



# To burn or not to burn: The question of straw burning and nitrogen fertilization effect on nitrous oxide emissions in sugarcane



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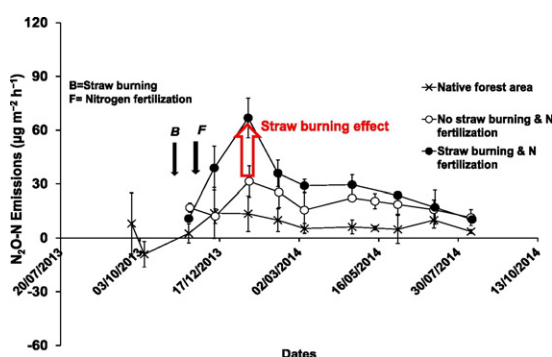
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## HIGHLIGHTS

- N<sub>2</sub>O emissions due to straw burning and N fertilization in sugarcane
- A native forest area adjacent to the sugarcane as reference evidenced the rainfall and temperature influence on N<sub>2</sub>O emission.
- The effect of N fertilization on N<sub>2</sub>O emission was much higher when straw was burned.
- N<sub>2</sub>O emission factor of the N applied was lower than the IPCC factor (0.73 vs 1.25%).
- Avoiding straw burning while adjusting N fertilizer would mitigate N<sub>2</sub>O emissions.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Nitrous oxide (N<sub>2</sub>O) is the main greenhouse gas emitted from farming systems and is associated with nitrogen (N) fertilizer application as well as decomposition of organic matter present in the environment. The objective of this study was to determine the effect of post-harvest straw burning and synthetic N fertilization on the dynamics of N<sub>2</sub>O emissions in the sugarcane-soil system in Tucumán, Argentina, compared with a native forest. Close-vented chambers were used to capture N<sub>2</sub>O during three consecutive growing seasons. The highest N<sub>2</sub>O emissions from the sugarcane-soil system coincided with the period of high soil and air temperatures, rainfall and soil N content. The effect of synthetic N fertilization on annual cumulative N<sub>2</sub>O emission was 7.4–61.5% higher in straw burned than in unburned treatments, especially during a wet growing season. There was a significant effect of treatments on N<sub>2</sub>O emission factors among growing seasons: 0.58–1.67% and 0.94–3.34% in the unburnt and burnt treatments, respectively. The emission factors for sugarcane are highly dependent on rainfall, temperature and crop management practices; regarding the latter, avoiding straw burning and reducing N soil availability, assessing alternative N fertilizers or new application modes such as split rates, seem to be the key for mitigating N<sub>2</sub>O emissions from the sugarcane-soil system in Tucumán, Argentina.

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## 1. Introduction

Greenhouse gas (GHG) emissions have increased since the Industrial Revolution due to anthropogenic action (IPCC, 1996), with agriculture

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being one of the most important sources, contributing 12–14% of the total human-generated GHGs (IPCC, 2006). Gas exchange between soil and the atmosphere contributes to GHG increment, leading to global climate change (Bouwman, 1990). Nitrous oxide (N<sub>2</sub>O) is the main GHG emitted by farming systems (IPCC, 2007). N<sub>2</sub>O emissions in agriculture are associated with nitrogen (N) fertilizer application (Bouwman, 1996; De Klein et al., 2006; Eichner, 1990) and decomposition of organic matter present in the environment (Aulakh et al., 1984; Vinther et al., 2004). N<sub>2</sub>O emissions are often limited by soil N availability, which in turn is affected by physical, chemical, biochemical and microbiological soil parameters (Butterbach-Bahl et al., 2013; Carter and Rennie, 1982); hence, environmental conditions have a direct effect on N<sub>2</sub>O exchange between soil and the atmosphere.

In Argentina, 27.8% of anthropogenic GHG emissions are from the agricultural and feedstock sector, which is responsible for 16.3% of anthropogenic N<sub>2</sub>O emissions (Secretaría de Ambiente y Desarrollo Sustentable de la Nación, 2015), and N<sub>2</sub>O emissions from agricultural soils have increased since 1992 in Argentina, as a consequence of a consistently increasing use of N fertilizers and decomposition of crop residues, since only sugarcane and cotton residues are burnt (Secretaría de Ambiente y Desarrollo Sustentable de la Nación, 2015). However, these estimations were based on default emission factors proposed by the Intergovernmental Panel on Climate Change (IPCC), and may not reflect the specific conditions of the agricultural sector in northern Argentina. Therefore, quantifying N<sub>2</sub>O emissions from croplands through field studies that obtain specific emission factors will be useful for identifying regional hotspots and developing strategies to mitigate GHG emissions from agricultural systems.

Sugarcane (*Saccharum* spp.) is a high-biomass crop and requires a substantial amount of N to achieve maximum yields (Wiedenfeld, 1995), ranking second in the rate of fertilizers used for crop production (216 kg ha<sup>-1</sup>) compared with the mean rate of 109 kg ha<sup>-1</sup> for other crops worldwide (FAO, 2006). In the main sugarcane area of Argentina, Tucumán province, 17% of total CO<sub>2</sub>eq. ha<sup>-1</sup> year<sup>-1</sup> emitted during the agricultural stage was found to be originated from N<sub>2</sub>O from N fertilization (Acreche and Valeiro, 2013). De Oliveira et al. (2013) also reported increased N<sub>2</sub>O emissions from the application of vinasse with respect to an unfertilized control. In a review, Lisboa et al. (2011) reported that 40 and 17% of the total GHG emissions from the ethanol-sugarcane production system derive from N fertilization and trash burning, respectively. In fact, the advantages gained by replacing fossil fuels with bioethanol in terms of GHG emissions N<sub>2</sub>O emissions can be offset by the effects of N fertilization in sugarcane production (Otto et al., 2016). If sugarcane-based biofuel production is a viable option to reduce energy-related GHG emissions, further knowledge regarding GHG sources related to agricultural management during sugarcane production is still needed (Lisboa et al., 2011).

