



## Towards a baseline for reducing the carbon budget in sugarcane: three years of carbon dioxide and methane emissions quantification



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### ARTICLE INFO

#### Keywords:

Carbon sequestration  
Climate change  
Nitrogen  
Straw decomposition

### ABSTRACT

Sugarcane straw burning or removal and N fertilization are management practices that modify the input of carbon (C) to the soil affecting greenhouse gases emissions and the potential of the soil for C sequestration. This study aimed to determine the effect of post-harvest straw burning and synthetic N fertilization on the dynamics of CO<sub>2</sub> and CH<sub>4</sub> fluxes in the sugarcane-soil system of Tucuman, Argentina; it also compared these emissions with those of a native forest and discussed a theoretical soil C balance based on C emissions. Close-vented chambers were used to capture CO<sub>2</sub> and CH<sub>4</sub> during three consecutive growing seasons. The higher CO<sub>2</sub> emissions coincided with the period of high soil and air temperatures and rainfalls. There was not a clear pattern in the dynamics of CH<sub>4</sub> flux for all sugarcane treatments, while the native forest consistently captured CH<sub>4</sub>; however, the cumulative CH<sub>4</sub> flows were negligible in term of C mass. Annual cumulative CO<sub>2</sub> emissions were 12.4–61.4 and 5.9–51.5% higher (for N-fertilized and unfertilized treatments, respectively) when straw was not burned regarding to the burned treatment. However, C losses -as CO<sub>2</sub> emissions- in unburnt treatments were lower than the C input from straw and roots, while C losses in burnt treatments were higher than C input from straw and roots. The soil-sugarcane system of Tucuman has a potential C sequestration estimated of 2.03 Mg of C ha<sup>-1</sup> yr<sup>-1</sup>. The results of this manuscript highlighted the importance of preserving straw as a way to maintain or increase soil organic carbon. They also demonstrated the importance of considering management practices when measuring CO<sub>2</sub> fluxes during the crop cycle for determining the soil C balance.

### 1. Introduction

Soils play a major role in the global carbon (C) cycle (Bot and Benites, 2005) representing over 40% of the total terrestrial biosphere reservoir of C (Ciais et al., 2013). Thus, soils are significantly able to affect the atmospheric carbon dioxide (CO<sub>2</sub>) concentrations (Murty et al., 2002), the main greenhouse gas (GHG) emitted by anthropogenic action (IPCC, 2014). Soils also play an important role in the variation of the concentration of atmospheric methane (CH<sub>4</sub>), the second most important anthropogenic GHG, being responsible for approximately 16% of the greenhouse effect (Oertel et al., 2016).

Soil organic matter (SOM) is one of the most important soil properties related to C cycle. The decomposition of SOM depends on soil microorganisms, the physical environment and the quality of the organic matter (Brussaard, 1994; Dalal et al., 2008). Depending on the variation of these factors, the decomposition of SOM could generate

different CO<sub>2</sub> and CH<sub>4</sub> fluxes. Thus, the loss of soil C stock (as CO<sub>2</sub> and/or CH<sub>4</sub>) can be intensified by land-use managements that modified the physical environment, the quality of the organic matter (Panosso et al., 2009; van Wesemael et al., 2010) and, especially, the diversity of species of microorganism (as in mono cropping) (Savario and Hoy, 2011).

Farming systems based on high crop residue (straw) maintenance and no-tillage tend to accumulate more C in the soil reducing it lost to the atmosphere (Cole et al., 1997). Therefore, agricultural soils can be either a source or sink for atmospheric CO<sub>2</sub> depending on land use type and soil management (Paustian et al., 1997). The fact that agricultural soils have potential for improving C sequestration provides a prospective way of mitigating the increased of atmospheric CO<sub>2</sub> (Lal, 2004). For that reason, determining the exchange of C between soil and atmosphere is relevant, mainly when current farming management practices are included. This could provide sustainable solutions for

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mitigating C losses as part of land management “best practice” and balancing national C budgets (Dawson and Smith, 2007). Accordingly, C exchange measurements as long-term CO<sub>2</sub> and CH<sub>4</sub> emissions/up-takes (i.e. representative data series) are needed.

Sugarcane (*Saccharum* spp.) is a high biomass crop that produces 5–16 Mg ha<sup>-1</sup> (dry matter) of straw at harvest in Tucuman (the main sugarcane crop area of Argentina) (Romero et al., 2007; Sopena et al., 2006). Straw burning—as in many sugarcane producing countries—frequently occurred in Argentina. Currently, about 85% of Argentina sugarcane area employs a ‘green harvest’ practice by use of modern machinery avoiding the pre-harvest burning (Valeiro and Acreche, 2014). However, despite legal restrictions, the post-harvest straw burning practice remains. Acreche and Valeiro (2013) estimated that sugarcane straw burning contributes over 30% of total GHG emissions during the sugarcane agricultural stage in Tucuman. However, there are controversial results reporting GHG emissions from different amounts of straw burned after harvest or left it in the field (Carmo et al., 2013; De Figueiredo et al., 2014).

As straw represents a variable input of C and nitrogen (N) to the soil, straw elimination can significantly modify the potential mitigation of GHG emissions offered by sugarcane as a bioenergy crop (Beeharry, 2001; Carvalho et al., 2017). Straw burning could accelerate SOC depletion by the emission of CO<sub>2</sub> and CH<sub>4</sub> due to the decomposition of the organic matter remaining in the soil, while N fertilization could rebuild SOC by increasing its production (Alvarez, 2005; Paustian et al., 1992). Moreover, straw burning or removal and N input reduce soil C/N ratio increasing N<sub>2</sub>O emissions (Chalco Vera et al., 2017). However, the quantitative long-term N fertilization effect on C fluxes and on the soil C balance for the sugarcane crop are unknown. Therefore, measurements of C fluxes from the sugarcane-soil system and the corresponding soil C balance associated with straw burning and N fertilization practices are needed in order to evaluate the sustainability of the sugarcane crop in Tucuman.

Although an expansion of the cultivated area with sugarcane over native forests in Argentina is uncertain, it is unknown which could be the impact of this land use change from natural areas to sugarcane on GHG-C emissions. To the best of our knowledge, no study has been conducted exploring the combined effect of straw burning and synthetic N fertilization on long-term CO<sub>2</sub> and CH<sub>4</sub> emissions from the sugarcane-soil system, taking into account a system without agricultural disturbance (native forest) as a reference. The scarcity of information with direct field measurements of GHG emissions from sugarcane in Argentina and the growing world biofuels demand highlight the necessity of field measurements from sugarcane in Tucuman. This may allow the industry to improve the precision and quality of life cycle assessments to better compete in the international biofuel market.

The objectives of this study were: i) determine the incidence of post-harvest straw burning and synthetic N fertilization on the dynamics of CO<sub>2</sub> and CH<sub>4</sub> fluxes from the sugarcane-soil system of Tucuman-Argentina, comparing these emissions with those of a native forest; ii) establish physical and chemical environmental attributes that could be related to CO<sub>2</sub> and CH<sub>4</sub> fluxes in this environment; and iii) discuss a theoretical soil C balance for this crop system based on C emissions. These objectives could contribute with criteria for sustainable sugarcane straw management and use. For this, a field experiment was carried out during three consecutive crop cycles.

## 2. Materials and methods

### 2.1. Field experiment

A field experiment was conducted at the Famailla Experimental Station of the National Institute of Agricultural Technology (27° 03' S, 65° 25' W, 363 m a.s.l.; Tucuman, Argentina) during 2012–2013, 2013–2014 and 2014–2015 growing seasons. The dynamics and magnitudes of mean temperature were similar among seasons, while

rainfalls showed similar dynamics and different magnitudes among growing seasons: considering the percentiles of the historical series 1968–2014, the 2012–2013 growing season was classified as dry (annual rainfall between percentiles 10 and 20); the 2013–2014 one as normal to dry (annual rainfall between percentiles 20 and 40); and the 2014–2015 growing season as very wet (annual rainfall higher than percentile 90). The climate data of this period can be found in the supplementary material (Table S1). Chalco Vera et al. (2017) described the full analysis of temperatures and rainfalls during the growing seasons of the experiment.

