Geoderma Regional 24 (2021) e00362

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Nitrous oxide emissions in maize on mollisols in the Pampas of Argentina

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ARTICLE INFO

Article history:
Received 26 January 2020
Received in revised form 18 December 2020
Accepted 14 January 2021

Keywords:
Sustainable intensification
Greenhouse gas emissions
Nitrogen
Mollisols
Soil management

ABSTRACT

The objectives of this study were i) to measure the soil N_2O fluxes in a cropping system currently adopted by farmers of the region (FP), and in an ecologically intensified cropping system (EI) over two consecutive maize growing seasons (2011–12 and 2012–13), and ii) to relate N_2O fluxes to soil factors. Gas fluxes were measured using vented static chambers, from October through April in each season. Fluxes of N_2O ranged from 3 to 88 μg N_2O-N m^{-2} h^{-1} in 2011–12, and between 3 and 97 μg N_2O-N m^{-2} h^{-1} in 2012–13. There was a significant ($p < 0.05$) interaction in N_2O fluxes between management systems and sampling dates ($p < 0.05$) in both seasons. The highest N_2O fluxes were observed often following a precipitation event and shortly after N fertilization. While management system impacted on maize grain yield, it had no significant ($p > 0.05$) effect on cumulative N_2O emissions, which were, on average across two seasons, 558 g N_2O-N ha^{-1} for the EI treatment and 578 g N_2O-N ha^{-1} for the FP treatment. Cumulative N_2O emissions tended to be 20% greater over 153 days in 2012–13 compared with over 156 days in 2011–12 mainly due to differences in total and timing precipitations. As there were no differences in cumulative N_2O emissions between managements but grain yield was higher under EI, this treatment had lower yield-based N_2O emissions (75 g N_2O-N Mg^{-1} grain) compared with FP treatment (94 g N_2O-N Mg^{-1} grain). The results showed that a moderate increase in N rate (10 kg N ha^{-1}), combined with N split-application and UAN (urea-ammonium nitrate) as N source, as well as other crop management practices, can be a viable alternative to improve maize productivity without increasing the N_2O environmental impact.

1. Introduction

The steady population and strong economic growth in developing countries have resulted in an increased demand for food, forage, fiber, biofuel, and biomaterials (OECD-FAO, 2018). Grain production should respond to the future global demand either by expanding the land area cultivated or increasing crop productivity on land already under cultivation. However, expansion of area would be limited as agriculture should not develop in marginal lands and ecosystems that are fragile and unlikely to sustain high yield crop production systems (UNEP, 2014). Another option is to implement intensive sustainable production systems with increased crop yields without increasing environmental impacts (Cassman, 1999; Foley et al., 2011; Alexandratos and Bruinsma, 2012; UNEP, 2014; Andrade, 2016).

Intensified agricultural systems require an increased efficiency and effectiveness in the use of resources such as water and nutrients, and ecologically-based soil and crop management practices. Increase of around 40–50% in the use of synthetic fertilizers is expected over the next 50 years and the largest contribution to the global increase in nutrient consumption is that resulting from developing countries (Sutton et al., 2013). However, high levels of nutrient use along with very low efficiency are associated with nutrient losses, which are threats for human health and ecosystem function. Considering the full chain, on average over 80% of nitrogen (N) and 25–75% of phosphorus (P) end up lost to the environment, and causing air contamination through emissions of greenhouse gas (GHG), nutrient losses to waters, climate change, land degradation, and biodiversity loss (Sutton et al., 2013).

The demand for agricultural products in the next years should be reached while maintaining or improving the quality of the natural resources involved in agricultural production and the life quality of rural and urban populations (Tillman et al., 2011; Andrade, 2016; Cassman, 2017; Lal, 2019). These requisites are encompassed in the ecological intensification (EI) concept defined by Cassman (1999, 2017), which includes a package of measures that focus on developing sustainable production systems with high production but minimal environmental

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https://doi.org/10.1016/j.geodrs.2021.e00362
2352-0094/

impact. The decisions on agronomic practices based on EI concepts are oriented to closing the gap between water limited yield potential (Yw) and actual yield, and improving natural resource and input productivities using a field-specific management. Soil, crop, and nutrient management under EI would imply changes in practices such as N rate, time, place or source (IPNI, 2012), which should enhance not only N use efficiency but also efficiencies of other resources (water, radiation) or inputs (fertilizer, pesticides) and/or result in improved maintenance of soil fertility (i.e., balanced N budgets) (Caviglia et al., 2019).

Agriculture contributes 23% of overall global GHG emissions, where 19% is related to global nitrous oxide (N_2O) (IPCC, 2019). Improvement of land management and agricultural practices has the potential to mitigate N emissions. Nitrification and denitrification processes are the main source of biogenic emissions of N_2O from soil (Johnson et al., 2007). Factors that significantly influence agricultural N_2O emissions are N application rate, crop type, fertilizer type, soil organic carbon (C) content, soil water content, temperature, pH and texture (Stehfest and Bouwman, 2006; Cosentino et al., 2013; Omonode et al., 2017). There is a large effect of soil moisture content on N_2O emissions (Farquharson and Baldock, 2008) which have their optimum in the range of 70–80% water filled pore space (WFPS) depending on soil type (Davidson et al., 2000). However, the complex interaction among soil properties, weather and management practices might explain the high variability of N_2O emissions in space and time as a result of “hot spots” and “hot moments” (Groffman et al., 2009). This complexity can make difficult to develop generalizations regarding the impact of management system on N_2O emissions (Snyder et al., 2009).

In Argentina, grain production has increased markedly in the last 25 years mostly as consequence of increases in cropped area under soybean, as well as increases in yields of sunflower and other grains, and increased yields and cropped area of wheat and maize (SAGPy A, 2018; Wingeyer et al., 2015). In the context of the global process of agriculture intensification, the livestock-grain systems in the Pampas of South America have changed to more intensive cropping systems (Manuel-Navarrete et al., 2009; Carreno et al., 2012; Wingeyer et al., 2015; Ernst et al., 2016). In addition, there were economic and technological local aspects that promoted the intensification process that led to changes in land-use in the Pampas (Manuel-Navarrete et al., 2009; Wingeyer et al., 2015). Fertilizer use has rapidly increased since the early 90´s, however nutrient budgets are still negative and Pampas agriculture might be considered as medium- or low-input agroecosystems (Norton et al., 2015; García and González Sanjuan, 2016).

The effect of annual cropping systems at Argentina on N_2O emissions has been explored in different studies. Sainz Rozas et al. (2001) determined the denitrification rates under maize crops, and Alvarez et al. (2012) reported field N_2O emissions in different crop sequences and tillage systems during a year in the central semiarid Pampas. The later research found that N_2O fluxes were low during winter but peaked in late spring, and NO_3-N content was the most important variable to explain N_2O emissions in the fallow period, while WFPS was in the crop growing period. Measuring the N_2O fluxes on soybean from sowing to harvest in two seasons, Lewczuk et al. (2017) showed that the N_2O net balance was $+1.45$ and $+0.96$ kg N_2O-N ha^{-1} in the first and second season, respectively. Della Chiesa et al. (2019) determined that N_2O emissions from croplands were higher than background emissions (unmanaged grasslands), but also that background represented an important fraction of cropland emissions (21–32%), depending on crop type (maize, soybean, double cropped wheat/soybean).

