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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