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

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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_2 and CH_4 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_2 and CH_4 during three consecutive growing seasons. The higher CO_2 emissions coincided with the period of high soil and air temperatures and rainfalls. There was not a clear pattern in the dynamics of CH_4 flux for all sugarcane treatments, while the native forest consistently captured CH_4; however, the cumulative CH_4 flows were negligible in term of C mass. Annual cumulative CO_2 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_2 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^{-1} yr^{-1}. 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_2 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_2) 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_4), 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_2 and CH_4 fluxes. Thus, the loss of soil C stock (as CO_2 and/or CH_4) 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_2 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_2 (Lal, 2004). For that reason, determinating 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_2 and CH_4 emissions/uptakes (i.e. representative data series) are needed.

Sugarcane (*Saccharum* spp.) is a high biomass crop that produces 5–16 Mg ha^{-1} (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_2 and CH_4 due to the decomposition of the organic matter remaining in the soil, while N fertilization could rebuild SOC by increasing it production (Alvarez, 2005; Paustian et al., 1992). Moreover, straw burning or removal and N input reduce soil C/N ratio increasing N_2O 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_2 and CH_4 emissions from the sugarcane-soil system, taking to 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_2 and CH_4 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_2 and CH_4 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^{-1}. 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^{-1} (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_2 and CH_4 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_2 and CH_4 concentrations were determined by gas chromatography by means of a flame ionization detector (GC 7890 A with autosampler 7697 A, Agilent Technologies, USA).

CO_2 and CH_4 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_2 and $r^2 \geq 0.7$ for CH_4. Results were expressed in mg CO_2-C m^{-2} h^{-1} and μg CH_4-C m^{-2} h^{-1}. Cumulative emissions, expressed as kg CO_2-C/CH_4-C ha^{-1} yr^{-1}, 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 × 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_2-C emissions (as CH_4 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_4 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 ≤ 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_2 and CH_4 fluxes by adjusting a mixed model. Likewise, ANOVAs were also performed for annual cumulative fluxes of CO_2 and CH_4. 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 ≤ 0.01) test was used for the comparison of mean values among treatments. The association among CO_2 or CH_4 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_2 emissions

There were significant differences among treatments, growing seasons and their interaction for mean CO_2 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_2 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_2 emissions (mg CO_2-C m^{-2} h^{-1}) for the interaction among treatments and growing seasons of sugarcane in Tucumán.

Treatment	CO_2 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_2 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_2 emission during the crop cycle: when N fertilizers were applied, the mean CO_2 emissions ranged from 16.9 ± 5.5 to 78.1 ± 6.4 and from 6.9 ± 3.0 to 106.1 ± 13.7 mg CO_2-C m^{-2} h^{-1} for the burnt and unburnt treatments, respectively. In the unfertilized treatments, the CO_2 emissions ranged from 12.9 ± 3.9 to 98.1 ± 20.3 and from 17.8 ± 2.9 to 115.3 ± 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_2 emissions. However, the rates of CO_2 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 growing season, respectively). This pattern was not true during the 2014–2015 growing season in which the rates of CO_2 of the native forest area were higher than that of the unburned 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_2 emissions

Treatments, growing seasons and their interaction significantly differed for annual cumulative CO_2 emission ($p < 0.001$) (Fig. 2).

The effect of straw on increasing the CO_2 emitted per growing season was much higher when N fertilization was performed. In fact, annual cumulative CO_2 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_2 during the