The sugarcane cycle in Argentina consists of five to six cuts, corresponding to one annual plant cycle plus four to five annual ratoon cycles. Generally, most of leaves and tops are burnt in the field before and/or after harvest, whereas stalks (cane) are machine-harvested and transported to the mills for juice extraction, usually by crushing. If harvested without previous burning (current trend in Argentina), sugarcane leaves important amounts of straw (crop residues) in the field. In Tucumán, 5–8 Mg ha<sup>-1</sup> (dry matter) of crop residues are left in the field (Sopena et al., 2006). Despite the legal restriction, straw burning—as in many sugarcane producing countries—frequently occurs in Argentina, either accidentally or to facilitate harvest process or—more frequently—to avoid difficulties in the following soil labors (Digonzelli et al., 2006; Scandaliaris et al., 2002). In Argentina, sugarcane straw burning contributes over 30% of total GHG emissions during the agricultural stage is the second main factor after gas oil use influencing the final GHG balance of the sugarcane industry (Acreche et al., 2013). In Brazil, it represents 98% of the total agricultural burning activities (Lima et al., 1999). Besides increasing soil C storage due to organic matter addition (Kern and Johnson, 1993), the presence of straw on the soil surface increases

N<sub>2</sub>O emissions (Acreche et al., 2013; do Carmo et al., 2013; de Oliveira et al., 2013; Weier, 1996). Thus, there are controversial results reporting the emissions of GHG from straw burnt or left in the field.

Although an expansion of the sugarcane cultivated area over native forests is uncertain, the impact of this land use change on N<sub>2</sub>O emissions is unknown. To the best of our knowledge, no study exploring the combined effect of straw burning and synthetic N fertilization on long-term N<sub>2</sub>O emissions from the system has been conducted, having an uncultivated system (native forest) as reference. Moreover, the scarcity of information with direct field measurements of N<sub>2</sub>O emissions from sugarcane in Argentina and the growing demand for biofuels highlight the need for field measurements of N<sub>2</sub>O emissions from sugarcane in Tucumán, the main crop area of Argentina. This may enable the industry to better compete in the international biofuel market.

The objectives of this study were: i) to determine the effect of post-harvest straw burning and synthetic N fertilization on the dynamics of N<sub>2</sub>O emissions in the sugarcane-soil system in Tucumán, Argentina; ii) to obtain emission factors for sugarcane under different crop residues and synthetic N fertilization management practices, having a native forest as reference; iii) to establish if N<sub>2</sub>O emissions in this environment are correlated with physical, chemical and microbiological environmental variables.

For this, a field experiment was carried out during three consecutive crop cycles. Our results will provide baseline information for upgrading the Argentinean GHG inventory and will help improve the understanding of the dynamics of N<sub>2</sub>O emissions from sugarcane soils, compared to an almost unaltered native forest area.

## 2. Materials and methods

### 2.1. Location and description of the study area

The study area was located in the province of Tucumán, northwestern Argentina. The experiment was conducted in the Famailá Experimental Station of the National Institute of Agricultural Technology (27°03' S, 65°25' W, 363 m a.s.l.) during the 2012–2013, 2013–2014 and 2014–2015 growing seasons. The soil is classified as Aquic Argiudoll characterized as silty loam with soil organic carbon content (SOC) and soil N content (SON) in the top 20 cm of 1.5 and 0.14%, respectively, and with a pH of 5.9. The climate is humid with a mean temperature in the warmest and coldest months of 25.2 and 12.2 °C (January and July), respectively; and an average annual rainfall of 1324 mm, concentrated from November to April. Meteorological data for the study period was obtained from a meteorological station located near the experiment site.

### 2.2. Experimental design and treatments

The experimental area was cultivated with the variety LCP 85-384, which covers >80% of the sugarcane area of Tucumán (Digonzelli, 2015). The crop was harvested mechanically; after each harvest, the following treatments were applied:

- i) straw burning and N fertilization
- ii) straw burning and no N fertilization
- iii) no straw burning and N fertilization
- iv) no straw burning and no N fertilization

Each sugarcane plot consisted of six 100-m long rows, with 1.60 m row spacing.

The experimental design was in a strip plot with three pseudo-replicates to comply with legal restrictions (Hurlbert, 1984). Treatments were planted over an area with similar topographic and edapho-climatic conditions. Soil N<sub>2</sub>O fluxes may vary significantly over space and time, usually exceeding 100% within a few meters (Butterbach-Bahl et al., 2011; Parkin and Venterea, 2010; Davidson et al., 2000; Verchot et al.,

**Table 1**

Dates of treatments, harvest, mean temperature and total rainfall during the 2012–2013, 2013–2014 and 2014–2015 sugarcane growing seasons in Tucumán, Argentina.