The experimental area has more than 50 years of sugarcane monocropping and from 2005 soybean was incorporated as crop rotation every 5 years of sugarcane. The fertilizer regularly used in the last 30 years of sugarcane was solid urea incorporated to 10–15 cm depth in the plant row band using a rate of 110–120 kg N ha<sup>-1</sup>. The content of sand, silt and clay of the experimental area was of 15, 54 and 31% (0–20 cm depth). The crop was harvested all years mechanically. At the beginning of the experiment (September 2012), the harvest left 12.23 Mg ha<sup>-1</sup> (dry matter) of sugarcane straw on the soil surface (n = 6). After this, the following treatments were applied for all growing seasons:

- 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

A native forest area representing the natural condition of the soil was used as a reference. This area was near the sugarcane plots (from 30 to 40 m from sugarcane plots), had the same soil type that sugarcane plots (Aquic Argiudoll) and was almost unaltered by anthropogenic action (it was never cropped but it had some alterations as paths and damage on the vegetation). More details of the experimental site and of dates of treatments and management practices are quoted in Chalco Vera et al. (2017).

### 2.2. Sampling and measurements

#### 2.2.1. CO<sub>2</sub> and CH<sub>4</sub> fluxes

Greenhouse gases were captured through closed vented chambers. Gas samplings were conducted monthly throughout the growing season. Gas samples were collected at 0, 20 and 40 min, between 9:00 AM and 12:30 PM to minimize diurnal variations. To capture the inherent soil heterogeneity within each treatment, chambers were randomly removed between successive samples. CO<sub>2</sub> and CH<sub>4</sub> concentrations were determined by gas chromatography by means of a flame ionization detector (GC 7890 A with autosampler 7697 A, Agilent Technologies, USA).

CO<sub>2</sub> and CH<sub>4</sub> fluxes were calculated from the change of the concentration of each GHG in the chambers. A linear regression between gas concentrations and sampling time (Parkin et al., 2003) was used. To discard sampling errors, concentrations were compared to a control sample at initial time. In addition, outliers' rates were prevented accepting linear regressions with a  $r^2 \geq 0.9$  for CO<sub>2</sub> and  $r^2 \geq 0.7$  for CH<sub>4</sub>. Results were expressed in mg CO<sub>2</sub>-C m<sup>-2</sup> h<sup>-1</sup> and µg CH<sub>4</sub>-C m<sup>-2</sup> h<sup>-1</sup>. Cumulative emissions, expressed as kg CO<sub>2</sub>-C/CH<sub>4</sub>-C ha<sup>-1</sup> yr<sup>-1</sup>, were estimated by integrating the mean monthly fluxes over time. For this, we multiply the average flux of two consecutive samplings by the time period between these samplings.

#### 2.2.2. Soil sampling and environmental measurements

After each gas sampling, six soil samples were extracted inside each chamber with a sample core of 1.7 cm diameter to the depth of 10 cm. From these samples, a composed 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 steam distillation (Keeney and Nelson, 1982). WFPS was determined as follows:  $WFPS = [(gravimetric\ water\ content \times SBD) / P]$ ; where  $P = [1 - (SBD (g\ cm^{-3}) / 2.65)]$ , with 2.65 ( $g\ cm^{-3}$ ) being the assumed particle density of the soil (Blake, 2008).

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

### 2.3. Theoretical soil C balance

In order to determine the potential depletion or restoration of soil C stock with different N fertilization and straw management in sugarcane, a theoretical soil C balance was performed. This balance was estimated with the variability of SOC content by considering differential rates of C inputs and outputs. Therefore, C from the crop straw (Digonzelli et al., 2011) and roots (Bolinder et al., 1999; Carvalho et al., 2013) were considered as C-inputs, while soil CO<sub>2</sub>-C emissions (as CH<sub>4</sub> emissions were negligible) were considered as C-outputs.

Due to N deficiency in the unfertilized treatments, it was estimated for Tucuman that straw generation was in average reduced 20% annually regarding the amount of straw produced in the previous cycle (Fogliata, 1995), while the average amount of straw in the treatments fertilized with N in all agricultural cycles were maintained as in the first cycle. The decrease in yield/straw production due to straw burning in the three growing cycles was considered as negligible. Fluxes of CH<sub>4</sub> were also considered negligible for the sugarcane soil in terms of mass. Likewise, C emissions as GHG during straw burning were not considered as direct soil losses during the crop cycle since this C was previously produced by crop photosynthesis (Table 4).

### 2.4. Statistical analysis

The experimental design was in a strip plot with three pseudo-replicates (Hurlbert, 1984). Pseudo-replication resulted from the lack of number of burning events as true replicated treatments since legal restrictions obligated us to perform burning treatment only one time per year and as controlled events over a strip plot design. Therefore, it was assumed the least error probability ( $p$ -value  $\leq 0.01$ ) to test treatments effect (Monica Balzarini, personal communication). Data from successive samplings and years were analyzed by mixed models that include functions for the heterogeneity of variances and the temporal correlation of errors. Thus, analysis of variance (ANOVA) was applied to CO<sub>2</sub> and CH<sub>4</sub> fluxes by adjusting a mixed model. Likewise, ANOVAs were also performed for annual cumulative fluxes of CO<sub>2</sub> and CH<sub>4</sub>. For estimations of annual C inputs and annual C balances, one-way ANOVAs were implemented considering only treatments as a source of variability (using growing seasons as replicates). The Fisher's ( $p$ -value  $\leq 0.01$ ) test was used for the comparison of mean values among treatments. The association among CO<sub>2</sub> or CH<sub>4</sub> fluxes and environmental variables was performed using analysis of correlation by means of Pearson coefficient. InfoStat software (Di Rienzo et al., 2014) was used.

## 3. Results

### 3.1. Dynamics of CO<sub>2</sub> emissions

There were significant differences among treatments, growing seasons and their interaction for mean CO<sub>2</sub> emission ( $p < 0.0001$ ). In general, the interaction showed that the higher the rainfall during the growing season was, the greater the differences among treatments were (Table 1).

There were positive fluxes of CO<sub>2</sub> from the sugarcane-soil system for the three growing seasons (Fig. 1a, b). Significant negative fluxes or

**Table 1**

Adjusted means and standard errors of CO<sub>2</sub> emissions ( $mg\ CO_2-C\ m^{-2}\ h^{-1}$ ) for the interaction among treatments and growing seasons of sugarcane in Tucumán.

Treatment	CO <sub>2</sub> emissions ( $mg\ CO_2-C\ m^{-2}\ h^{-1}$ )		
	Growing season		
	2012–2013	2013–2014	2014–2015
Straw burning & N fertilization	26.7 ± 4.53 ab	25.3 ± 5.3 a	39.6 ± 4.5 bcd
No straw burning & N fertilization	31.8 ± 4.7 abc	40.0 ± 5.1 bcd	55.9 ± 4.8 efg
No straw burning & no N fertilization	33.2 ± 4.6 abc	32.6 ± 5.1 abc	56.9 ± 4.9 fg
Straw burning & no N fertilization	26.7 ± 4.4 a	37.0 ± 5.5 abcd	48.6 ± 4.8 def
Native forest area	28.8 ± 4.9 ab	43.4 ± 5.7 cde	65.7 ± 5.7 g

Different letters indicate significant differences for the interaction among treatments and growing seasons according to ANOVA and Fisher's test at 0.01 level.

uptakes were not found (Fig. 1a, b). Differences among sugarcane treatments in the first months of each growing season (September to November) were not clear. Carbon dioxide emissions were high for all treatments from November to March in all growing seasons, coinciding with the period of high soil and air temperatures and rainfalls. After this period, emissions were low and steady during winters. The exception was the burnt and fertilized treatment of the 2014–2015 growing season that extends the period of high CO<sub>2</sub> emissions until May (Fig. 1a, b). In the dry months (April to September) of each growing season, differences between sugarcane straw managements for unfertilized treatments were not significant; while in fertilized treatments, this trend was observed only in the first growing season, being the emissions of the unburnt and N fertilized treatment of the 2013–2014 and 2014–2015 the highest (Fig. 1a, b).