Currently, there is a need of data about the effect of intensive crop management systems on GHG emissions, which are designed to improve the use efficiency and effectiveness of resources and inputs, including cultivars of high yield potential, with resistance and/or tolerance to diseases, pests and herbicides, optimized planting date, population and spacing, and best management practices for fertilizer (source, rate, time, place), in pursuit of sustainable agriculture. Thus, a great challenge is to maximize crop production while at the same time reducing negative impacts on environment, climate and human health by optimizing resource and input use efficiency. Improving resource and input productivity is a key step towards sustainable intensification (Caviglia et al., 2019). Adviento-Borbe et al. (2007) concluded that intensification of cropping systems does not necessarily increase GHG emissions of agricultural systems as long as crops are grown by implementation of best management practices and reaching yields near potential levels, resulting in high resource use efficiency. Zhao et al. (2016) calculated that total GHG emission was 29.8% lower in ecologically intensified system when compared to current farmer's practice system, by adopting fertilizer right source, right rate, time and placement, and optimizing plant density and plant hybrid selection.

The main objectives of our study were: i) to evaluate the effect of using alternative crop management systems on N_2O emissions from soil, and ii) to relate N_2O flux rates to soil factors over two maize growing seasons under conditions of the southern Pampas of Argentina. One management system, termed current farmer practices system, mimic the one adopted by farmers of the region, and the other system, named ecologically intensified cropping system, was recommended according to available information and based to achieve a maize yield of 9 Mg ha^{-1} with minimal impact on natural resources (air, land, water).

2. Materials and methods

2.1. Site description and experimental design

The study was conducted from October to April during two consecutive maize growing seasons (2011–12 and 2012–13) at the Agricultural Research Station of the Agricultural Technology National Institute (INTA) located in Balcarce (37° 45′S lat., 58° 18′W long.; 130 m above sea level), at Buenos Aires province (Argentina). The climate of the region is mesothermal, subhumid-humid, characterized by a mean annual temperature of 13.9 °C, and an annual precipitation of 955 mm (period 1971–2007) that is concentrated in spring and autumn. The soil at the experimental site is a complex of Mar del Plata series (fine, mixed, thermic Typic Argiudoll) and Balcarce series (fine, mixed, thermic Petrocalcic Argiudoll). The petrocalcic horizon of Balcarce series is below 0.7 m. The properties at the beginning of the field experiment in the surface soil (0–20 cm) were: pH $_{water}$ of 6.2, 225 g kg^{-1} of clay, 344.0 g kg^{-1} of silt, 430.6 g kg^{-1} of sand, 26.2 g kg^{-1} of organic C content, 1.9 g kg $^{-1}$ of total N content, a C/N ratio of 13.7, and 19 mg kg^{-1} of available Bray-1 P.

The experiment was established in 2009, being the crop sequence: maize (*Zea mays* L.) followed by winter wheat (*Triticum aestivum* L.) and double cropped soybean (*Glycine* max (L.) Merr). Prior 2009, the site was cropped with annual crops for more than 20 years.

The study compared two managements: 1) current farmer practices (FP) that included management practices implemented by farmers in the production fields of the region, and 2) ecologically intensified management (EI) that was designed according to available information from research in the region. Both treatments, EI and FP, were randomized in a complete block design with three replicates. The two phases of the sequence, wheat/soybean and maize, were included every year, thus our study evaluated maize in one phase in 2011–12 and maize in the other phase in 2012–13.

Agricultural practices for both managements over the two maize growing seasons are summarized in Table 1. Each management system was a combination of crop management practices: hybrid, plant populations, row spacing, and source, rate and time application of N and P fertilizers. In FP treatment, crop management included the average input level as well as most commonly used practices, based on the opinion of expert agronomists who are devoted to advice farmers in the region. Applied N rate was derived from a N budget based on soil analysis and a target yield of 7000 kg ha^{-1} (average for leading farmers of the region). For the EI treatment, agronomical practices were decided based on

Table 1
Agricultural practices in maize under current management system (FP) and ecologically intensified management system (EI).

	2011–2012		2012–2013	
	FP	EI	FP	EI
Previous crop	Wheat/soybean			
Hybrid	KWS KM 3601 RR2	DK 670 MG RR2	KWS KM 3601 RR2	DK 670 MG RR2
Planting date	18-10-2011 18-10-2011		18-10-2012 18-10-2012	
Plant population (seeds m^{-2})	6.5	8	6.4	8.2
Row spacing (m)	0.7	0.525	0.7	0.525
Emergence date	01-11-2011	01-11-2010	27-10-2012	30-10-2012
DAP application date	18-10-2011	18-10-2011	18-10-2012	18-10-2012
DAP (kg ha^{-1})	73	80	73	83
P (kg ha^{-1})	15	16	15	16
N (kg ha^{-1})	13	14	13	14
Urea application date	05-11-2011	–	18-10-2012	–
Urea (kg ha^{-1})	80.5	–	90.3	–
N (kg ha^{-1})	37	–	43	–
UAN application date	–	25-11-2011	–	28-11-2012
UAN (L ha^{-1})	–	125	–	142
N (kg ha^{-1})	–	46	–	52
S (kg ha^{-1})	–	8.6	–	9.7
Total N (kg ha^{-1})	50	60	56	66

DAP: diammonium phosphate; UAN: urea-ammonium nitrate.

previous knowledge and recent research in order to increase grain production together with an increase in resource productivity (Cassman, 1999, 2017) with respect to FP. The particular combination of input level and other management decisions in EI was based on the attainable yield, estimated to be 80% of Yw, because farmers' yields tend to plateau at 75–85% of Yw (Van Ittersum et al., 2015; Sadras et al., 2015). For Balcarce, maize Yw was estimated at 12,500 kg ha^{-1} by Aramburu Merlos et al. (2015). Further information on the treatments is available at Caviglia et al. (2019).

Treatments were arranged in a randomized complete block design with three blocks, plots were of 50 m long by 10 m wide. All operations were carried out with common farmer field equipment.

Maize was grown under no-tillage in both managements. In FP treatment, fertilizer sources were diammonium phosphate (DAP) and urea. The DAP was banded and incorporated into the soil at planting (5 cm to the side of the seed and at 2 cm depth) and urea was surface-broadcast. In EI treatment, fertilizer sources were DAP and urea-ammonium nitrate (UAN). The DAP was banded and incorporated at planting (5 cm to the side of the seed and at 2 cm depth), while UAN was surface-dribble at the six leaves growth stage (V6) of maize. Timing and N source for EI were selected to improve synchronicity of N supply and plant N uptake, and to reduce potential ammonia volatilization losses, respectively, according to previous research in the region (García et al., 1999; Sainz Rozas et al., 1999, 2001).

2.2. Nitrous oxide emission measurements

Emissions of N_2O were monitored weekly over two maize seasons, from 2 November 2011 to 3 April 2012, and from 31 October 2012 to 5 April 2013. Fluxes of gas from soil were measured, in situ, using non-steady-state, vented and closed chambers composed of a base and cap (Parkin and Venterea, 2010). Bases made with rings of polyvinyl chloride (30 cm diameter and 15 cm height) were inserted to a depth of 8–9 cm into the soil. Within each plot, two bases were installed between maize rows a few days after planting. Temporally, the bases were removed to allow some field activities (application of herbicide or fertilizer) and later reinserted in the same location. The polyvinyl chloride cap had a vent tube and rubber stopper used as a port for air sample withdrawal. Gas samplings were generally made between 10:00 and 12:00 h to minimize the diurnal variation in the flux rates (Parkin and Venterea, 2010). Caps were placed over the bases immediately before gas sampling, and gas samples of 10 mL were taken at regular intervals (0, 15 and 30 min.) from the chamber headspace through the septum by inserting a syringe. Immediately, gas samples were transferred into evacuated 6 mL glass vials and kept at room temperature until chromatographic analysis. The gas chromatograph (Shimadzu GC 2014 model "Greenhouse") used to quantified the gas concentration was equipped with an automatic sample injection system at 250 °C, a column at 70 °C, a ^{63}Ni electron capture detector set at 350 °C for N_2O. The N_2 was the carrier gas, flowing at 30 mL min^{-1}.