Ratooning	Burning date	N-fertilization date	Harvest date	Temperature (°C) <sup>a</sup>	Rainfall (mm)
Plant cane	–	–	15/09/2012	–	–
First ratoon	28/09/2012	31/10/2012	18/09/2013	19.7 ± 5.7	1040.3
Second ratoon	27/09/2013	07/11/2013	27/09/2014	19.8 ± 5.6	1102.4
Third ratoon	09/10/2014	08/11/2014	20/09/2015	19.9 ± 5.2	1637.6

<sup>a</sup> Mean daily temperature ± standard deviation.

1999). Therefore, sampling chambers with a minimum distance of 20 m were considered experimental units.

An almost unaltered native forest area adjacent to the sugarcane plantation was used as reference. It represents the soil natural condition, having 1.7 and 0.19% of SOC and SON in the top 20 cm soil, respectively, and a pH of 7.0. Here, a 0.4-ha area was used for GHG sampling.

In order to represent current farmer practices in Tucumán, N fertilization was performed by furrowing with solid urea incorporated to 10–15 cm depth in the plant row band using the commercial rate (110 kg N ha<sup>-1</sup>). Weeds were controlled by hand labor and/or with recommended herbicides. Details of dates of treatments, harvest, mean temperature and total rainfall are shown in Table 1.

### 2.3. Sampling and measurements

#### 2.3.1. Nitrous oxide fluxes

Close-vented chambers (Baker et al., 2003; Hutchinson and Livingston, 2001) were used to capture N<sub>2</sub>O throughout the crop cycle. Chambers (10.7 L in volume) were of non-reactive PVC. Gases were collected using vacuum pumps and were stored in evacuated 10 mL vials; they were always collected between 9:00 AM and 12:30 PM to minimize diurnal variations. For each sample site, two chambers located in the row and inter-row space were used, totalling six chambers per sugarcane treatment plus three chambers in the forest area. To capture the inherent soil heterogeneity within each treatment, chambers were randomly removed between successive samples. Gas samplings, performed at 0, 20 and 40 min, were conducted monthly throughout the growing season, with the first sampling being conducted after the harvest of the preceding crop cycle (before straw burning) and the last one immediately before the harvest of the current crop cycle. At each gas sampling, an air sample was taken as control. N<sub>2</sub>O concentrations were determined by gas chromatography using an electron capture detector (GC 7890 A with autosampler 7697 A, Agilent Technologies, USA).

Nitrous oxide fluxes were calculated from the rate of concentration change in the chamber. A linear regression between N<sub>2</sub>O concentration and sampling time (Baker et al., 2003) was used. To discard sampling errors, concentrations were compared to the control sample at initial time. In addition, outlier rates were avoided by accepting linear regressions with a  $r^2 \geq 0.7$ . Results were expressed in  $\mu\text{g N}_2\text{O-N m}^{-2} \text{h}^{-1}$ . Cumulative emissions, expressed as  $\text{kg N}_2\text{O-N ha}^{-1} \text{year}^{-1}$ , were estimated by integrating the mean monthly fluxes over time. For this purpose, the average flux of two consecutive samplings was multiplied by the time elapsed between these samplings.

#### 2.3.2. Soil sampling and environmental measurements

After each gas sampling, six soil samples were taken from each chamber with a sample core of 1.7 cm diameter to a depth of 10 cm. From these samples, a composite sample was prepared to determine soil moisture content, soil nitrate and ammonium contents, soil bulk density (SBD), soil porosity (P) and water-filled pore space (WFPS). Soil moisture content was determined gravimetrically by drying samples to constant weight at 110 °C for 72 h, and soil nitrate and ammonium contents were determined by stream distillation (Bremner, 1965; Keeney and Nelson, 1982).

At each sampling, air and soil temperature were also measured using manual digital thermometers. Air temperature was measured at 20 cm above the soil surface, and soil temperature was measured at 5 cm depth.

Total microbial activity (TMA) was estimated by hydrolysis of fluorescein diacetate (FDA) method, as described by Schnurer and Rosswall (1982). TMA was expressed as released fluorescein after hydrolysis in  $\mu\text{g h}^{-1} \text{g}^{-1}$  of soil dry mass, according to Margesin (2005). In each growing season, FDA (measured three times in a mixed soil sample per treatment, under laboratory conditions) was determined on four dates:

- about 5 days after harvest of the preceding crop cycle (before straw burning)
- about 15 days after straw burning
- about 15 days after N fertilization
- at the end of tillering stage (approximately 45 days after N fertilization).

### 2.4. Statistical analysis

Due to pseudo-replication in the experimental design (Hurlbert, 1984), we assumed the least error probability ( $p$ -value  $\leq 0.01$ ) to test differences among treatments. Analysis of variance (ANOVA) was applied to N<sub>2</sub>O fluxes strictly following Schank and Koehnle (2009), by adjusting a mixed model. This included the heterogeneity of variances and the temporal correlation of errors due to successive samplings and years. Likewise, cumulative emissions and FDA values were subjected to ANOVAs. The Fisher's ( $p$ -value  $\leq 0.01$ ) test was used to compare mean values among treatments. The association between N<sub>2</sub>O fluxes and environmental variables was performed using analysis of correlation with Pearson coefficient. InfoStat software (Di Rienzo et al., 2014) was used for all the analyses.