Clearly, the presence of straw increased CO<sub>2</sub> emission during the crop cycle: when N fertilizers were applied, the mean CO<sub>2</sub> emissions ranged from  $16.9 \pm 5.5$  to  $78.1 \pm 6.4$  and from  $6.9 \pm 3.0$  to  $106.1 \pm 13.7\ mg\ CO_2-C\ m^{-2}\ h^{-1}$  for the burnt and unburnt treatments, respectively. In the unfertilized treatments, the CO<sub>2</sub> emissions ranged from  $12.9 \pm 3.9$  to  $98.1 \pm 20.3$  and from  $17.8 \pm 2.9$  to  $115.3 \pm 6.5\ mg\ CO_2-C\ m^{-2}\ h^{-1}$  for the burnt and unburnt treatments, respectively (Fig. 1a, b).

The native forest area showed a similar trend than sugarcane treatments in the dynamics of CO<sub>2</sub> emissions. However, the rates of CO<sub>2</sub> emission were lower than that of the unburnt 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 growing season, respectively). This pattern was not true during the 2014–2015 growing season in which the rates of CO<sub>2</sub> of the native forest area were higher than that of the unburnt and N-fertilized treatment (Fig. 1a, b). This growing season was characterized by heavy rains during spring and summer (Chalco Vera et al., 2017).

### 3.2. Cumulative CO<sub>2</sub> emissions

Treatments, growing seasons and their interaction significantly differed for annual cumulative CO<sub>2</sub> emission ( $p < 0.001$ ) (Fig. 2).

The effect of straw on increasing the CO<sub>2</sub> emitted per growing season was much higher when N fertilization was performed. In fact, annual cumulative CO<sub>2</sub> emission was 12.4–61.4% higher in the unburnt and N-fertilized treatment than in the burnt and N-fertilized treatment, whereas the unburnt and unfertilized treatment was 5.9–51.5% higher than the burnt and unfertilized treatment (Fig. 2).

The native forest area emitted significant amounts of CO<sub>2</sub> during the

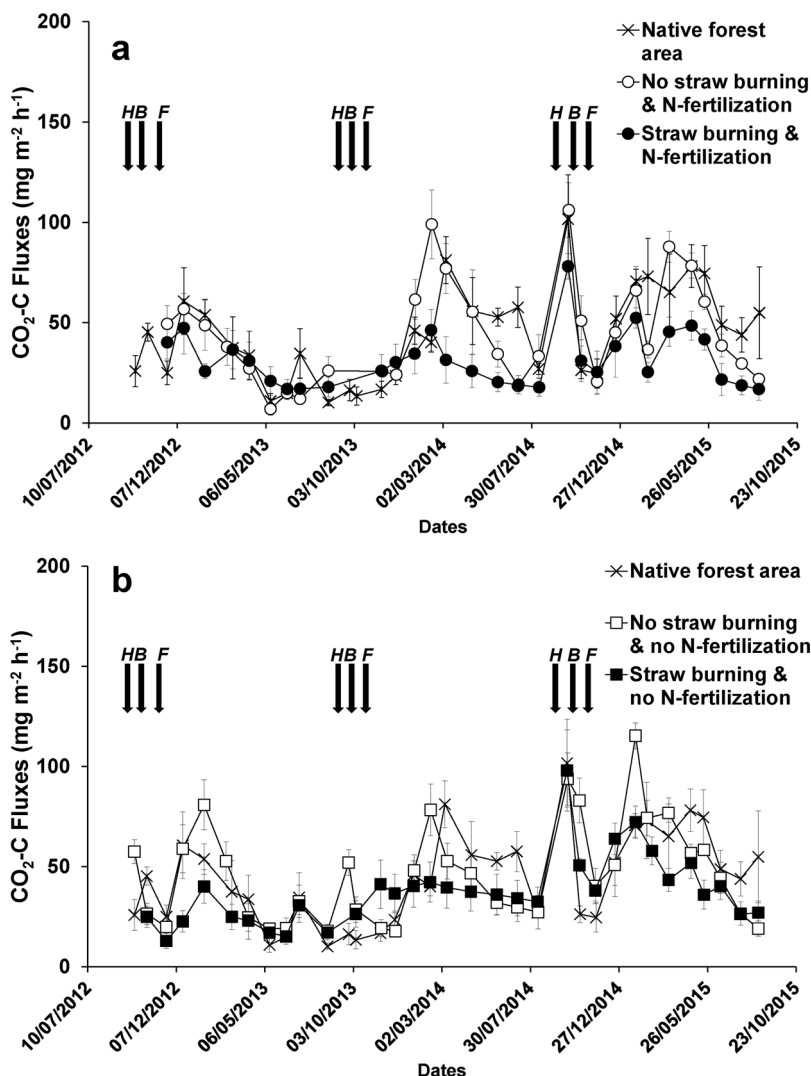


Fig. 1. Dynamics of CO<sub>2</sub>-C emissions for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Arrows indicate harvest (H), burning (B) and N fertilization (F) dates. Bars represent the standard error.

three crop growing seasons. In fact, native forest area emitted as well as the unburnt treatments, whereas it emitted, on average, 27.5% more than the burnt treatments (Fig. 2).

### 3.3. Dynamics of CH<sub>4</sub> fluxes

There were significant differences among treatments for mean CH<sub>4</sub> fluxes ( $p < 0.0001$ ). Growing seasons and the interaction among treatments and growing seasons did not show difference for mean CH<sub>4</sub> fluxes ( $p > = 0.1682$ ) (Table 2). In general, there were CH<sub>4</sub> uptakes in

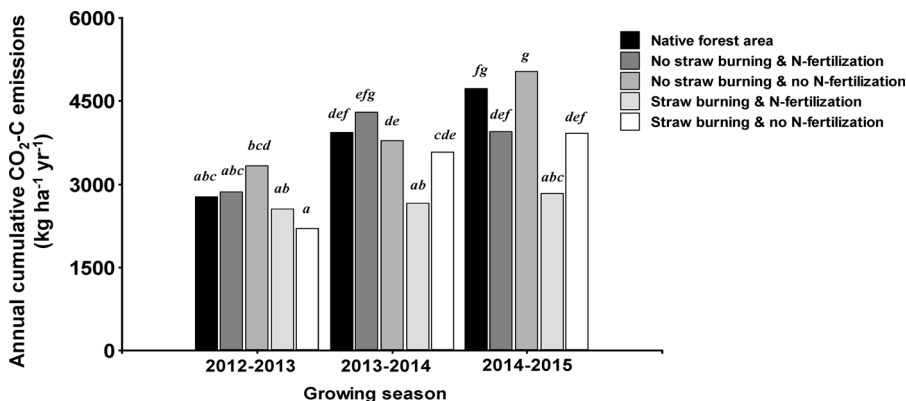
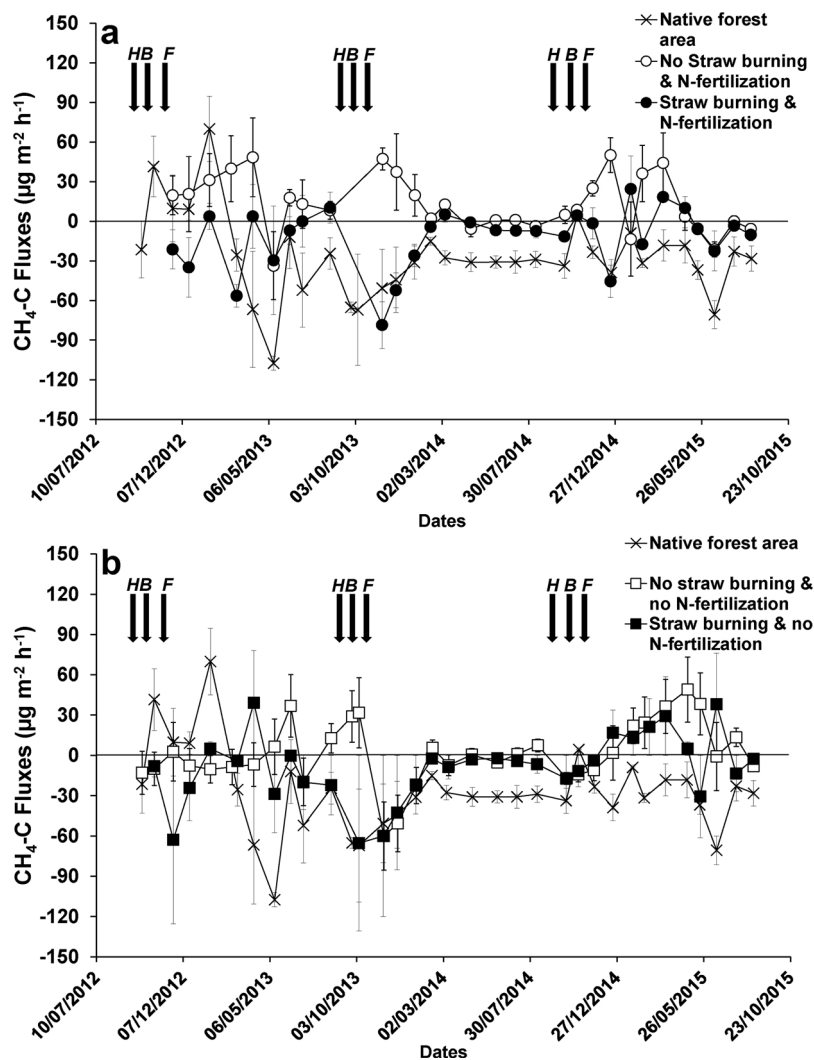