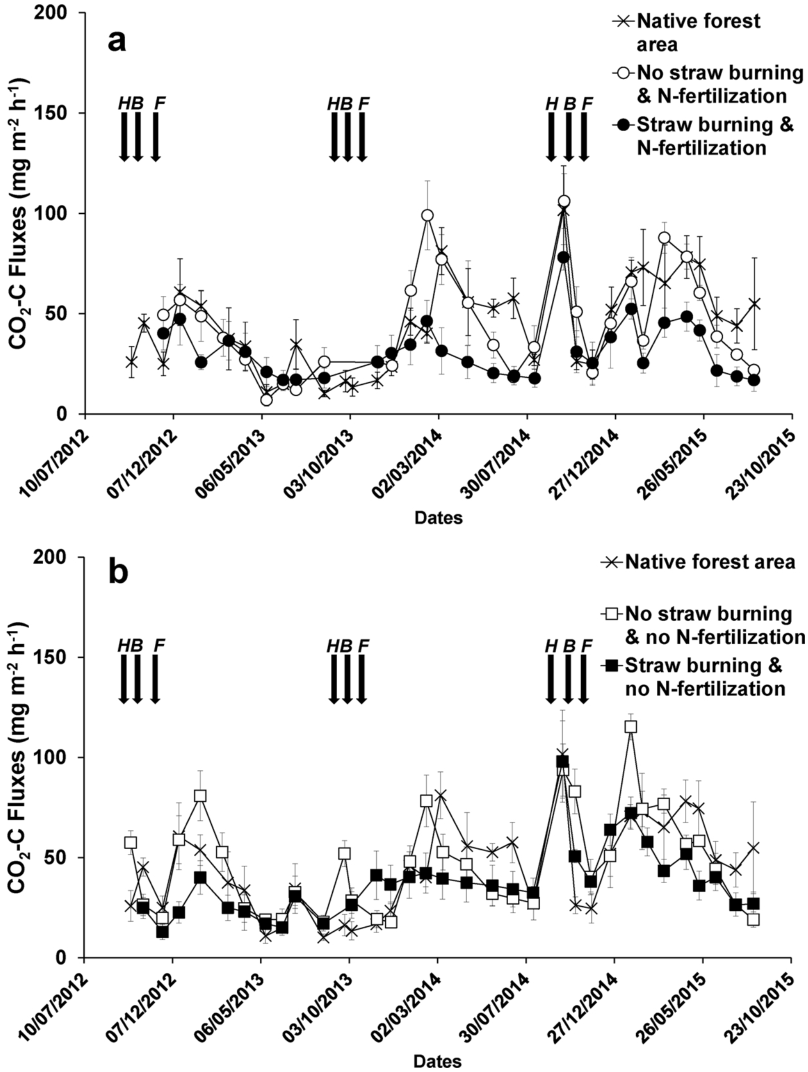

Fig. 1. Dynamics of CO_2-C emissions for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Arrows indicate harvest (H), burning (B) and N fertilization (F) dates. Bars represent the standard error.

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_4 fluxes

There were significant differences among treatments for mean CH_4 fluxes ($p < 0.0001$). Growing seasons and the interaction among treatments and growing seasons did not show difference for mean CH_4 fluxes ($p > = 0.1682$) (Table 2). In general, there were CH_4 uptakes in

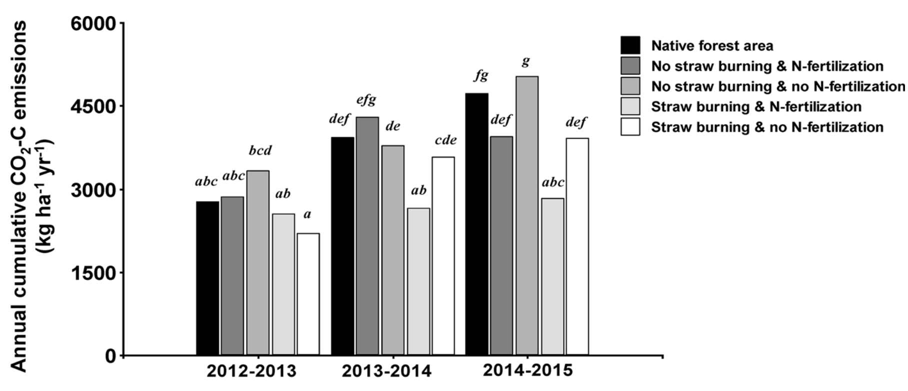

Fig. 2. Annual cumulative CO_2-C emissions for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Different letters indicate significant differences among mean values for the interaction among treatments and growing seasons according to ANOVA and Fisher's test at 0.01 level.

Table 2
Adjusted means and standard errors of CH_4 fluxes (μg m^{-2} h^{-1}) for all treatments in Tucuman.

CH_4-C Fluxes (μg m^{-2} h^{-1})				
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.