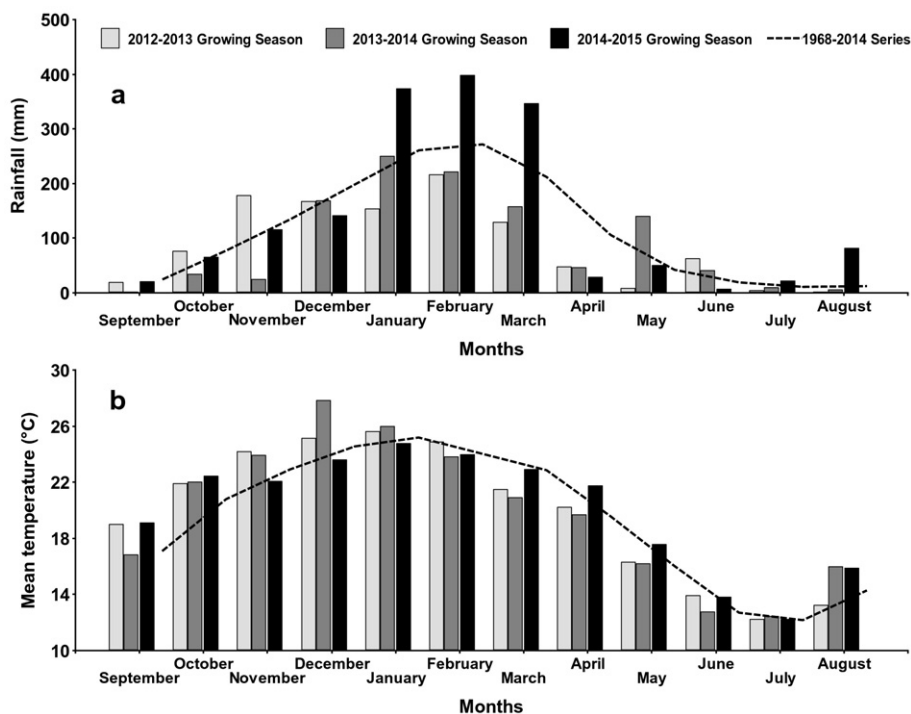
## 3. Results

### 3.1. Temperature and rainfall during the growing seasons

The seasonal dynamics of mean temperature and rainfall was similar among the three growing seasons and between them and the average value for the 1968–2014 series (Fig. 1). However, the magnitudes of rainfalls were different among them. The 2012–2013 growing season was dry, the 2013–2014 one was normal to dry, and the 2014–2015 growing season was very wet (Fig. 1a). Monthly mean temperature showed few differences among growing seasons. The 2012–2013 and 2013–2014 were similar, being 0.61 °C higher in spring-summer than the average value of the 1968–2014 series, whereas mean temperature in the remaining seasons was similar to the historical series. The 2014–2015 growing season had a similar mean temperature during spring-summer, whereas it was 1.3 °C higher than the 1968–2014 series in the remaining period (Fig. 1b).

### 3.2. Dynamics of N<sub>2</sub>O emissions

Mean N<sub>2</sub>O emission differed significantly ( $p < 0.0001$ ) among treatments, with no differences among growing seasons ( $p \geq 0.16$ ). However, there was a significant interaction between growing seasons and treatments ( $p < 0.0001$ ) (Table 2).



**Fig. 1.** Dynamics of rainfall (a) and mean temperature (b) during the 2012–2013, 2013–2014 and 2014–2015 sugarcane growing seasons in Tucuman, Argentina. Lines represent the mean values for the 1968–2014 series.

In general, there were positive fluxes of  $N_2O$  from the sugarcane-soil system of for the three growing seasons (Fig. 2a, b). Significant negative fluxes or uptakes were found mainly for the native forest area and unfertilized treatments, and for the last measurement of the no straw burned-N fertilized treatment in the wet season (Fig. 2a, b). Nitrous oxide emissions were high for the N-fertilized treatments from November to March in all growing seasons, coinciding with the period of high soil and air temperatures, rainfalls and soil N content. In winter, emissions were low and steady, except for the burnt and fertilized treatment of the 2014–2015 growing season, whose period of high  $N_2O$  emissions extended until May (Fig. 2a, b). In the N-fertilized treatments, mean  $N_2O$  emissions ranged from  $5.2 \pm 2.9$  to  $123.6 \pm 46.8$  and from  $-2.6 \pm 3.4$  to  $81.9 \pm 19.6 \mu g N_2O-N m^{-2} h^{-1}$  for the burnt and unburnt treatments, respectively. In the unfertilized treatments,  $N_2O$  emissions ranged from  $-30.3 \pm 10.9$  to  $36.9 \pm 29.4$  and from  $-15.4 \pm 7.1$  to  $62.0 \pm 16.5 \mu g N_2O-N m^{-2} h^{-1}$  for the burnt and unburnt treatments, respectively (Fig. 2a).

Straw burning increased  $N_2O$  emissions only when N fertilizes were applied (November–December), ranging from  $12.1 \pm 5.2$  to  $81.9 \pm 19.6$  and from  $10.8 \pm 3.5$  to  $123.6 \pm 46.8 \mu g N_2O-N m^{-2} h^{-1}$  for the unburnt and burnt treatments, respectively (Fig. 2a, b).

The native forest area treatment did not show any clear trend in the dynamics of  $N_2O$  emissions. The rates of  $N_2O$  emission were lower than that of the unburned and N-fertilized treatment (the most common practice in this sugarcane area) in the 2012–2013 and 2013–2014 growing seasons, a dry and a normal to dry season, respectively. However, the  $N_2O$  rates of the native forest area during the 2014–2015 growing season were higher than those of the unburned and N-fertilized treatment (Fig. 2a, b). This growing season was characterized by heavy rains during spring and summer (Fig. 1a).