Fig. 2. Annual cumulative CO<sub>2</sub>-C emissions for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Different letters indicate significant differences among mean values for the interaction among treatments and growing seasons according to ANOVA and Fisher's test at 0.01 level.

**Table 2**  
Adjusted means and standard errors of CH<sub>4</sub> fluxes (μg m<sup>-2</sup> h<sup>-1</sup>) for all treatments in Tucuman.

CH <sub>4</sub> -C Fluxes (μg m <sup>-2</sup> h <sup>-1</sup> )				
No straw burning & N fertilization	No straw burning & no N fertilization	Straw burning & Fertilization	Straw burning & no N fertilization	Native forest area
7.3 ± 2.8 a	-0.01 ± 2.6 ab	-6.1 ± 2.76 ab	-8.4 ± 2.7 ab	-20.3 ± 3.3 c

Different letters indicate significant differences among treatments according to ANOVA and Fisher's test at 0.01 level.



**Fig. 3.** Dynamics of CH<sub>4</sub>-C fluxes 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.

the native forest and sugarcane burnt treatments (independently of N fertilization), while there were CH<sub>4</sub> emissions in the treatment of N-fertilized sugarcane without straw burning (Table 2).

There were negative and positive fluxes (uptakes and emissions, respectively) of CH<sub>4</sub> from the sugarcane-soil system for the three growing seasons (Fig. 3a, b). Consistent CH<sub>4</sub> emissions were found only for the unburned and fertilized treatment from November to March in all growing seasons, coinciding with the period of high temperatures (soil and air temperatures) and rainfalls. For the other sugarcane treatments, uptakes of CH<sub>4</sub> were found from November to March in the 2012–2013 and 2013–2014 growing seasons, while in the 2014–2015 growing season (the wet season) all treatments showed positive fluxes. In the latter growing season, the unfertilized treatments extended the period of high CH<sub>4</sub> emissions until May (Fig. 3a, b). During winters, CH<sub>4</sub> emissions were low (nearly to zero) and steady in all sugarcane

treatments. There was not a clear dynamic of CH<sub>4</sub> fluxes in the native forest area during the three growing seasons; however, significant uptakes of CH<sub>4</sub> were found ranging -107.5 ± 5.3 to 69.9 ± 24.7 μg CH<sub>4</sub>-C m<sup>-2</sup> h<sup>-1</sup> (Fig. 3a, b).

The dynamics of CH<sub>4</sub> fluxes showed that the presence of straw increased CH<sub>4</sub> emissions when N fertilizers were applied: CH<sub>4</sub> fluxes ranged from -33.7 ± 25.7 to 50.1 ± 13.2 and from -60.1 ± 25.4 to 48.9 ± 24.2 μg CH<sub>4</sub>-C m<sup>-2</sup> h<sup>-1</sup> for the fertilized and unfertilized treatments, respectively. In the burnt treatments, the CH<sub>4</sub> fluxes ranged from -78.6 ± 17.7 to 24.5 ± 7.9 and from -65.4 ± 17.8 to 39.2 ± 23.4 μg CH<sub>4</sub>-C m<sup>-2</sup> h<sup>-1</sup> for the fertilized and unfertilized treatments, respectively (Fig. 3a, b). The highest differences between unburnt and burnt treatments were mainly observed for the time period when N fertilizers were applied (November–December), ranging from 19.7 ± 14.7 to 50.1 ± 13.2 and from -78.6 ± 17.7 to 1.5 ± 11.7 μg

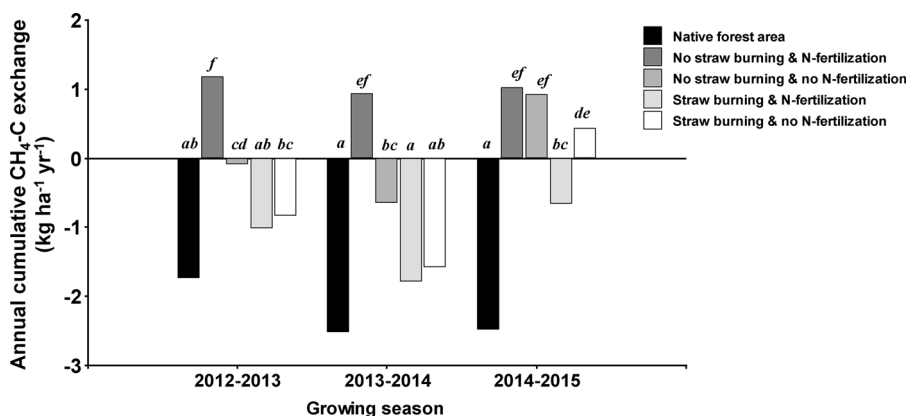


Fig. 4. Annual cumulative CH<sub>4</sub>-C fluxes for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Different letters indicate significant differences among mean values for the interaction among treatments and growing seasons according to ANOVA and Fisher's test at 0.01 level.

CH<sub>4</sub>-C m<sup>-2</sup>h<sup>-1</sup> for the unburnt and burnt treatments, respectively (Fig. 3a, b). However, the rates of CH<sub>4</sub> uptakes of the native forest area during the three growing seasons were higher than that of the unburnt treatments (Fig. 3a, b).

### 3.4. Cumulative CH<sub>4</sub> emissions

Treatments, growing seasons and their interaction significantly differed for annual cumulative CH<sub>4</sub> emission ( $p < 0.0001$ ) (Fig. 4).

The effect of N fertilization on the CH<sub>4</sub> exchange per growing season was much higher in the unburnt treatments when a dry (2012–2013) and normal to dry (2013–2014) growing seasons occurred: the mean annual fluxes were 1.1 and  $-0.36$  kg CH<sub>4</sub>-C ha<sup>-1</sup> yr<sup>-1</sup> for the fertilized and unfertilized treatments, respectively. However, when a wet growing season occurred (2014–2015), there were not significant differences between both unburnt treatments (N-fertilized and unfertilized) (Fig. 4).

In the burnt treatment, both fertilized and unfertilized treatments uptake CH<sub>4</sub> when a dry (2012–2013) and normal to dry (2013–2014) growing season occurred; however, the N fertilization increased the annual CH<sub>4</sub> uptake (17.4% regarding the unfertilized and burnt treatment). When considering a wet growing season (2014–2015), this difference was much higher: the burnt and N-fertilized treatment showed an annual cumulative CH<sub>4</sub> uptake of  $-0.66$  kg of CH<sub>4</sub>-C ha<sup>-1</sup> yr<sup>-1</sup>, whereas the burnt and unfertilized treatment showed a cumulative CH<sub>4</sub> emission of  $0.44$  kg of CH<sub>4</sub>-C ha<sup>-1</sup> yr<sup>-1</sup> (Fig. 4).