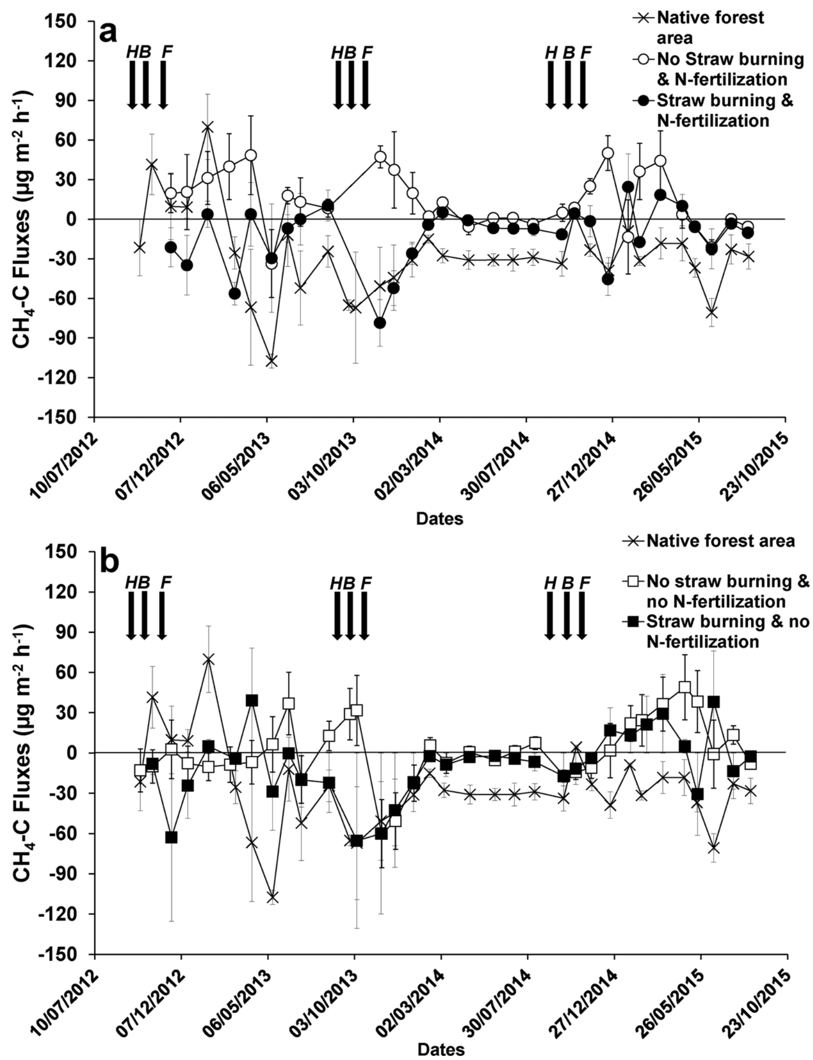

Fig. 3. Dynamics of CH_4-C fluxes for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Arrows indicate harvest (H), burning (B) and fertilization (F) dates. Bars represent the standard error.

the native forest and sugarcane burnt treatments (independently of N fertilization), while there were CH_4 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_4 from the sugarcane-soil system for the three growing seasons (Fig. 3a, b). Consistent CH_4 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_4 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_4 emissions until May (Fig. 3a, b). During winters, CH_4 emissions were low (nearby to zero) and steady in all sugarcane treatments. There was not a clear dynamic of CH_4 fluxes in the native forest area during the three growing seasons; however, significant uptakes of CH_4 were found ranging -107.5 ± 5.3 to 69.9 ± 24.7 μg CH_4-C m^{-2} h^{-1} (Fig. 3a, b).

The dynamics of CH_4 fluxes showed that the presence of straw increased CH_4 emissions when N fertilizers were applied: CH_4 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_4-C m^{-2} h^{-1} for the fertilized and unfertilized treatments, respectively. In the burnt treatments, the CH_4 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_4-C m^{-2} h^{-1} 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 fertilizes 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

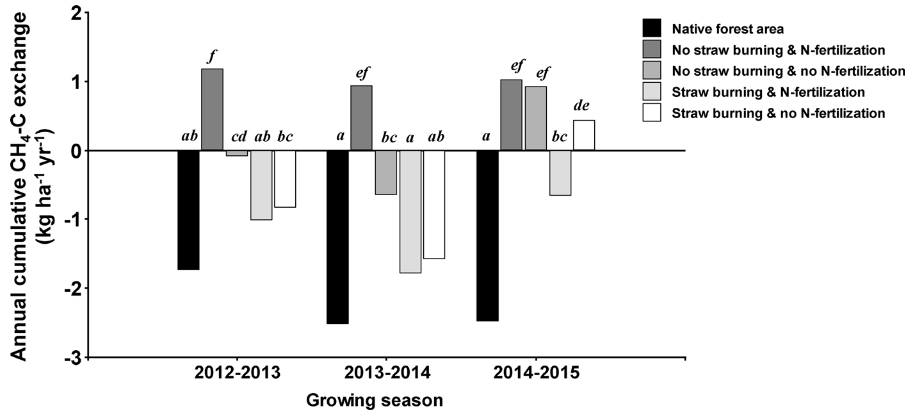

Fig. 4. Annual cumulative CH_4-C fluxes for the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. Different letters indicate significant differences among mean values for the interaction among treatments and growing seasons according to ANOVA and Fisher's test at 0.01 level.

CH_4-C $m^{-2} h^{-1}$ for the unburnt and burnt treatments, respectively (Fig. 3a, b). However, the rates of CH_4 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_4 emissions

Treatments, growing seasons and their interaction significantly differed for annual cumulative CH_4 emission ($p < 0.0001$) (Fig. 4).