### 3.3. Cumulative $N_2O$ emissions

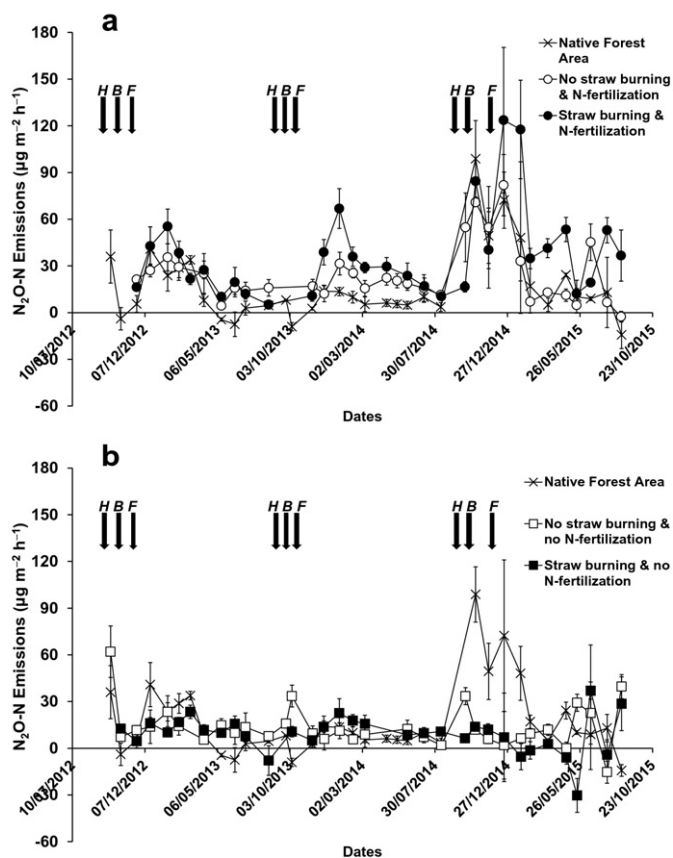
Annual cumulative  $N_2O$  emission differed significantly for treatment, growing season and their interaction ( $p < 0.01$ ) (Fig. 3). The effect of N fertilization on the  $N_2O$  emitted per growing season was much higher when straw was burned, particularly when growing season was wet (2014–2015). In fact, in the dry (2012–2013) and normal to dry (2013–2014) growing seasons (Fig. 1), annual cumulative  $N_2O$  emission was 73% higher in the N-fertilized and unburnt treatment than the in the unfertilized and unburnt treatment, whereas in the burnt treatment, N fertilization increased mean annual  $N_2O$  emissions

**Table 2**

Adjusted means and standard errors of  $N_2O$  emissions for the interaction between treatment and growing season.

Treatment	$N_2O$ emissions ( $\mu g N_2O-N m^{-2} h^{-1}$ )					
	Growing season					
	2012–2013		2013–2014		2014–2015	
Straw burning & N fertilization	$17.1 \pm 3.0$	<i>b</i>	$20.9 \pm 3.5$	<i>b</i>	$40.3 \pm 4.1$	<i>a</i>
No straw burning & N fertilization	$16.9 \pm 2.4$	<i>b</i>	$17.5 \pm 1.9$	<i>b</i>	$11.4 \pm 3.2$	<i>bc</i>
No straw burning & no fertilization	$11.9 \pm 1.9$	<i>bc</i>	$9.2 \pm 2.1$	<i>bcd</i>	$8.8 \pm 4.2$	<i>bcd</i>
Straw burning & no fertilization	$9.4 \pm 1.9$	<i>bcd</i>	$9.6 \pm 2.4$	<i>bcd</i>	$-0.4 \pm 3.5$	<i>d</i>
Native forest area	$4.4 \pm 2.7$	<i>cd</i>	$4.9 \pm 2.2$	<i>cd</i>	$19.9 \pm 3.9$	<i>b</i>

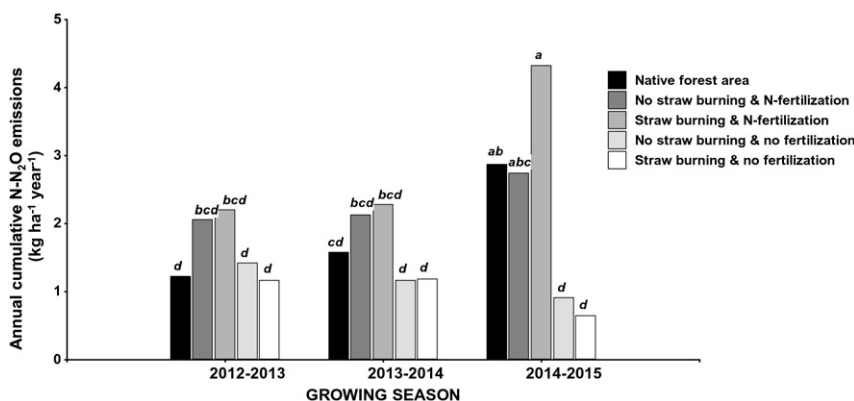
Different letters indicate significance differences for the interaction between treatment and growing season at 0.01 level.