It is important to note that the cumulative CH<sub>4</sub> flows were negligible in term of C mass (Fig. 4).

### 3.5. Associations among CO<sub>2</sub> or CH<sub>4</sub> fluxes and environmental conditions

Although CO<sub>2</sub> and CH<sub>4</sub> fluxes from the sugarcane-soil system in Tucuman were correlated between them (Table 3), each GHG was affected by different environmental variables. Sugarcane-soil CO<sub>2</sub> fluxes were significant and positively (from highest to lowest) correlated with soil and air temperature, soil gravimetric moisture and nitrate content (Table 3). Apparently, the most important environmental variables related to CO<sub>2</sub> fluxes were temperature and soil moisture. Although the interactions among these variables could contribute to explain the CO<sub>2</sub> rates, each one was not enough to determine by itself the differences showed by treatments (Pearson's coefficient < 0.5).

On the other hand, CH<sub>4</sub> fluxes were positive and significantly associated with water-filled pore space and soil bulk density, while the correlation of this GHG with porosity was significant and negative (Table 3). Thus, CH<sub>4</sub> pattern was poorly related to climate variables but it was associated with soil physic properties.

Table 3

Correlation coefficients among fluxes of CO<sub>2</sub>-C or CH<sub>4</sub>-C and environmental variables of sugarcane in Tucuman.

Variables	n	Pearson's coefficients	
		CO <sub>2</sub> -C (mg m <sup>-2</sup> h <sup>-1</sup> )	CH <sub>4</sub> -C (μg m <sup>-2</sup> h <sup>-1</sup> )
C-CH <sub>4</sub> (μg m <sup>-2</sup> h <sup>-1</sup> )	674	0,11 (**)	–
Soil temperature	674	0,33 (***)	0,02 (ns)
Air temperature	674	0,33 (***)	0,03 (ns)
Soil gravimetric moisture	674	0,14 (**)	0,06 (ns)
Soil bulk density	674	–0,08 (ns)	0,15 (**)
Porosity	674	0,08 (ns)	–0,15 (**)
Water filled pore space	674	–0,02 (ns)	0,22 (***)
NO <sub>3</sub> content	489	0,12 (**)	–0,01 (ns)
NH <sub>4</sub> content	152	–0,03 (ns)	–0,09 (ns)

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

### 3.6. Theoretical soil C balance

There were significant differences among treatments for soil C balance ( $p < 0.01$ ) (Table 4). The soil C balance for sugarcane ranged from  $-2.99$  to  $0.87$  and from  $-1.28$  to  $2.87$  (Mg of C ha<sup>-1</sup> yr<sup>-1</sup>) for sugarcane with and without straw burning, respectively (data not shown). Apparently, N fertilization promoted soil C gain, being the unfertilized treatments the worst scenarios. In N-fertilized treatments, straw burning practice led to mean net C loss of  $1.35$  (Mg C ha<sup>-1</sup> yr<sup>-1</sup>). Conversely, straw conservation promoted a net C gain of  $2.03$  and  $0.66$  (Mg C ha<sup>-1</sup> yr<sup>-1</sup>) for fertilized and unfertilized treatments, respectively (Table 4). When straw was kept without burning (no considering C emission at burning moment), C output during the growing season were 38 and 25% higher than when the straw was burning for the fertilized and unfertilized treatments, respectively. Regarding to unfertilized treatments, N fertilization decreased 8.5 and 17% the CO<sub>2</sub>-C output in the unburnt and burnt treatments, respectively.

## 4. Discussion

### 4.1. CO<sub>2</sub> fluxes

The pattern of CO<sub>2</sub> fluxes during the growing seasons reflected the specific conditions of the climate-soil-sugarcane system of Tucuman: the highest CO<sub>2</sub> emissions corresponded to the period of high air and soil temperatures, high rainfalls and soil moisture. Many studies agree that CO<sub>2</sub> emission rates depend on the seasonal fluctuation of the climate characteristic of each experimental site (Lundegårdh, 1927; Singh and Gupta, 1977). However, our results indicated that the differences in CO<sub>2</sub> emissions between burnt and unburnt treatments were also associated with changes in the C availability contributed by sugarcane straw

**Table 4**

Average carbon flows and potential soil carbon balances generated with inputs and outputs of carbon into soil under different sugarcane-soil management systems for three consecutive growing seasons in Tucuman.

	Treatments			
	No straw burning & N fertilization	No straw burning & no N fertilization	Straw burning & N Fertilization	Straw burning & no N fertilization
	Mean C flows (Mg C ha <sup>-1</sup> yr <sup>-1</sup> )			
C input from straw* and root system**	5.73 a	4.71 a	1.33 b	1.13 b
C output (CO <sub>2</sub> -C soil emissions)	3.7	4.05	2.68	3.23
Potential soil C balance	2.03 a	0.66 ab	-1.35 b	-2.11 b

Different letters indicate significant differences among treatments according to one way ANOVA and Fisher's test at 0.01 level. For C input and C balance only treatments were considered as source of variability (using growing seasons as replicates).

(\*) estimated data: for sugarcane straw burning systems it was assumed a straw burning efficiency (combustion factor) of 0.8. The C content of aboveground biomass residues (leaves and tops) used was 45% for LCP 85–384 sugarcane variety cropped in Tucumán (Digonzelli et al., 2011); (\*\*) the annual rate of soil organic carbon from root system was estimated as 0.23 Mg ha<sup>-1</sup> (Bolinder et al., 1999; Carvalho et al., 2013).

and the straw decomposition effect on CO<sub>2</sub> emissions from November to March. In fact, the highest rates of CO<sub>2</sub> emissions were found in unburned treatments (with greatest C availability for microorganisms' oxidation). Moreover, the physical effect of the straw promoting retention of soil moisture (Badagliacca et al., 2017; Yamaguchi et al., 2017) was an additional and secondary effect on CO<sub>2</sub> production, especially in the rainy season. The relevance of soil moisture on CO<sub>2</sub> emissions was also reported by Panosso et al. (2009) and Vargas et al. (2014).

On the other hand, CO<sub>2</sub> fluxes during the first months after the harvest in Tucuman (September to November) were similar between treatments with and without straw burning. As this period is characterized by the scarcity of rainfall, the soil moisture likely had the same effect on CO<sub>2</sub> from both burnt and unburnt treatments. Also the absence of differences could be associated with the short-term effect of straw elimination that increased CO<sub>2</sub> emissions as a consequence of the increased soil temperature, equating the emission rates of soil with straw maintenance on surface (Corradi et al., 2013; De Figueiredo et al., 2014).

Under adequate temperature and humidity conditions, N availability plays a key role in the straw decomposition process (Potrich et al., 2014) increasing CO<sub>2</sub> emissions. De Klein et al. (2006) reported that fertilizing sugarcane with urea led to an extra loss of CO<sub>2</sub>, while Vargas et al. (2014) did not find a significant N effect (21 kg N ha<sup>-1</sup>) on sugarcane soil respiration. However, our results showed that unfertilized treatments had higher annual cumulative CO<sub>2</sub> emissions than the N-fertilized treatment. Manzoni et al. (2010) reported that microorganisms have a fixed nutrient ratio (e.g. C/N) and during the straw decomposition process they impose their own stoichiometry to the transformed material. Thus, straw rich in C (as sugarcane straw) and low N availability causes microorganisms to release more C as CO<sub>2</sub> to the atmosphere as the microbes try to maintain their healthy C/nutrients ratio by lowering their carbon-use efficiency to exploit residues with low initial nitrogen concentration (Manzoni et al., 2008). Also, a temporarily C retaining in the soil as inorganic C and/or a leaching of C as bicarbonate in deep groundwater could occurred, decreasing CO<sub>2</sub> emissions (De Klein et al., 2006). Hence, N fertilization could have the effect of reducing CO<sub>2</sub> losses. This could be associated to the fact that N fertilizer application allowed soil microorganisms to have an easily available source of N leading their activity to slow down the process of straw (with a high C/N ratio) decomposition. On the other hand, the experiments where the highest GHG emissions were attributed to the presence of sugarcane straw and apparently not to the C/N ratio of it had high humidity conditions and/or used vinasse (organic nitrogen fertilizer) as a fertilizer, which probably promoted a rapid availability of C and N from the straw (Carmo et al., 2013; Wang et al., 2016).