Concentrations of N_2O obtained by gas chromatograph were converted to mass units using the ideal gas law:

$$PV = nRT$$

Where P is atmospheric pressure (atm), V is the gas volumen (L), n is the number of moles of the gas, R is the universal gas constant (0.0821 L atm mol^{-1} K^{-1}) and T is air temperature in °K. The daily N_2O fluxes were calculated from the rate of change of gas concentration as a function of three consecutive measurements over the sampling time, using the method proposed by Venterea (2010) with linear regression. This method was designed to calculate the magnitude of underestimation of flux due to suppression of gas concentration gradient at the soil surface after chamber closure, and in order to correct this effect, it uses correction factors which takes into consideration some specific soil conditions and chamber characteristics (Venterea et al., 2011).

Cumulative N_2O emissions (g N_2O-N ha^{-1}) were estimated by linear interpolation and integration of fluxes measured daily. Cumulative N_2O emissions correspond to the total emissions calculated over 153 days in the 2011–12 season and 156 days in the 2012–13 season. Cumulative yield-scaled N_2O emissions (g N_2O-N kg^{-1} grain) were calculated by dividing cumulative N_2O emissions by the corresponding grain yield (Mg grain ha^{-1}).

2.3. Soil and weather variables

At each time of gas sampling, composite soil samples were obtained from each plot by taking about 15 cores (2.5 cm diameter) to a depth of 0 to 10 cm, near the chambers. Soil samples were placed in sealed plastic bags, returned to laboratory, and homogenized. Subsamples were weighed for gravimetric water content determination by oven drying at 105 °C for 24 h, and the remaining field moist soil was used to determine the concentration of nitrate-N (NO_3^--N). NO_3^--N analyses were performed by extracting 20 g of soil with 100 mL of KCl (1 mol L^{-1}) and shaking for 60 min at 250 revolutions min^{-1}. Extracts were filtered through Whatman nº. 42 filter paper and then analyzed following the procedure described by Keeney and Nelson (1982). NO_3^--N values are expressed on a dry soil basis.

Soil bulk density was determined in the 0–10 cm soil layer by using the core method described by Blake and Hartge (1986). Soil gravimetric water content and bulk density values were used to calculate WFPS, expressed as percent, using the following equation:

$$\text{WFPS}\ (\%) = (\theta/p) \times 100$$

where θ is volumetric soil water content and p is soil porosity, and p was calculated as:

$$p = 1-(\text{dry bulk density}/\text{soil particle density})$$

where soil particle density of 2.65 Mg m^{-3} was assumed.

Simultaneously, at the time of each flux measurement and soil sampling, soil temperature was recorded by using a digital thermometer inserted to a depth of 10 cm and located very close to the chamber.

Daily precipitation and air temperature data were obtained from the meteorological station located at the Research Station, approximately 500 m away from the field experiment.

2.4. Grain yield

When crops reached physiological maturity, maize ears were manually harvested from the middle two rows of each plot. Ears were air dried, shelled, and further dried for 3 days at 65 °C and weighed to obtain dry grain yields.

2.5. Statistical analysis

Prior to statistical analysis, data were tested for homogeneity of variance and normality, and transformed when necessary. Soil N_2O fluxes and NO_3^--N concentrations were log-transformed because the original data were non-normally distributed. Soil N_2O fluxes and edaphic variables were analyzed for the 2011–12 season separately from the 2012–13 season, while cumulative N_2O emissions, yields, yield-scaled N_2O emissions and fertilizer-induced N_2O emissions were pooled together.

Analyses of soil temperature, water content and NO_3^--N concentration at each sampling time were done by ANOVA, to detect differences between treatments. Autocorrelation analysis of N_2O fluxes measured in individual plots with time was not significant, therefore no attempt was made to combine the analysis of dates within a year using a mixed model ANOVA with dates as repeated measures to statistically examine the response with time. Pearson correlation coefficients were determined to analyze the relation between soil N_2O fluxes and soil variables. Statistical significance was evaluated at $p < 0.05$. All statistical analyses were performed using R software (R Core Team, 2016).

3. Results

3.1. Air temperature and precipitation

In the two growing seasons, daily air temperature showed a dynamic similar to historical records (Fig. 1; Table 2). During the gas measurement period, the mean daily air temperature was 1 °C warmer (19.8 °C) in 2011–12 compared with that registered (18.9 °C) in 2012–13. In both seasons, the mean air temperature was slightly higher than the 30-yr average of 17.5 °C (1980–2010).

Precipitation and frequency of rainfall events per month varied between the two maize growing seasons (Fig. 1, Table 2). This first season (2011–12, 153 days), was characterized by a drought stress on late December-mid January, around maize silking stage. During the gas measurement period, total precipitation was 416 mm. Rainfall events occurred on 29 different days of which 15 days never exceeded 10 mm of daily rainfall, 11 days recorded daily rains between 10 and 30 mm, and 3 days had daily precipitation between 45 and 65 mm.

In the second season (2012–13,156 days), total precipitation was 649 mm and rainfall events were more frequent, recording 38 days with precipitation. There were 9 days with precipitation above 25 mm of which 7 days were between 33 and 88 mm, 8 days had total daily