**Fig. 2.** Dynamics of N<sub>2</sub>O emissions for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Arrows indicate harvest (H), burning (B) and fertilization (F) dates. Bars represent the standard error.

by 105% with respect to the burnt and unfertilized treatment (Fig. 3). However, these differences were much higher in the wet (2014–2015) growing season (131 and 325%, respectively) (Fig. 3).

Although the effect of N fertilization on N<sub>2</sub>O emissions appears evident, the mean annual cumulative N<sub>2</sub>O emitted by the unburned and N-fertilized treatment was slightly higher than the mean annual N<sub>2</sub>O emitted by the native forest area (2.14 and 1.72 kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup> for unburned and N-fertilized sugarcane and native forest, respectively). In fact, the native forest area emitted important amounts of N<sub>2</sub>O during the three crop growing seasons. In the dry and normal to dry growing seasons (2012–2013 and 2013–2014), it emitted as much as the unfertilized treatments, whereas in the wet season (2014–2015), it emitted a similar amount to that of the fertilized and unburned treatment. Hence,



**Fig. 3.** Annual cumulative N<sub>2</sub>O emissions for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Different letters indicate significance differences among mean values from three replicates for the interaction between treatments and growing seasons according to ANOVA and Fisher's test at 0.01 level.

**Table 3**

Mean emission factors ± standard error for urea applied and incorporated to the sugarcane soil in Tucumán, Argentina, expressed as percentage of N<sub>2</sub>O-N per kg of N applied.

Treatments	Emission factors (% N <sub>2</sub> O-N per kg of N applied)				
	Growing season			Mean	
	2012–2013	2013–2014	2014–2015	A	B
Straw burning & N fertilization	0.94 ± 0.13	0.99 ± 0.07	3.34 ± 0.8	0.97	1.76
No straw burning & N fertilization	0.58 ± 0.15	0.87 ± 0.3	1.67 ± 0.31	0.73	1.04

A = average emission factor between 2012–2013 and 2013–2014 growing seasons. B = average emission factor among 2012–2013, 2013–2014 and 2014–2015 growing seasons.

the amount of rainfalls of each season had a very large effect on N<sub>2</sub>O emissions from the native forest area.

### 3.4. The N<sub>2</sub>O emission factor of solid urea applied to the soil

In order to evaluate the amount of N<sub>2</sub>O-N emitted per unit of N inputs applied as solid urea, the mean emission factors for each growing season were calculated (Table 3). Our results showed that the annual application of 110 kg of N ha<sup>-1</sup> as urea resulted in a mean N<sub>2</sub>O emission factor of 1.04 and 1.76% for the unburned and burnt treatments, respectively (Table 3). However, there was important variability in the N<sub>2</sub>O emission factors among growing seasons: 0.58–1.67% in the unburned and 0.94–3.34% in the burnt treatments, respectively. The extremely high N<sub>2</sub>O emission factor in the 2014–2015 growing season could be associated with the abnormal rainfalls that occurred during spring and summer (Fig. 1).

### 3.5. Associations between N<sub>2</sub>O emissions and environmental conditions

There were significant correlations between N<sub>2</sub>O emissions and soil moisture ( $p < 0.001$ ), soil temperature at 5 cm depth, air temperature at 10 cm ( $p < 0.01$ ) and soil nitrate content at 10 cm depth ( $p < 0.05$ ) (Table 4). However, the coefficients of correlation explained only part of the N<sub>2</sub>O emissions. Water-filled pore space (WFPS), bulk density, soil porosity and soil ammonium content were not correlated with N<sub>2</sub>O emissions.

### 3.6. Total microbial activity and its relationship with N<sub>2</sub>O emissions

Total microbial activity (TMA), measured as FDA hydrolysis, was significantly different among treatments ( $p < 0.0001$ ), whereas it was not affected by growing season ( $p \geq 0.18$ ). However, the interaction between treatment and growing season was significant ( $p < 0.01$ ) (Table 5).

**Table 4**  
Correlation coefficients between N<sub>2</sub>O-N emissions and environmental variables.

Variable (1)	Variable (2)	n	Pearson	p-Value
N-N <sub>2</sub> O ( $\mu\text{g m}^{-2} \text{h}^{-1}$ )	Air temperature	715	0.10	**
	Soil temperature	715	0.11	**
	Soil gravimetric moisture	715	0.2	***
	Water filled pore space	715	-0.01	ns
	Soil bulk density	715	-0.04	ns
	Porosity	715	0.04	ns
	NO <sub>3</sub> content	522	0.12	*
	NH <sub>4</sub> content	161	0.06	ns

\*( $p < 0.05$ ); \*\*( $p < 0.01$ ); \*\*\*( $p < 0.0001$ ); ns (not significant).

In general, the native forest area presented higher values of FDA hydrolysis during the three growing seasons than all sugarcane treatments, which did not differ among them (Table 5). Thus, there was no effect of burned and N fertilization on FDA hydrolysis. The FDA values ranged between 8.7 and 57.8  $\mu\text{g}$  fluorescein  $\text{g}^{-1}$  of dry soil  $\text{h}^{-1}$  for the native forest area, whereas the range for the four sugarcane treatments was between 4.6 and 43.7  $\mu\text{g}$  fluorescein  $\text{g}^{-1}$  of dry soil  $\text{h}^{-1}$ . Although not significant, there was a trend to increasing N<sub>2</sub>O emissions as FDA values increased ( $p = 0.053$ ;  $n = 117$ ).