#### 4.2. CH<sub>4</sub> fluxes

The dynamic of CH<sub>4</sub> fluxes in sugarcane treatments did not show regular patterns during growing seasons, and their annual cumulative values were very low compared to those of CO<sub>2</sub> (-1.8 to 1.1 kg CH<sub>4</sub>-C ha<sup>-1</sup> yr<sup>-1</sup>). The environmental conditions also affected the CH<sub>4</sub> fluxes of the sugarcane-soil system in Tucuman: the dry (2012–2013) and normal to dry (2013–2014) growing seasons showed the same annual CH<sub>4</sub> emission or capture in all treatments, while the wet growing season (2014–2015) altered these trends generating mainly emissions in almost all the sugarcane treatments. The excessive rainfall of the 2014–2015 growing season could have produced temporary anaerobic conditions, prevailing methanogenesis (Serrano-Silva et al., 2014; Watanabe et al., 2007).

Uptakes of CH<sub>4</sub> occurred consistently in the burnt treatments (especially when it was fertilized) and in the native forest of our experiment. The exception was the unburnt and fertilized treatment that maintained an annual cumulative CH<sub>4</sub> emission close to 1 kg CH<sub>4</sub>-C ha<sup>-1</sup> in all growing season. Vargas et al. (2014) reported uptakes and emissions of CH<sub>4</sub> that resulted in negligible cumulative net fluxes (values close to zero). Le Mer and Roger (2001) appreciated large variability in CH<sub>4</sub> fluxes; however, they reported that aerated soils oxidize (uptake) more CH<sub>4</sub> than they produce. Vargas et al. (2014) also concluded that soil moisture, plant residues presence or N-fertilizer did not significantly alter ( $p > 0.1$ ) the CH<sub>4</sub> emission and uptake processes since both mechanisms (methanotrophy and methanogenesis) occurred throughout the period of evaluation (60 days). Probably, these two processes counterbalance de CH<sub>4</sub> fluxes.

The native forest consistently uptakes CH<sub>4</sub>, although the annual mean uptake was relatively low (-2.2 kg C-CH<sub>4</sub> ha<sup>-1</sup> yr<sup>-1</sup>). In fact, forests are considered important sinks of CH<sub>4</sub> (Grunwald et al., 2012). The lower soil bulk density and the greater porosity (and probably a better distribution of the porous space among small, medium and large pores) in the native forest could have produced lower conditions of anaerobiosis, favouring methanotrophy. This demonstrates that CH<sub>4</sub> emissions could be used as a marker that indicates the degree of anthropogenic disturbance of agricultural systems, particularly in sugarcane where strong soil compaction was reported for Tucuman (Tesouro et al., 2016).

#### 4.3. Cumulative C emissions and theoretical soil C balance

The C balance of the most representative treatment for the sugarcane area of Tucuman (no straw burning and N fertilization) was 2.03 Mg of C ha<sup>-1</sup> yr<sup>-1</sup>, similar to those reported by assessing soil C stocks in Brazil (Ceri et al., 2011; Oliveira et al., 2016). However, there are reports that show that C gains in sugarcane soils without burning would be lower than those reported here (Galdos et al., 2009;

Razafimbelo et al., 2006).

Apparently, N fertilization acts as buffer decreasing C soil losses in both burnt and unburnt treatments. This could be associated with i) the highest biomass generation (higher C input) (Wiedenfeld, 1995), ii) the soil C/N ratio modification, which can increase the microbial C biomass (Graham and Haynes, 2005; Liang et al., 2011) and reduce the organic matter decomposition process (since additional N is easily available) (Craine et al., 2007), and iii) the edaphic characteristics of the soil site (Liang et al., 2016). However, N fertilization increase significantly N<sub>2</sub>O emissions (Chalco Vera et al., 2017; Eustice et al., 2011). In fact, Lugato et al. (2018) reported that the variation in N<sub>2</sub>O emissions may offset or enhance soil C sequestration.

It is important to note that the balance of C presented in this manuscript could be underestimating the losses of C as CO<sub>2</sub> that are produced at the moment of performing soil management practices. This means that the abrupt increase of CO<sub>2</sub> emissions that occurred immediately after a soil management (that lasted a brief period) was probably omitted due to the difficulty of capture them (De Figueiredo et al., 2014; La Scala et al., 2006). In addition, it assumes a fixed scenario regarding the efficiency of burning/combustion of straw (80%, recommended value by the IPCC). Therefore, the values of the potential loss of SOC estimated in this work could be higher or lower depending on the efficiency of straw burning.

## 5. Conclusions

The dynamic of CO<sub>2</sub> fluxes from sugarcane-soil system of Tucuman was positive (emissions) and strongly influenced by the environmental conditions: the wetter the growing season was, the higher the emission rates or annual cumulative CO<sub>2</sub> emissions were for all sugarcane treatments and native forest. Maintaining straw (unburnt straw treatments) increased the annual cumulative CO<sub>2</sub> emissions during the crop cycle. N fertilization decreased the annual cumulative CO<sub>2</sub> emissions during the crop cycle, mainly when the straw was burned. The annual cumulative CO<sub>2</sub> emissions from the native forest were at least equal to the highest emissions of sugarcane (unburned treatments). There was not a clear pattern in the CH<sub>4</sub> flux dynamics, nor a tendency towards the uptake or emission of this GHG with the straw burning and/or N fertilization in sugarcane treatments. However, the native forest always uptake CH<sub>4</sub>.

CO<sub>2</sub> fluxes were associated to climate variables or variables that directly depend on climate (temperature and soil gravimetric content), while CH<sub>4</sub> fluxes were associated with soil physic properties (soil bulk density and porosity). The soil-sugarcane system of Tucumán has a potential C sequestration estimated of 2.03 Mg of C ha<sup>-1</sup> yr<sup>-1</sup> when the crop straw is unburnt and fertilized with 110 kg of N ha<sup>-1</sup> of solid urea incorporated. However, it was also estimated that the straw burning transforms the C sequestration capacity of this system in a C-emitting system gradually depleting the C of the soil. The baseline for reducing the carbon budget in sugarcane would be uphold or reduce the N fertilization and preserve the amount of the straw necessary for maintaining the SOC (balance = zero). More experiments are needed in order to determine the sustainable amount of straw that would be extracted to generate a positive or close to zero soil C balance and gradually restore or avoid the loss of soil C in this environment.

## Acknowledgements

We thank the field team of the sugarcane section of EEA Famaillanta for their technical assistance in conducting the experiment. The study was partially funded by grants from INTA (PNIND 2013-2019 N° 1108064 and PNNAT 2013-2019 N° 1128023), and Ministry of Science and Technology of Argentina (PICT 2008 N° 307 and PME 2008 N° 75-08). J.Ch.V. has a fellowship from CONICET.

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.agee.2018.08.022>.