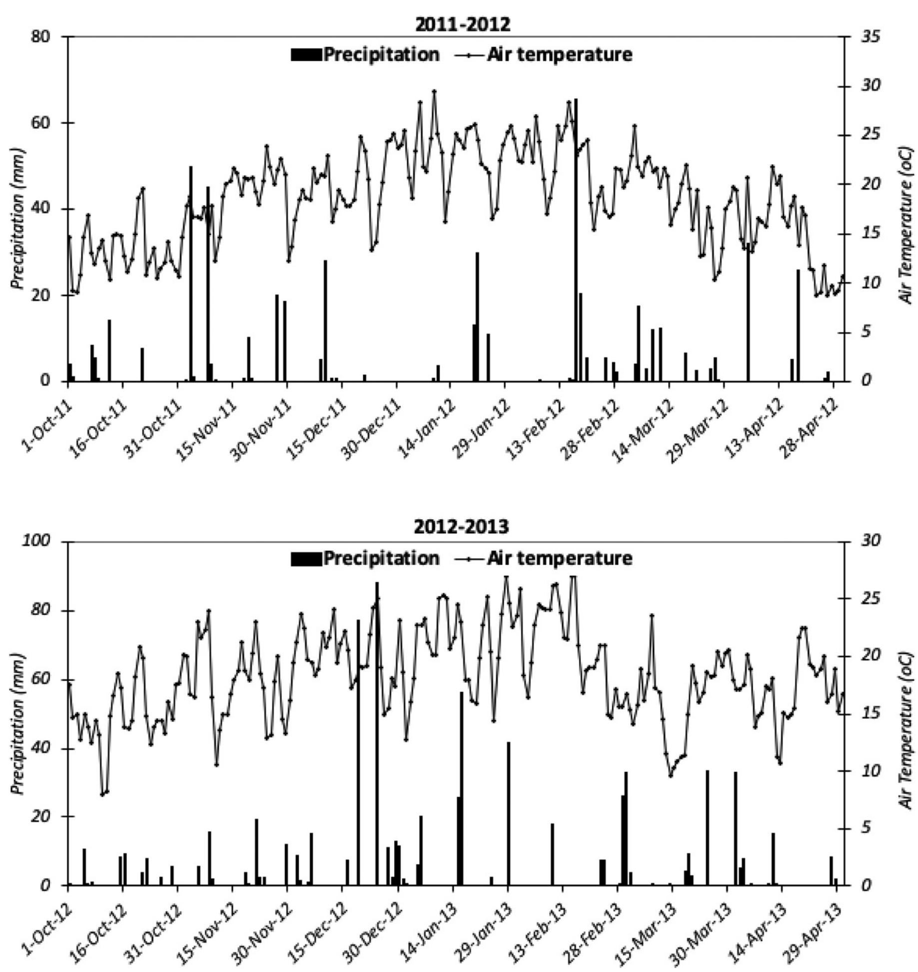


Fig. 1. Daily air temperature and precipitation from October to April 2011–2012 and 2012–2013, recorded at the Research Station of Agricultural Technology National Institute (INTA) Balcarce, Argentina.

Table 2
Precipitation (mm) and mean air temperature (°C) during 2011–2012 and 2012–2013 maize growing seasons, and normal data from the 30-year series 1980–2010 for the experimental site.

Month	Precipitation (mm)			Air temperature (°C)		
	2011–2012	2012–2013	1980–2010	2011–2012	2012–2013	1980–2010
October	41	51	93	13.0	14.9	13.5
November	151	64	92	18.7	17.8	16.2
December	36	239	99	19.9	20.2	18.9
January	58	152	111	23.2	21.1	20.8
February	105	33	84	22.0	21.1	20.0
March	67	114	95	18.7	16.4	18.3
April	66	74	85	14.7	17.2	14.6
Total	523	726	659			

rainfalls between 10 and 25 mm, and the rest of daily rains were below 10 mm. Total precipitation during October through April, was 136 mm lower in 2011–12 (523 mm) than the 30-year mean of 659 mm, but in 2012–13 (726 mm) it was 67 mm above the 30-yr average (Table 2).

3.2. Soil temperature, water content, and nitrate concentration

In 2011–12, neither soil temperature nor water content were significantly ($p > 0.05$) affected by the management system, however there were significant differences ($p < 0.05$) in both variables between sampling dates. Soil temperature gradually increased from around 17 °C on 2 November 2011 to 26 °C on 29 December 2011 but at the end of January 2012 decreased to 21 °C. It again increased during February 2012, declined to 18 °C at the end of this month and stayed relatively constant for the rest of the study period (Fig. 2a). Soil water content reached peaks of 0.25, 0.27 and 0.24 g g^{-1} on 10 November 2011, and 1 and 13 December 2011; respectively, as a result of rainfall events that occurred days before (Fig. 3a). During the next 57-day period (20 December 2011–15 February 2012), water content decreased to reach a value of 0.08 g g^{-1}, except on 26 January 2012 when increased to 0.19 g g^{-1} due to previous precipitation of 50 mm. At the end of February 2012 and during March 2012, soil water content increased to about 0.25–0.28 g g^{-1} in response to late-season rainfalls and remained stable by early April 2012. The highest moisture contents recorded on 10 November 2011, 1 December 2011, 20 and 29 February 2012, and 14 March 2012 were not different ($p > 0.05$) from those recorded after physiological maturity, 15 March 2012.

In 2012–13, there were significant ($p < 0.05$) differences in soil temperature and moisture due to management system and sampling date. Soil temperature and water content were greater ($p < 0.05$) in FP than in EI, but the difference between the two treatments was very small (0.25 °C and 0.006 g g^{-1}) for both variables. Soil temperature increased from around 16 °C at the end of October 2012 to 21 °C at the middle of December 2012. Then, it decreased to 16 °C during the last week of December and first week of January 2013 and gradually increased to 23 °C in the middle of February 2013. Finally, soil temperature decreased to the initial value in the first days of April 2013 (Fig. 2b). With regard to soil water content, after decreasing from 0.27 g g^{-1} to 0.22 g g^{-1} on 7 November 2012, it increased to 0.28 g g^{-1} at the end of November 2012 and beginning of December 2012, but declined to about 0.17 g g^{-1} during the next days in December. Soil water content peaked, following rainfall events. Mean soil water content was higher in the 2012–13 season (average 0.23 g g^{-1}, range 0.16–0.32 g g^{-1}) than in the 2011–12 season (average 0.19 g g^{-1}, range 0.07–0.28 g g^{-1}), with the greatest differences being observed during middle December to middle February period, when severe drought was recorded in 2011–12.

The WFPS followed a pattern similar to that of soil water content and rainfall event (data not shown). Treatment-average WFPS ranged from 13% to 52%, with most of the values being between 13% and 40%, in the 2011–12 season. Meanwhile, in the 2012–13 season, treatment-average WFPS varied from 31% to 60%, with most of the values between 40% and 60%, but only one date showing a WFPS of 60%.

Analysis of variance indicated that soil NO_3^--N concentrations in the upper 10 cm were significantly ($p < 0.05$) affected by the interaction management system × sampling date in both growing seasons. In general, NO_3-N availability increased during November or December, depending on the treatment, as a result of N fertilizer applications and organic N mineralization from soil and residues of the previous crop, and decreased along the maize cycle because of plant uptake (Fig. 4a and b).

3.3. Soil nitrous oxide fluxes and cumulative emissions

Soil N_2O fluxes ranged between 3 and 97 μg N_2O-N m^{-2} h^{-1}, and were significantly ($p < 0.05$) affected by management system × sampling date interaction, in both growing seasons (Fig. 5). Peaks of N_2O flux were observed following precipitations events and/or N fertilizer applications in both seasons, i.e. November 2011 for FP and December 2011 for EI, and late February 2012 for both systems on 2011–12; and late November 2012, late December 2012, and late January 2013 for EI and FP on 2012–13. There were significant ($p < 0.05$) differences between management systems in sampling dates following fertilizer applications coupled with rainfall events, on 10 November 2011, 1 and 6 December 2011, 14 November 2012, and March 2013. For the rest of the measurement periods, N_2O fluxes remained very low, in general without differences between both managements.

There were no significant ($p > 0.05$) effects of management system or season, and management system × season interaction on cumulative N_2O emissions. Averaged across the two managements, total N_2O emissions were 508 g N_2O-N ha^{-1} during 153 days in 2011–12 compared with 628 g N_2O-N ha^{-1} during the period time of 156 days in 2012–13. Cumulative N_2O emissions in EI averaged across the two seasons were 558 g N_2O-N ha^{-1} relative to 578 g N_2O-N ha^{-1} in FP.

The result of two-way ANOVA shows that significant management system × season interaction was found for grain yield. Grain yield in EI was higher than under FP in 2011–12 ($p < 0.05$), but there were no differences in the 2012–13 season (Table 3). Cumulative N_2O emissions expressed per unit grain yield, were only affected by management system ($p < 0.05$) (Table 3). The FP treatment had higher emissions based on yield than the EI treatment, yield-scaled N_2O emissions were of 75–77 g N_2O-N Mg $yield^{-1}$ for EI and 85–115 g N_2O-N Mg $yield^{-1}$ for FP.