The dates of FDA determination and their interaction with treatment were not significant ( $p \geq 0.09$ ). However, the highest mean value of FDA hydrolysis (28.6  $\mu\text{g}$  fluorescein  $\text{g}^{-1}$  of dry soil  $\text{h}^{-1}$ ) was observed after N fertilization.

#### 4. Discussion

The dynamics of N<sub>2</sub>O emissions from the sugarcane-soil system in Tucuman, Argentina, showed the occurrence of positive N<sub>2</sub>O fluxes during the whole crop cycle. The peak of N<sub>2</sub>O emissions occurred between the end of spring and the end of summer, showing that N<sub>2</sub>O emissions were mainly associated with the high mean temperature and rainfall conditions of that period, probably due to higher rates of organic matter decomposition. This was confirmed by the positive and significant correlations between N<sub>2</sub>O emissions and soil moisture, soil nitrate content, soil temperature and air temperature reported in our study. This pattern is similar to those reported by Acreche et al. (2013), Allen et al. (2010) and Jantalia et al. (2008) for sugarcane grown in Argentina, Australia and Brazil, respectively.

The magnitude of N<sub>2</sub>O emissions in Tucuman (0–124  $\mu\text{g}$  N<sub>2</sub>O-N  $\text{m}^{-2} \text{h}^{-1}$ ) was similar to that reported by Jantalia et al. (2008) for an oxisol in Passo Fundo, Brazil (1–183  $\mu\text{g}$  N<sub>2</sub>O-N  $\text{m}^{-2} \text{h}^{-1}$ ); however, those authors did not report the negative fluxes or uptakes of N<sub>2</sub>O that do occur in Tucumán. Other experiments reporting N<sub>2</sub>O emissions in sugarcane showed higher N<sub>2</sub>O emissions than our results. De Oliveira et al. (2013) reported N<sub>2</sub>O emissions within the range of 0.6–592  $\mu\text{g}$  N<sub>2</sub>O-N  $\text{m}^{-2} \text{h}^{-1}$  for an oxisol in Piracicaba, Brazil. However, de Oliveira experimented with N coming from vinasse, which may have generated anaerobic conditions that increased the denitrification process.

In unfertilized treatments, emission peaks were not evident, showing lower emission ranks than fertilized ones. As observed in the native

forest area, low and/or significant negative N<sub>2</sub>O fluxes could be associated with low inorganic N available and low soil temperature at particular moments in the cycle. In fact, works reporting this type of records were reviewed by Chapuis-lardy et al. (2007), who concluded that negative fluxes or uptakes of N<sub>2</sub>O could be caused by denitrifiers and probably by nitrifiers within a range of conditions often connected to low N and low O<sub>2</sub>.

The annual cumulative N<sub>2</sub>O emission was influenced by rainfalls during the growing season that generated a range of 0.64 to 3.67 kg N<sub>2</sub>O-N  $\text{ha}^{-1} \text{year}^{-1}$ ; thus, the highest annual cumulative N<sub>2</sub>O emission was associated with the wet growing season. This phenomenon may be related to the high denitrification occurred, the main process of N<sub>2</sub>O generation in agricultural soils (Dalal et al., 2003; Nevison, 2000). Accordingly, under the abnormal and excessive rainfalls of the spring and summer of the 2014–2015 growing season, the soil was almost saturated, and high denitrification occurred. Vargas et al. (2014) reported two-fold higher N<sub>2</sub>O emissions for incubated clayey eutrodox soils with straw cover and higher moisture than without straw and low moisture.

N<sub>2</sub>O emission was substantially increased by synthetic N fertilization when straw was burned than when straw was not burned. This result could be explained by the different C/N ratios between treatments: unburnt treatment contributes high carbon input to the soil (i.e. a higher C/N ratio) given by the sugarcane straw. In fact, sugarcane straw is characterized by a high C/N ratio, ranging between 101 and 142 (Digonzelli et al., 2011; Muhammad et al., 2011) and its addition has been reported to produce significant immobilization of soil N (Muhammad et al., 2011). Accordingly, Gentile et al. (2008) reported immobilization of N when high C/N ratio crop residues are incorporated into the soil, leading to lower N<sub>2</sub>O losses. However, de Oliveira et al. (2013) did not observe interaction between N fertilization and straw burning, with similar N<sub>2</sub>O emissions due to N fertilization with vinasse being detected in the burned and unburned treatments. Siqueira Neto et al. (2016) did not find differences in N<sub>2</sub>O emissions between different amounts of sugarcane straw left on the soil; however, they conducted a short-term experiment without analyzing a combined effect of N addition. In our work, annual cumulative N<sub>2</sub>O emission depended on the interaction between synthetic N fertilization and straw burning.

The application of 110 kg of N  $\text{ha}^{-1}$  as urea resulted in mean emission factors of 1.04 and 1.76% for the unburnt and burnt treatments, respectively. However, these values were influenced by the abnormal rainfalls that occurred during 2014–2015 spring and summer. The normal to dry 2013–2014 growing season (Fig. 1) showed emission factors of 0.87 and 0.99% for the unburned and burned treatments, respectively. Our results agree with those of Signor (2010), who reported an N<sub>2</sub>O emission factor of 0.84% for the application of 60 kg N  $\text{ha}^{-1}$  of urea in sugarcane from an oxisol in Piracicaba, Brazil. De Oliveira et al. (2013) also reported a higher N<sub>2</sub>O emission factor due to straw burning (0.44%) than in unburned treatments (0.68%) when N was applied, which were lower than our results. This difference could be associated with the type of N source they used (vinasse at 46 kg N  $\text{ha}^{-1}$ ).