## References

- Acreche, M.M., Valeiro, A.H., 2013. Greenhouse gasses emissions and energy balances of a non-vertically integrated sugar and ethanol supply chain: a case study in Argentina. *Energy* 54, 146–154. <https://doi.org/10.1016/j.energy.2012.12.046>.
- Alvarez, R., 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. *Soil Use Manage.* 21, 38–52. <https://doi.org/10.1079/SUM2005291>.
- Badagliacca, G., Ruisi, P., Rees, R.M., Saia, S., 2017. An assessment of factors controlling N<sub>2</sub>O and CO<sub>2</sub> emissions from crop residues using different measurement approaches. *Biol. Fertil. Soils* 53, 547–561. <https://doi.org/10.1007/s00374-017-1195-z>.
- Beeharry, R.P., 2001. Carbon balance of sugarcane bioenergy systems. *Biomass Bioenergy* 20, 361–370. [https://doi.org/10.1016/S0961-9534\(00\)00094-5](https://doi.org/10.1016/S0961-9534(00)00094-5).
- Blake, G.R., 2008. Particle density. In: Chesworth, W. (Ed.), *Encyclopedia of Soil Science*. Springer, pp. 504–505.
- Bolinder, M.A., Angers, D.A., Giroux, M., Laverdiere, M.R., 1999. Estimating C inputs retained as soil organic matter from corn (Zea Mays L.). *Plant Soil* 215, 85–91. <https://doi.org/10.1023/A>.
- Bot, A., Benites, J., 2005. The importance of soil organic matter. *FAO Soils Bull.* <https://doi.org/10.1080/03650340214162>.
- Brussaard, L., 1994. Interrelationships between biological activities, soil properties and soil management. In: Greenland, D.J., Szabolcs, I. (Eds.), *Soil Resilience and Sustainable Land Use*. Wiley/CAB International, pp. 309–329.
- Carmo do, J.B., Filoso, S., Zotelli, L.C., De Sousa Neto, E.R., Pitombo, L.M., Duarte-Neto, P.J., Vargas, V.P., Andrade, C.A., Gava, G.J.C., Rossetto, R., Cantarella, H., Neto, A.E., Martinelli, L.A., 2013. Infield greenhouse gas emissions from sugarcane soils in Brazil: effects from synthetic and organic fertilizer application and crop trash accumulation. *GCB Bioenergy* 5, 267–280. <https://doi.org/10.1111/j.1757-1707.2012.01199.x>.
- Carvalho, J.L.N., Otto, R., Junqueira Franco, H.C., Ocheuze Trivelin, P.C., 2013. Input of sugarcane post-harvest residues into the soil. *Sci. Agric.* 70, 336–344. <https://doi.org/10.1590/S0103-90162013000500008>.
- Carvalho, J.L.N., Hudiburg, T.W., Franco, H.C.J., DeLucia, E.H., 2017. Contribution of above- and belowground bioenergy crop residues to soil carbon. *GCB Bioenergy* 9, 1333–1343. <https://doi.org/10.1111/gcbb.12411>.
- Cerri, C.C., Galdos, M.V., Maia, S.M.F., Bernoux, M., Feigl, B.J., Powlson, D., Cerri, C.E.P., 2011. Effect of sugarcane harvesting systems on soil carbon stocks in Brazil: an examination of existing data. *Eur. J. Soil Sci.* 62, 23–28. <https://doi.org/10.1111/j.1365-2389.2010.01315.x>.
- Chalco Vera, J., Valeiro, A., Posse, G., Acreche, M.M., 2017. To burn or not to burn: the question of straw burning and nitrogen fertilization effect on nitrous oxide emissions in sugarcane. *Sci. Total Environ.* 587–588, 399–406. <https://doi.org/10.1016/j.scitotenv.2017.02.172>.
- Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao, S., Thornton, P., 2013. Carbon and other biogeochemical cycles. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Cole, C.V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, D., Zhao, Q., 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutr. Cycl. Agroecosyst.* 49, 221–228. <https://doi.org/10.1023/A:1009731711346>.
- Corradi, M.M., Panosso, A.R., Martins Filho, M.V., La Scala Junior, N., 2013. Crop residues on short-term CO<sub>2</sub> emissions in sugarcane production areas. *Eng. Agric.* 33, 699–708. <https://doi.org/10.1590/S0100-69162013000400009>.
- Craine, J.M., Morrow, C., Fierer, N., 2007. Microbial nitrogen limitation increases decomposition. *Ecology* 88, 2105–2113. <https://doi.org/10.1890/06-1847.1>.
- Dalal, R.C., Allen, D.E., Livesley, S.J., Richards, G., 2008. Magnitude and biophysical regulators of methane emission and consumption in the Australian agricultural, forest, and submerged landscapes: a review. *Plant Soil* 309, 43–76. <https://doi.org/10.1007/s11104-007-9446-7>.
- Dawson, J.J.C., Smith, P., 2007. Carbon losses from soil and its consequences for land-use management. *Sci. Total Environ.* 382, 165–190. <https://doi.org/10.1016/j.scitotenv.2007.03.023>.
- De Figueiredo, E.B., Panosso, A.R., Reicosky, D.C., La Scala, N., 2014. Short-term CO<sub>2</sub>-C emissions from soil prior to sugarcane (*Saccharum* spp.) replanting in southern Brazil. *GCB Bioenergy* 7, 316–327. <https://doi.org/10.1111/gcbb.12151>.
- De Klein, C., Novoa, R.S.A., Ogle, S., Smith, K.A., Rochette, P., Wirth, T.C., 2006. N<sub>2</sub>O emissions from managed soils, and CO<sub>2</sub> emissions from lime and urea application. 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry and Other Land Use. pp. 11.1–11.54 Geneva.
- Di Rienzo, J.A., Casanoves, F., Balzarini, M.G., Gonzalez, L., Tablada, M., Robledo, C.W., 2014. InfoStat. Grup. Infoestat. FCA, Univ. Nac., Córdoba, Argentina.
- Digonelli, P.A., Romero, E.R., Alonso, L., Fernández de Ullivarri, J., Rojas Quinteros, H., Scandaliaris, J., Fajre, S., 2011. Assessing a sustainable sugarcane production system in Tucumán, Argentina: part 1: dynamics of sugarcane harvest residue (trash)