The relationship between N_2O fluxes and some soil variables are shown in Table 4. Positive and significant relationships between N_2O flux and NO_3^--N concentration and water content were found for both managements in the two seasons. Concentrations of NO_3^--N were more highly correlated (positively) with N_2O fluxes in the FP treatment ($r = 0.67$) compared to the EI treatment ($r = 0.40$) in 2011–12, while in 2012–13 the correlation between both variables was lower but significant in the two treatments ($r = 0.30$ for CM; $r = 0.35$ for IM). However, water content was most strongly related to N_2O fluxes in both management systems ($r = 0.58$ for CM; $r = 0.55$ for IM) in 2012–13. Fluxes of

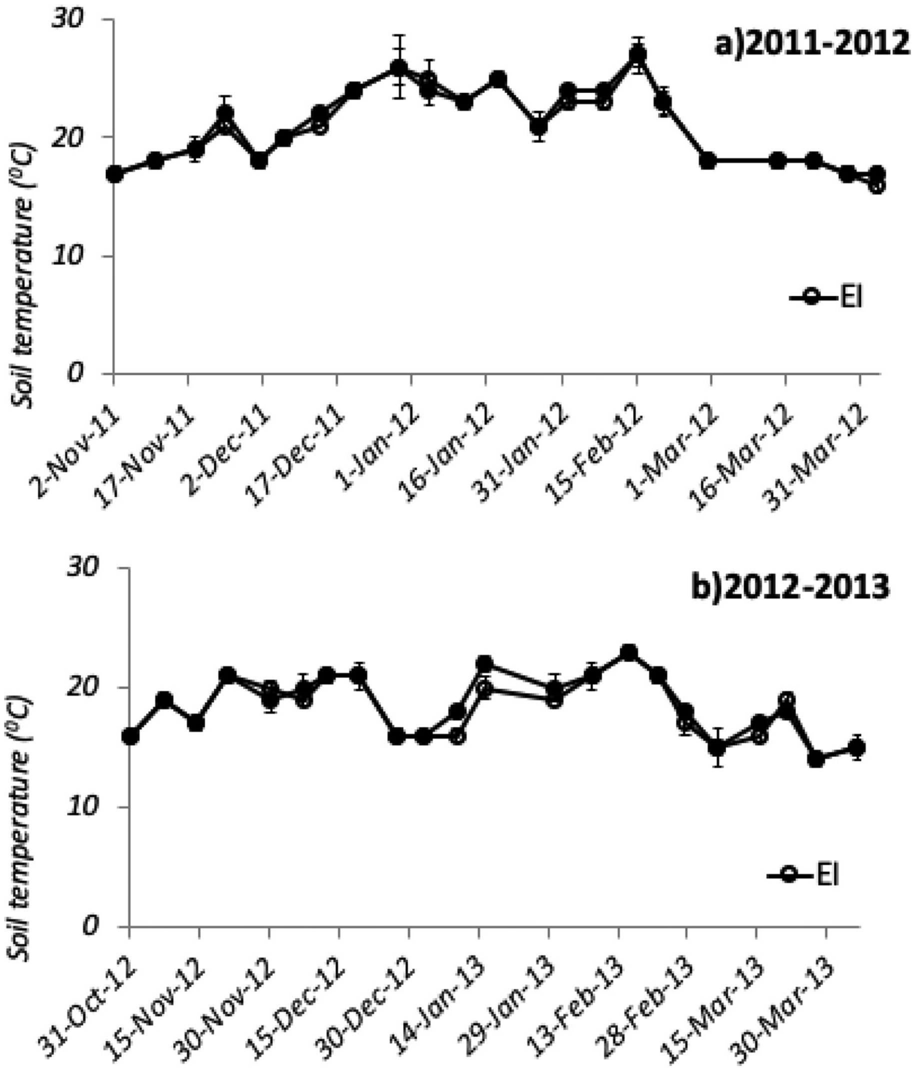


Fig. 2. Daily soil temperature at 10 cm depth at each gas sampling for current management system (FP) and ecologically intensified management system (EI) in a) 2011–2012 and b) 2012–2013 maize growing seasons. Vertical bars represent the standard deviation and those not shown were smaller than the symbols.

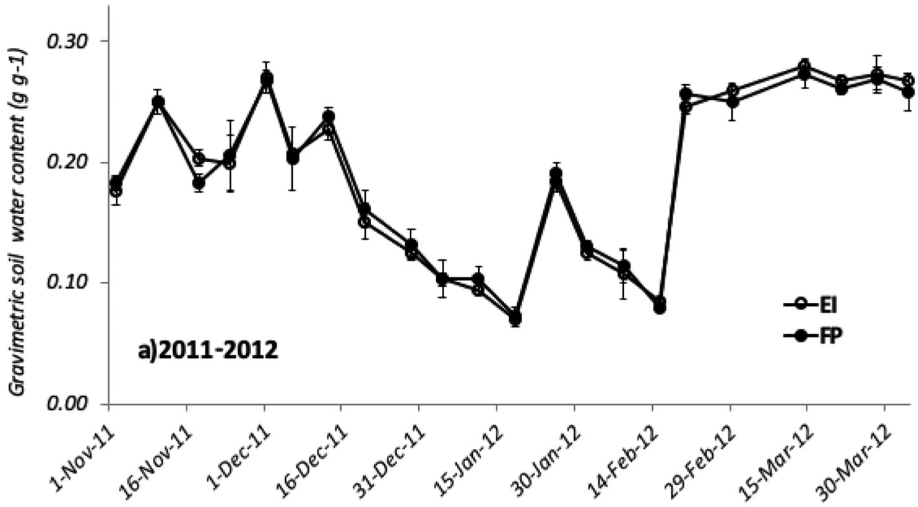
N_2O, on the other hand, were positively correlated with soil temperature only in the FP treatment during the 2011–12 season.

4. Discussion

The dynamics of N_2O fluxes during the maize growing season exhibited pronounced fluctuations in both management systems. These N_2O fluxes are in the same range as those observed by Venterea et al. (2016) over two maize growing seasons in Minnesota (1–140 μg N_2O-N m^{-2} h^{-1}). The highest N_2O fluxes took place during relatively brief periods and following applications of N fertilizer in the wettest months, mid-late spring and early summer, and even when soil temperature was relatively low (<20 °C) as in 2011–12 and NO_3^--N concentration was around 5 mg NO_3^--N kg^{-1} as in 2012–13. These results agree with those reported in several studies that have shown highest N_2O fluxes during late spring and early summer, in response to rainfall events after N fertilizer was applied (Parkin and Kaspar, 2006; Omonode et al., 2010; Venterea et al., 2011; Della Chiesa et al., 2019). Also, soil drying-rewetting events can induce N_2O emission pulses (Beare et al., 2009; Pelster et al., 2011; Guo et al., 2014), because they produce disruption of soil microstructure (Reatto et al., 2009), and release of previously inaccessible substrates for use by microbes. Soil rewetting probably explains the peaks observed after a dry period, for example late in the maize cycle on 20 February 2012 when soil water content increased from 0.08 to 0.25 g g^{-1}, after heavy rainfall.