The effect of N fertilization on the CH_4 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_4-C $ha^{-1} yr^{-1}$ 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_4 when a dry (2012–2013) and normal to dry (2013–2014) growing season occurred; however, the N fertilization increased the annual CH_4 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_4 uptake of -0.66 kg of CH_4-C $ha^{-1} yr^{-1}$, whereas the burnt and unfertilized treatment showed a cumulative CH_4 emission of 0.44 kg of CH_4-C $ha^{-1} yr^{-1}$ (Fig. 4).

It is important to note that the cumulative CH_4 flows were negligible in term of C mass (Fig. 4).

3.5. Associations among CO_2 or CH_4 fluxes and environmental conditions

Although CO_2 and CH_4 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_2 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_2 fluxes were temperature and soil moisture. Although the interactions among these variables could contribute to explain the CO_2 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_4 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_4 pattern was poorly related to climate variables but it was associated with soil physic properties.

Table 3
Correlation coefficients among fluxes of CO_2-C or CH_4-C and environmental variables of sugarcane in Tucuman.

Variables	n	Pearson's coefficients CO_2-C (mg $m^{-2} h^{-1}$)	CH_4-C (μg $m^{-2} h^{-1}$)
C-CH_4 (μg $m^{-2} h^{-1}$)	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_3 content	489	0,12 (**)	−0,01 (ns)
NH_4 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 $ha^{-1} yr^{-1}$) 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 $ha^{-1} yr^{-1}$). Conversely, straw conservation promoted a net C gain of 2.03 and 0.66 (Mg C $ha^{-1} yr^{-1}$) 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_2-C output in the unburnt and burnt treatments, respectively.

4. Discussion

4.1. CO_2 fluxes

The pattern of CO_2 fluxes during the growing seasons reflected the specific conditions of the climate-soil-sugarcane system of Tucuman: the highest CO_2 emissions corresponded to the period of high air and soil temperatures, high rainfalls and soil moisture. Many studies agree that CO_2 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_2 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 season in Tucuman.

	Treatments			
	No straw burning & N fertilization Mean C flows (Mg C ha^{-1} yr^{-1})	No straw burning & no N fertilization	Straw burning & N Fertilization	Straw burning & no N fertilization
C input from straw* and root system**	5.73 *a*	4.71 *a*	1.33 *b*	1.13 *b*
C output (CO_2-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^{-1} (Bolinder et al., 1999; Carvalho et al., 2013).

and the straw decomposition effect on CO_2 emissions from November to March. In fact, the highest rates of CO_2 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_2 production, especially in the rainy season. The relevance of soil moisture on CO_2 emissions was also reported by Panosso et al. (2009) and Vargas et al. (2014).

On the other hand, CO_2 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_2 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_2 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_2 emissions. De Klein et al. (2006) reported that fertilizing sugarcane with urea led to an extra loss of CO_2, while Vargas et al. (2014) did not find a significant N effect (21 kg N ha^{-1}) on sugarcane soil respiration. However, our results showed that unfertilized treatments had higher annual cumulative CO_2 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_2 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_2 emissions (De Klein et al., 2006). Hence, N fertilization could have the effect of reducing CO_2 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_4 fluxes

The dynamic of CH_4 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_2 (−1.8 to 1.1 kg CH_4-C ha^{-1} yr^{-1}). The environmental conditions also affected the CH_4 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_4 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_4 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_4 emission close to 1 kg CH_4-C ha^{-1} in all growing season. Vargas et al. (2014) reported uptakes and emissions of CH_4 that resulted in negligible cumulative net fluxes (values close to zero). Le Mer and Roger (2001) appreciated large variability in CH_4 fluxes; however, they reported that aerated soils oxidize (uptake) more CH_4 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_4 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_4 fluxes.

The native forest consistently uptakes CH_4, although the annual mean uptake was relatively low (−2.2 kg C−CH_4 ha^{-1} yr^{-1}). In fact, forests are considered important sinks of CH_4 (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_4 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^{-1} yr^{-1}, similar to those reported by assessing soil C stocks in Brazil (Cerri 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_2O emissions (Chalco Vera et al., 2017; Eustice et al., 2011). In fact, Lugato et al. (2018) reported that the variation in N_2O 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_2 that are produced at the moment of performing soil management practices. This means that the abrupt increase of CO_2 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_2 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_2 emissions were for all sugarcane treatments and native forest. Maintaining straw (unburnt straw treatments) increased the annual cumulative CO_2 emissions during the crop cycle. N fertilization decreased the annual cumulative CO_2 emissions during the crop cycle, mainly when the straw was burned. The annual cumulative CO_2 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_4 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_4.

CO_2 fluxes were associated to climate variables or variables that directly depend on climate (temperature and soil gravimetric content), while CH_4 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^{-1} yr^{-1} when the crop straw is unburnt and fertilized with 110 kg of N ha^{-1} 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.

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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.

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