**Table 5**  
Adjusted means from three replicates and standard errors of FDA hydrolysis for the interaction between treatment and growing season according to ANOVA and Fisher's test at 0.01 level.

Treatments	FDA Hydrolysis ( $\mu\text{g}$ fluorescein $\text{g soil}^{-1} \text{h}^{-1}$ )					
	Growing season					
	2012–2013		2013–2014	2014–2015		
Straw burning & N fertilization	21.1 ± 5.1	abc	20.0 ± 3.7	bcde	19.3 ± 4.6	e
No straw burning & N fertilization	22.4 ± 4.6	ab	8.7 ± 2.9	cde	22.9 ± 4.4	de
No straw burning & no fertilization	13.2 ± 3.4	bcd	7.5 ± 2.8	cde	19.3 ± 3.9	e
Straw burning & no fertilization	20.9 ± 4.3	bcd	18.3 ± 3.6	cde	25.8 ± 4.1	cde
Native forest area	31.1 ± 4.9	a	37.7 ± 4.9	bcd	45.4 ± 5.3	cde

Different letters indicate significance differences for the interaction between treatment and growing season at 0.01 level.

The mean emission factor for the unburned treatment in the dry and normal to dry growing seasons of our study (0.73%) was lower than that proposed by the IPCC (1.25% of the N applied to soils is emitted as N<sub>2</sub>O). In fact, we found that when straw was not burned and solid urea was applied, N<sub>2</sub>O emissions due to N fertilizer were 10.6 to 37.3% (depending on the emissions factor used; see cases A and B of Table 3) lower than the value (1.28 kg N<sub>2</sub>O-N ha<sup>-1</sup>) reported by Acreche and Valeiro (2013) in Tucuman, using IPCC emission factors. It seems that the emission factor proposed by the IPCC is too general, generating differences for sugarcane growing under different environmental conditions and management practices, as in Tucuman. In fact, the IPCC emission factor for the application of N fertilizers was found to be overestimated for different locations (de Oliveira et al., 2013; Dobbie and Smith, 2003; Jantalia et al., 2008; Rochette, 2004; Siqueira Neto et al., 2016). However, in a thorough review Lisboa et al. (2011) reported that the mean emission factor for N fertilization in unburned areas was 3.87%, more than double the emission factor for unburned and N-fertilized treatment during the very wet growing season reported in our study. However, this value was obtained by extrapolating some data from a wide range of management practices (types of fertilizer and application rates) and edapho-climatic conditions.

It is evident that N<sub>2</sub>O emission factors for sugarcane do not depend only on N inputs and/or N mineralization. Therefore, our emission factors should be used for management and environmental conditions similar to those reported in our study and should be used as a reference value in order to reduce N<sub>2</sub>O emission from N applied to sugarcane fields in Argentina.

It appears evident that sugarcane emits important N<sub>2</sub>O amounts during the crop cycle, especially when the soil is N-fertilized and the postharvest residue (straw) is burned. However, annual cumulative N<sub>2</sub>O emitted from the native forest area (which could be considered the baseline for N<sub>2</sub>O emission) was similar to or even higher than the treatments without N fertilization, and was only 20% lower than the unburned and N-fertilized treatment, the most common management practice applied in the Argentinian sugarcane production.

Total microbial activity (TMA) measured as FDA hydrolysis is related to the amount of N inputs (Vinther et al., 2004). However, in our study, no significant effects of straw burning and N fertilization on TMA were evident, probably due to a reduced cumulative effect of treatments (only three consecutive growing seasons) and/or the low sensitive level of this technique. In fact, Rachid et al. (2012) found significant differences in the diversity of ammonia-oxidizing and denitrifying bacterial communities among the control (native Brazilian Cerrado vegetation) and the burnt and unburnt sugarcane straw treatments, using the denaturing gradient gel electrophoresis (DGGE) technique. However, our results reflected significant differences in TMA between the native forest area and the sugarcane treatments, given by the land conversion to agricultural use; hence, differences in TMA could be used as a potential, economic and fast indicator of land use change impact. The high level of labile C in soil, characteristic of the native forest area, would have led to the high FDA hydrolysis in our study. The high TMA would have generated anaerobic conditions due to high O<sub>2</sub> consumption, which would then contribute partially to the loss of N<sub>2</sub>O due to denitrification.

## 5. Conclusion

The dynamics of N<sub>2</sub>O emissions from the sugarcane-soil system in Tucuman was closely related to moisture, temperature and nitrate contents in the top 10 cm soil. Synthetic nitrogen fertilization as urea and straw burning also increased N<sub>2</sub>O emissions. The emission factors for sugarcane are highly dependent on rainfall, temperature and crop management: avoiding straw burning and reducing N soil availability, assessing alternative N fertilizers or new application modes, such as split rates, seems to be the key for mitigating N<sub>2</sub>O emissions from the sugarcane-soil system in Tucumán, Argentina. This paper provides information that can be used for upgrading the Argentinian GHG

inventory, and contributes to our understanding of the dynamics of N<sub>2</sub>O emissions from sugarcane soils, compared with an almost unaltered native forest area.

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