The peaks of N_2O emissions can make an important contribution to total N_2O emissions (Jacinthe and Dick, 1997; Parkin and Kaspar, 2006). In 2011–12, 31% of the cumulative N_2O emission was due to the two peaks that occurred on 10 November and 13 December 2011, while in 2012–13, the peaks that covered a period of 27 days from 30 November and 27 December 2012 accounted for 29% of the total N_2O emissions. Similarly, Parkin and Kaspar (2006) reported that 45% and 49% of the cumulative N_2O flux in plots under maize was due to two peaks which occurred at 29 and 14 days apart; respectively. In Australia in a cropped soil, 75 to 85% of the annual fluxes were attributed to peaks due to isolated and summer rainfall events (Barton et al., 2013). Therefore, if peaks of N_2O fluxes are not captured, in particular following N fertilizer applications, irrigation/rains, and soil rewetting or spring-thaw events, the total N_2O emissions calculated from field measurements are underestimated (Parkin and Kaspar, 2006; Barton et al., 2015) causing uncertainties in the global N_2O budgets.

Since soil moisture content is a determinant factor of soil N_2O emission as it regulates the oxygen availability to soil microorganisms (Linn and Doran, 1984; Butterbach-Bahl et al., 2013), which carry out denitrification and/or nitrification process, the effect of N fertilizer depends if



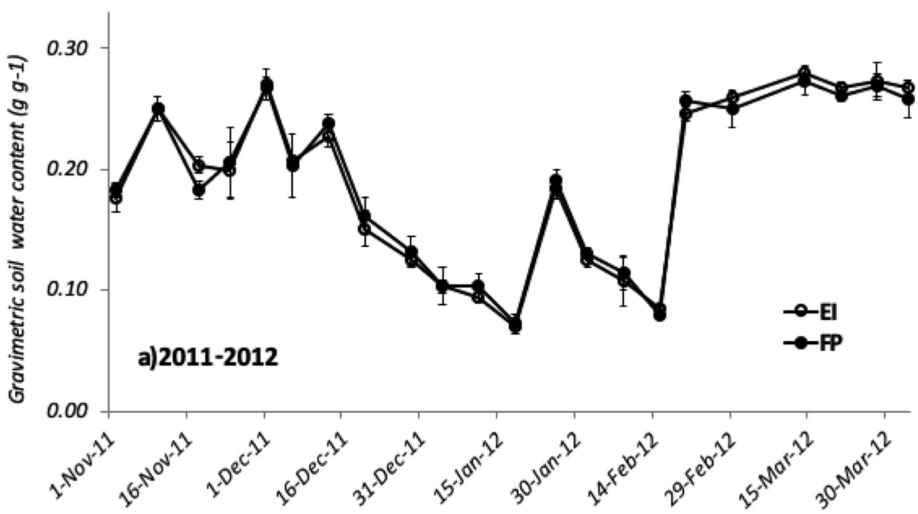


Fig. 3. Seasonal variation of gravimetric soil water content at 10 cm depth at each gas sampling for current management system (FP) and ecologically intensified management system (EI) in a) 2011–2012 and b) 2012–2013 maize growing seasons. Vertical bars represent the standard deviation and those not shown were smaller than the symbols.

its application time matches with timing and quantity of rainfall. In the 2011–12 season, N_2O fluxes began to be monitored on 2 November 2011, 15 days after applying 14 and 13 kg N ha^{-1} as DAP in EI and FP, respectively, but before the application of high rates of N in both treatments (46 kg N ha^{-1} as UAN in EI and 37 kg N ha^{-1} as urea in FP). However, the low precipitation (one rain event of 7.5 mm and another of 0.4 mm) recorded over the mentioned period probably did not affect N_2O fluxes. In fact, at the first sampling date, soil water content was relatively low, 0.18 g g^{-1}. In the 2012–13 season, N_2O emissions began to be measured on 31 October 2012, about 13 days after whole rate of N fertilizer (as DAP + urea) was applied in FP. During that period of time, sporadic and low intensity rains (<8 mm) were registered with a total precipitation of 20 mm, therefore it was not expected a major effect of rainfall on N_2O emissions. If the temporal variability of N_2O fluxes is not considered, the precision of cumulative N_2O emissions calculated from field measurements with soil chambers would be affected (Parkin, 2008).

The optimum level of WFPS for N_2O emissions was suggested to be in the range 70–80%, depending on soil type (Davidson et al., 2000). However, Bateman and Baggs (2005) demonstrated that autotrophic nitrification was the predominant process contributing to N_2O production at WFPS values between 35% and 60% while denitrification process accounted for 100% of the N_2O emitted at 70% of WFPS. In our study, WFPS largely remained below 40% 2011–12, while in 2012–13 most of daily N_2O fluxes occurred between 40% and 60% of WFPS. As a reference, WFPS values of 40% and 60% correspond to soil water contents that are below and close, respectively, to field capacity for a Typic Argiudol in agricultural soils of the region (Falasca and Ulberich, 2006). Then, considering that in our experiment WFPS never exceeded 60% even after heavy rainfall, nitrification is thought to be the major process responsible of N_2O emissions. In a field study conducted under optimal drainage, where WFPS frequently remained below 40%, nitrification process was suggested as main responsible for low emissions of N_2O (Jantalia et al., 2008). Similarly, Skiba et al. (1994) observed that N_2O was produced predominantly by nitrification process when soil was dry in contrast to denitrification process that was the dominant source of N_2O under wet soil conditions.

Although correlations between N_2O fluxes and soil factors were somewhat low, their functional relationship and effects on fluxes were highly significant in most cases ($p < 0.001$). The multiple interactions among factors that control the production and consumption processes of gases, and the delay between production and emission of gases (Wagner-Riddle et al., 2008), usually result in poor or no correlations between soil properties (N content, water content and temperature) and N_2O fluxes (Rochette et al., 2004). In addition, each individual factor explains part of the variation of the gas emission. The correlation

