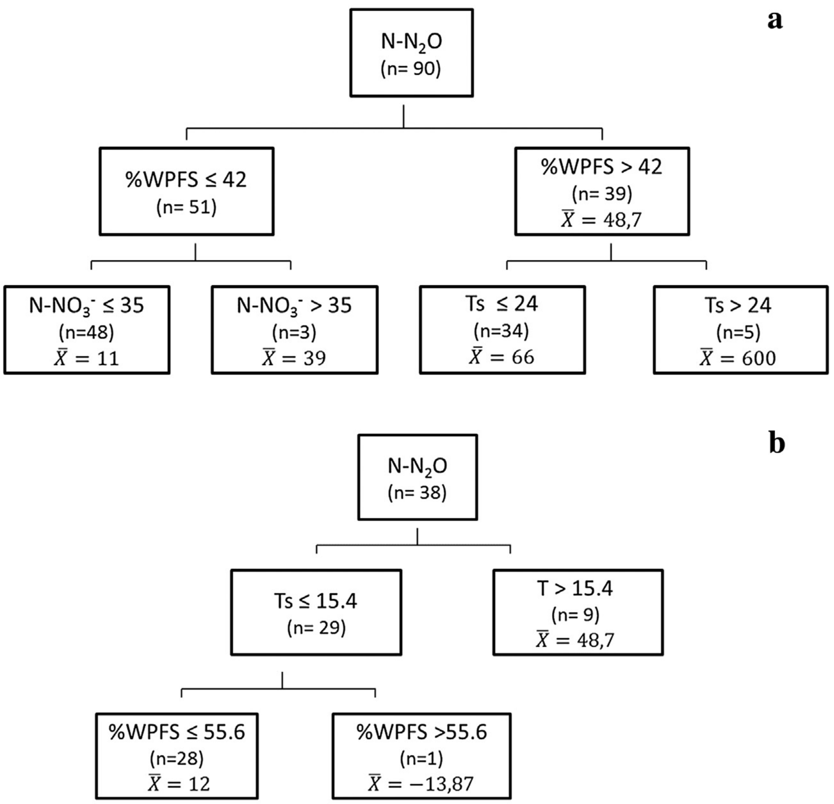

Fig. 5. Regression tree for the growing season (a) and fallow period (b). Dependent variables were N_2O emissions in μg N_2O-N m^{-2} h^{-1}. The regressor variables were % WFPS, soil temperature (Ts) and NO_3-N content. n: number of observations, X = mean rate value.

Conflict of interest

The authors declare that there was no conflict of interest associated with this article.

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