- decomposition. *Rev. Ind. agric. Tucumán* 88, 1–12.
- Eustice, B., Van Der Laan, M., Van Antwerpen, R., 2011. Comparison of greenhouse gas emissions from trashed and burnt sugarcane cropping systems in South Africa. *Proc. S. Afr. Sug. Technol. Ass.* 326–339.
- Fogliata, F.A., 1995. La caña de azúcar - La fertilización, in: *Agronomía de La Caña de Azúcar: Tecnología, Costos, Producción*. Tomo 3. El Graduado, Tucumán, Argentina, pp. 1081–1451.
- Galdos, M.V., Cerri, C.C., Cerri, C.E.P., Paustian, K., Van Antwerpen, R., 2009. Simulation of soil carbon dynamics under sugarcane with the CENTURY model. *Soil Sci. Soc. Am. J.* 73, 802–811. <https://doi.org/10.2136/sssaj2007.0285>.
- Graham, M.H., Haynes, R.J., 2005. Catabolic diversity of soil microbial communities under sugarcane and other land uses estimated by Biolog and substrate-induced respiration methods. *Appl. Soil Ecol.* 29, 155–164. <https://doi.org/10.1016/j.apsoil.2004.11.002>.
- Grunwald, D., Fender, A.C., Erasmí, S., Jungkunst, H.F., 2012. Towards improved bottom-up inventories of methane from the European land surface. *Atmos. Environ.* 51, 203–211. <https://doi.org/10.1016/j.atmosenv.2012.01.025>.
- Hurlbert, S.H., 1984. Pseudoreplication and the design of ecological field experiments. *Ecol. Monogr.* 54, 187–211.
- IPCC, 2014. *Climate Change 2014: Mitigation of Climate Change*, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. <https://doi.org/10.1017/CBO9781107415416>.
- Keeney, D.R., Nelson, D.W., 1982. *Methods of Soil Analysis. Part 2, Chemical and Microbiological Properties*, Second. ed. American Society of Agronomy, Inc. Soil Science Society of America, Inc., Madison, Wisconsin USA.
- La Scala, N., Bolonhezi, D., Pereira, G.T., 2006. Short-term soil CO<sub>2</sub> emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. *Soil Tillage Res.* 91, 244–248. <https://doi.org/10.1016/j.still.2005.11.012>.
- Lal, R., 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* 123, 1–22. <https://doi.org/10.1016/j.geoderma.2004.01.032>.
- Le Mer, J., Roger, P., 2001. Production, oxidation, emission and consumption of methane by soils: a review. *Eur. J. Soil Biol.* 37, 25–50. [https://doi.org/10.1016/S1164-5563\(01\)01067-6](https://doi.org/10.1016/S1164-5563(01)01067-6).
- Liang, B., Yang, X., He, X., Zhou, J., 2011. Effects of 17-year fertilization on soil microbial biomass C and N and soluble organic C and N in loessial soil during maize growth. *Biol. Fertil. Soils* 47, 121–128. <https://doi.org/10.1007/s00374-010-0511-7>.
- Liang, F., Li, J., Yang, X., Huang, S., Cai, Z., Gao, H., Ma, J., Cui, X., Xu, M., 2016. Three-decade long fertilization-induced soil organic carbon sequestration depends on edaphic characteristics in six typical croplands. *Sci. Rep.* 6, 30350. <https://doi.org/10.1038/srep30350>.
- Lugato, E., Leip, A., Jones, A., 2018. Mitigation potential of soil carbon management overestimated by neglecting N<sub>2</sub>O emissions. *Nat. Clim. Change* 2040. <https://doi.org/10.1038/s41558-018-0087-z>.
- Lundegårdh, H., 1927. Carbon dioxide evolution of soil and crop growth. *Soil Sci.* 23, 417–453.
- Manzoni, S., Jackson, R.B., Trofymow, J.A., Porporato, A., 2008. The global stoichiometry of litter nitrogen mineralization. *Science* (80-. ) (321), 684–686. <https://doi.org/10.1126/science.1159792>.
- Manzoni, S., Trofymow, J.A., Jackson, R.B., Porporato, A., 2010. Stoichiometric controls on carbon, nitrogen, and phosphorus dynamics in decomposing litter. *Ecol. Soc. Am.* 80, 89–106.
- Murty, D., Kirschbaum, M.U.F., Mcmurtrie, R.E., MCGilvray, H., 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Glob. Change Biol.* 8, 105–123. <https://doi.org/10.1046/j.1354-1013.2001.00459.x>.
- Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., Erasmí, S., 2016. Greenhouse gas emissions from soils—a review. *Chemie der Erde - Geochem.* 76, 327–352. <https://doi.org/10.1016/j.chemer.2016.04.002>.
- Oliveira, D.M., da, S., Paustian, K., Davies, C.A., Cherubin, M.R., Franco, A.L.C., Cerri, C.C., Cerri, C.E.P., 2016. Soil carbon changes in areas undergoing expansion of sugarcane into pastures in south-central Brazil. *Agric. Ecosyst. Environ.* 228, 38–48. <https://doi.org/10.1016/j.agee.2016.05.005>.
- Panosso, A.R., Marques, J., Pereira, G.T., La Scala, N., 2009. Spatial and temporal variability of soil CO<sub>2</sub> emission in a sugarcane area under green and slash-and-burn managements. *Soil Tillage Res.* 105, 275–282. <https://doi.org/10.1016/j.still.2009.09.008>.
- Parkin, T., Mosier, A., Smith, J., Venterea, R., Johnson, J., Reicosky, D., Doyle, G., Mccarty, G., Baker, J., 2003. USDA-ARS GRACenet chamber-based trace gas flux measurement protocol. *Trace Gas Protoc. Dev. Comm.*
- Paustian, K., Parton, W.J., Persson, J., 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. *Soil Sci. Soc. Am. J.* 56, 476. <https://doi.org/10.2136/sssaj1992.03615995005600020023x>.
- Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO<sub>2</sub> emissions. *Soil Use Manage.* 13, 230–244. <https://doi.org/10.1111/j.1475-2743.1997.tb00594.x>.
- Potrich, D.C., Marchetti, M.E., Potrich, D.C., Ensinas, S.C., Serra, A.P., da Silva, E.F., de Souza, N.H., 2014. Decomposição de resíduos culturais de cana-de-açúcar submetidos a diferentes doses de nitrogênio. *Semin. Ciências Agrárias* 35, 1751. <https://doi.org/10.5433/1679-0359.2014v35n4p1751>.
- Razafimbelo, T., Barthès, B., Larré-Larrouy, M.C., De Luca, E.F., Laurent, J.Y., Cerri, C.C., Feller, C., 2006. Effect of sugarcane residue management (mulching versus burning) on organic matter in a clayey oxisol from southern Brazil. *Agric. Ecosyst. Environ.* 115, 285–289. <https://doi.org/10.1016/j.agee.2005.12.014>.
- Romero, E.R., Scandaliaris, J., Digonzelli, P., Alonso, L., Leggio-Neme, F., Giardina, J., Casen, S., Tonatto, J., Fernández de Ullivarri, J., 2007. Sugarcane potential trash estimation: variety and cane yield effect. *Proc. Int. Soc. Sugar Cane Technol.* 26, 421–425.
- Savario, C.F., Hoy, J.W., 2011. Microbial communities in sugarcane field soils with and without a sugarcane cropping history. *Plant Soil* 341, 63–73. <https://doi.org/10.1007/s11104-010-0622-9>.
- Serrano-Silva, N., Sarria-Guzmán, Y., Dendooven, L., Luna-Guido, M., 2014. Methanogenesis and methanotrophy in soil: a review. *Pedosphere* 24, 291–307. [https://doi.org/10.1016/S1002-0160\(14\)60016-3](https://doi.org/10.1016/S1002-0160(14)60016-3).
- Singh, J.S., Gupta, S.R., 1977. Plant decomposition and soil respiration in terrestrial ecosystems. *Bot. Rev.* 43, 449–528. <https://doi.org/10.1007/BF02860844>.
- Sopena, R.A., Mariotti, J.A., Terán, C.H., 2006. Variation and evolution of potential vegetative trash during the harvest season in the main sugarcane varieties at Tucumán, Argentina. 8th ISSCT Agricultural Engineering Workshop.
- Tesouro, O., Roba, M., Romito, Á., Fernandez de Ullivarri, E., Donato, L., Neiman, O., 2016. Cultivo de caña en Famaillá: Estudio de caso. *Propiedades físicas del suelo: Evolución e impacto en el rendimiento del cultivo*. Inf. Técnicos INTA.
- Valeiro, A.H., Acreche, M., 2014. Mejora de la eficiencia energética a partir de residuos de caña de azúcar. In: *Pascale Medina, C., Zubilliaga, M.M., Taboada, M.A. (Eds.), Suelos, Producción Agropecuaria y Cambio Climático: Avances En La Argentina*. Ministerio de Agricultura, Ganadería y Pesca de la Nación Argentina, Buenos Aires, Argentina, pp. 110–130.
- van Wesemael, B., Paustian, K., Meersmans, J., Goidts, E., Barancikova, G., Easter, M., 2010. Agricultural management explains historic changes in regional soil carbon stocks. *Proc. Natl. Acad. Sci. U. S. A.* 107, 14926–14930. <https://doi.org/10.1073/pnas.1002592107>.
- Vargas, V.P., Cantarella, H., Martins, A.A., Soares, J.R., do Carmo, J.B., de Andrade, C.A., 2014. Sugarcane crop residue increases N<sub>2</sub>O and CO<sub>2</sub> emissions under high soil moisture conditions. *Sugar Tech* 16, 174–179. <https://doi.org/10.1007/s12355-013-0271-4>.
- Wang, W.J., Reeves, S.H., Salter, B., Moody, P.W., Dalal, R.C., 2016. Effects of urea formulations, application rates and crop residue retention on N<sub>2</sub>O emissions from sugarcane fields in Australia. *Agric. Ecosyst. Environ.* 216, 137–146. <https://doi.org/10.1016/j.agee.2015.09.035>.
- Watanabe, T., Kimura, M., Asakawa, S., 2007. Dynamics of methanogenic archaeal communities based on rRNA analysis and their relation to methanogenic activity in Japanese paddy field soils. *Soil Biol. Biochem.* 39, 2877–2887. <https://doi.org/10.1016/j.soilbio.2007.05.030>.
- Wiedenfled, R.P., 1995. Effects of irrigation and N fertilizer application on sugarcane yield and quality. *Food Crop. Res.* 43, 101–108. [https://doi.org/10.1016/0378-4290\(95\)00043-P](https://doi.org/10.1016/0378-4290(95)00043-P).
- Yamaguchi, C.S., Ramos, N.P., Carvalho, C.S., Marlene, A., Pires, M., De Andrade, C.A., 2017. Sugarcane straw decomposition and carbon balance as a function of initial biomass and vinasse addition to soil surface. *Bragantia* 76, 135–144. <https://doi.org/10.1590/1678-4499.580>.