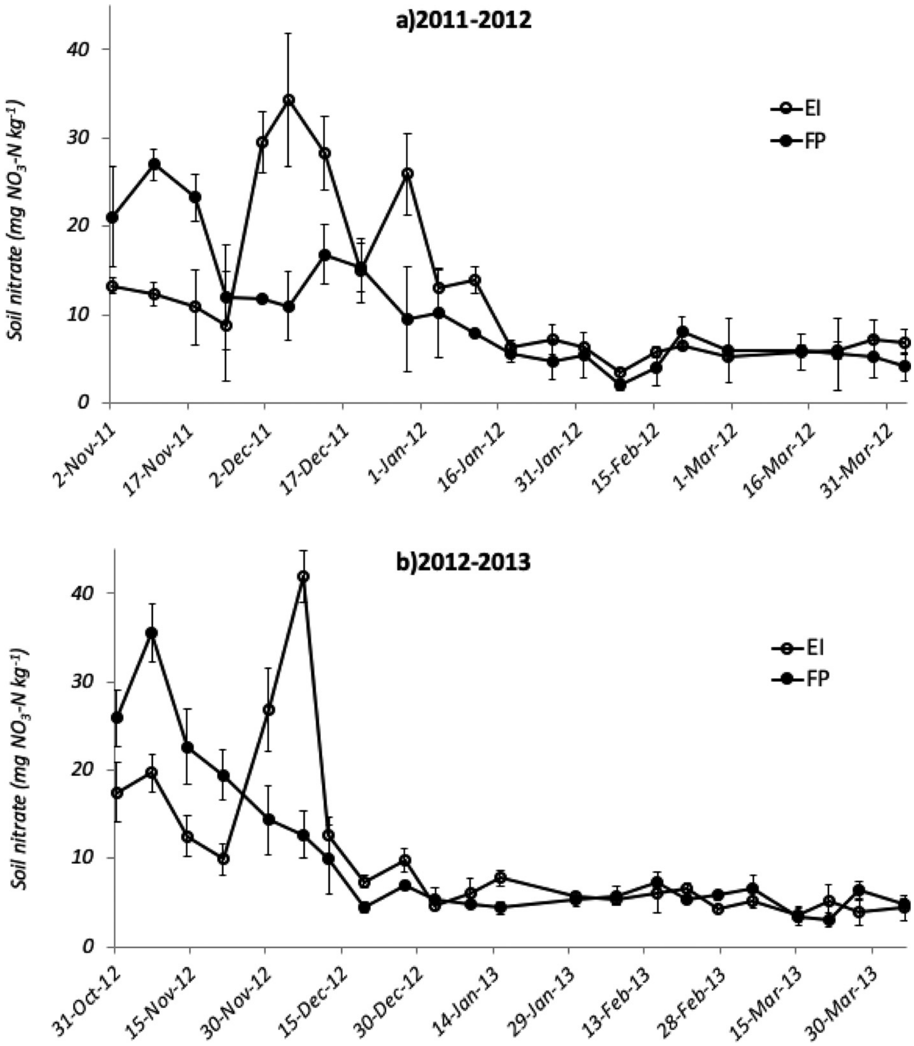


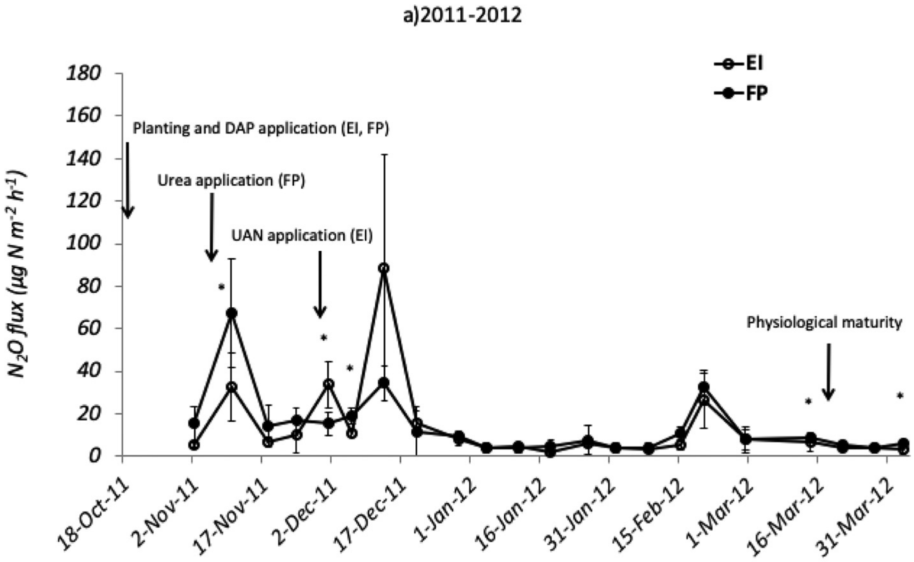
Fig. 4. Soil nitrate (NO_3-N) concentration at 10 cm depth at each gas sampling in a maize crop under current management system (FP) and ecologically intensified management system (EI) during a) 2011–2012, and b) 2012–2013 growing seasons. Vertical bars represent the standard deviations and those not shown were smaller than the symbols.

between N_2O flux and NO_3^--N concentration was stronger for FP compared to EI in the 2011–12 season, while water content was best correlated to N_2O flux under both managements during the 2012–13 season. These relationships can be expected since NO_3^- is required for N_2O production generated via nitrification-coupled denitrification and heterotrophic denitrification, and water content regulates the oxygen concentration which affects the activity of nitrifier and denitrifier microorganisms (Bateman and Baggs, 2005). Fluxes of N_2O were correlated to soil temperature but only in the FP treatment. Temperature is also an important driver of both, nitrification and denitrification in soils (Voroney and Heck, 2015; Cosentino et al., 2013), because it influences microbial kinetics that mediates the mentioned processes, and soil respiration which in turn can affect oxygen availability.

Management system did not significantly ($p > 0.05$) affect cumulative soil N_2O emissions, which were on average 558 and 578 g N_2O-N ha^{-1} for EI and FP, respectively, although EI received a higher N rate. In general, it has been reported that N_2O emissions increase with increasing N fertilizer application rates, especially when N is applied above crop requirements (Eagle et al., 2017; Han et al., 2017; Omonode et al., 2017; Zhao et al., 2017). However, in our study, the different fertilization strategies (N source and timing of application), plus improved crop management practices, would have contributed to reducing N_2O losses in EI compared to FP despite the higher rate of N. Furthermore, for these experiments, Caviglia et al. (2019) reported an increase in the N utilization efficiency by applying a target set of agronomic practices, which included an increase in the N rate in EI. Thus, increases in N rates without exceeding crop N requirements in a medium-input system would allow to improve N use efficiency and avoid significant N_2O-N losses (Van Groenigen et al., 2010; Caviglia et al., 2019).

Similar to this study, where the difference in N rate between the two treatments was small (20%), Venterea et al. (2016) did not find differences in area scaled-N_2O emissions when urea was single and split applied at 100% of the recommended N rate compared to split urea application at 85% of the recommended N rate during the maize growing seasons.

There was also no significant season effect on total N_2O emissions but they tended to be 20% greater over 153 days in 2012–13 (average of 627 g N_2O-N ha^{-1} for both systems) than over 156 days in 2011–12 (average of 508 g N_2O-N ha^{-1} for both systems). This trend may be partly attributed to differences in total precipitation between both seasons. Total precipitation was lower (416 mm) and WFPS was generally below 40% during the time of N_2O flux sampling in 2011–12, while the higher amount of total precipitation (649 mm) together with a group of individual rainfall events, some of them very intensive, resulted in WFPS values between 40% and 60% during most of the sampling time in 2012–13. Minor differences in soil temperature and NO_3^--N concentration would also have contributed to differences in cumulative N_2O emissions between seasons.



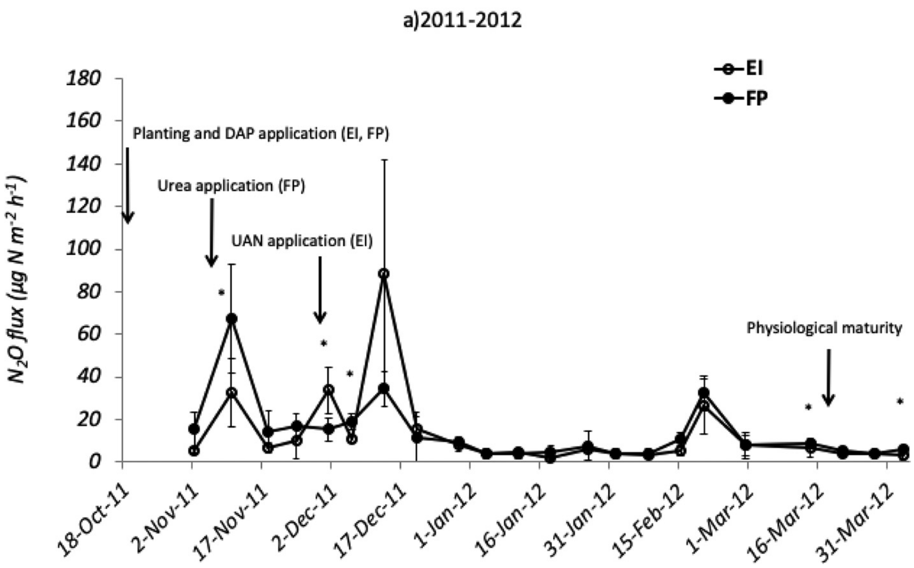


Fig. 5. Mean nitrous oxide (N_2O—N) fluxes from soil in maize crop under current management system (FP) and ecologically intensified management system (EI) in a) 2011–2012, and b) 2012–2013 growing seasons. Vertical bars associate with each data point represent the standard deviations and those not shown were smaller than the symbols.

Grain yield was significantly (p < 0.05) higher for EI than FP in 2011–12 and showed a similar trend in 2012–13. Thus, integrated crop and nutrient management practices would improve grain yield by improving resource productivity and efficiency (water, radiation and N) (Caviglia et al., 2019). Decreased grain yields in 2011–12 compared to 2012–13 were probably related to greater precipitation during the early vegetative stages (November) and a prolonged dry period that covers late vegetative and early reproductive stages.

Several authors (Van Groenigen et al., 2010; Venterea et al., 2011; Grassini and Cassman, 2012; Burzaco et al., 2013; Maharjan et al., 2014) have suggested to evaluate the impact of management practices on the environment, expressing GHG emissions per unit of grain yield instead of per unit area. According to Van Groenigen et al. (2010), expressing N_2O emissions in terms of crop productivity is a useful tool to identify the N rate application that optimizes yields and reduces N_2O losses per unit of yield.

Yield-based N_2O emissions in our study (75 to 115 g N_2O-N Mg yield^{-1}) are within the range reported by Venterea et al. (2011) evaluating controlled-release fertilizers and conventional urea in maize under conventional tillage and no-tillage, and by Zhao et al. (2017) for N rates lower than 171 kg N ha^{-1} under a broad variety of soils and climate conditions; but higher than those reported by Maharjan et al. (2014) for fully and minimum irrigated maize plots, respectively (30 and 52 g N_2O-N Mg yield^{-1}). In contrast, yield-scaled emissions are lower than those found in other maize studies where yield-scaled N_2O-N emissions averaged 1.86 kg N_2O-N Mg yield^{-1} for different N fertilizers and N rates (Gagnon et al., 2011), or ranged from 167 to 328 g N_2O-N Mg yield^{-1} for N rates of 0 to 180 kg N ha^{-1}, respectively (Burzaco et al., 2013).

The EI management system decreased ($p < 0.05$) yield-scaled N_2O emissions by 24% compared with the FP management system due to higher grain yield (+21%), since there were no significant differences in cumulative N_2O emissions between both managements. Therefore, these results demonstrate that a moderate increase in N rate (10 kg N ha^{-1}), when combined with N split application and UAN as N source, as well as other crop management practices (Caviglia et al., 2019; Table 1), might increase grain yield and reduce the yield-scaled N_2O emissions during maize growing season. Considering the yield-

Table 3
Cumulative N_2O emissions, grain yield and grain yield-scaled N_2O emissions in maize under current management system (FP) and ecologically intensified management system (EI) for season 2011–2012 and 2012–2013.

Management	Cumulative N_2O emissions	Grain yield	Yield-scaled N_2O emissions
	g N_2O-N	Mg ha^{-1}	g N_2O-N Mg^{-1} grain
2011–2012			
EI	494	6.56 b	75 b
FP	523	4.57 c	115 a
2012–2013			
EI	622	8.12 a	77 b
FP	633	7.56 a	85 a
	p value		
Block	0.521	0.922	0.526
Season (S)	0.145	0.076	0.156
Management (M)	0.638	0.003	0.020
S*M	0.832	0.024	0.063

Grain yield maize at 0% grain moisture content.
Values within a column followed by different letters are significantly different at 5% level of significance.

scaled N_2O emissions, if the same yield were produced under EI and FP, the FP system would emit more N_2O compared with EI and would require additional land. Thus, our data supports the hypothesis that intensive crop management systems do not necessarily increase GHG emissions per unit of crop or food production, preventing the conversion of natural areas to cropland while meeting global needs for food, fiber, and biofuel (Cassman, 1999; Snyder et al., 2009; Venterea et al., 2016; Zhao et al., 2016).

The experimental design does not allow to estimate fertilizer N-based N_2O emissions as there were not control plots (no application of N). However, even without subtracting cumulative N_2O emissions from control plots, and thus considering all N_2O emissions coming from fertilizer N, total N_2O-N emissions were below 1% of the fertilizer N applied at any of both treatments. This would allow us to suppose that, under conditions of the argentine Pampas, the emission N_2O factor of fertilizer N in maize would be lower than the index of 1% recommended by the IPCC (2007). Studies conducted in the semiarid region of Argentina (Alvarez et al., 2012) and at in southern Brazil (Jantalia et al., 2008) found that N_2O emissions estimated by integrating fluxes with time, were lower than those calculated by applying the IPCC direct emission factor (Tier 1 = 1%) to the amounts of N added as fertilizers and returned as crop residues. These data indicate that the IPCC-emission factor of 1% would overestimate true N_2O emissions from no-tillage cropping systems of southern South America.

Our results indicate that the highest N_2O fluxes occurred during relatively short periods and following applications of N fertilizer during the wettest months, mid-late spring and early summer, in both management systems at the two maize growing seasons. Cumulative N_2O emissions were not significantly affected by management system. However, when expressed per unit of yield grain, N_2O emissions decreased in IE compared with FP. The lower yield-scaled N_2O emissions in IE indicate that intensive systems in this climate regimen might increase crop yield without increasing N_2O emissions or reducing N inputs.

Table 4
Pearson correlation coefficients between nitrous oxide (N_2O-N) fluxes and soil variables (nitrate (NO_3-N) concentration, temperature, water content) during 2011–2012 and 2012–2013 growing seasons.

	Soil properties		
	NO_3-N	Temperature	Water content
2011–2012			
EI	0.40 **	0.21 ns	0.40 **
FP	0.67 ***	0.42 **	0.52 ***
2012–2013			
EI	0.35 *	−0.01 ns	0.55 ***
FP	0.30 *	0.05 ns	0.58 ***

*; **; *** significant at 0.05, 0.01 and 0.001 probability levels, respectively.

The N_2O emissions were obtained by collecting data only along the maize growing season, without considering differences during the fallow period and/or the presence of another crop in the rotation. Therefore, future research should concentrate on demonstrating the potential impact of such management systems on quantification of annual N_2O emissions, considering complete rotation.

In conclusion, for current medium-input agroecosystems such as those of maize on mollisols in the Pampas of Argentina (Caviglia et al., 2019), a moderate increase in N rate (10 kg N ha^{-1}), combined with N split-application and UAN (urea-ammonium nitrate) as N source, as well as other crop management practices, can be a viable alternative to improve maize productivity without increasing the N_2O environmental impact.

Declaration of Competing Interest

None.

Acknowledgments

This research was supported by the International Plant Nutrition Institute (IPNI), Instituto Nacional de Tecnología Agropecuaria (INTA), Facultad de Ciencias Agrarias.- Universidad Nacional de Mar del Plata (FCA-UNMdP), and *Agencia Nacional de Promoción Científica y Tecnológica* (ANPCyT PID 2011-0025). We would further like to thank Fertilizar Civil Association and Profertil S.A., for their support and cooperation.

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