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Effects of sugarcane trash burning and nitrogen fertilization on soil-carbon balances in Argentina

J Chalco Vera[1,2], L Erazzú[3] and M Acreche[1,2]

[1]*Instituto Nacional de Tecnología Agropecuaria, EEA Salta. Ruta Nac. 68, Km 172, Cerrillos (4403) Salta, Argentina*; chalcovera.jorge@inta.gob.ar

[2]*CONICET, Argentina*

[3]*Instituto Nacional de Tecnología Agropecuaria, EEA Famaillá. Ruta Prov. 301, Km 32, 4132 Famaillá, Tucumán, Argentina*

Abstract Sugarcane leaves a huge amount of trash in the field trash at harvest that could be used for co-generating additional energy and to prevent burning of it in the field. However, a sustainable criterion for trash extraction based on its impact on soil C and/or GHG emissions is still required. The dynamic of C emissions as carbon dioxide (CO_2) and methane (CH_4) from the sugarcane-soil system was assessed in order to quantify C outputs and to determine and discuss a theoretical soil-C balance. A field experiment during three consecutive growing seasons of sugarcane was carried out at Tucuman, Argentina. Measurements of CO_2 and CH_4 fluxes from the sugarcane-soil system were performed through the static (close-vented) chambers method. Theoretical soil-C balances were estimated by the difference between the carbon returning into the soil mainly by sugarcane trash and the C that leaves the system in the form of cumulative C emissions. The main CO_2 fluxes were higher in the November-March period (the rainy and warm period) ranging from 25.1 ± 5.6 to 71.5 ± 13.0 mg CO_2-C m^{-2} h^{-1}, being boosted by trash presence. There were positive and negative fluxes of CH_4 that resulted in negligible cumulative values for all sugarcane systems. Trash burning resulted in negative soil carbon balances: -1.35 and -2.11 t C ha^{-1} yr^{-1} for the fertilized and unfertilized treatments, respectively. Thus, trash burning transforms the C sequestration capacity of the sugarcane-soil system of Tucumán in a C-emitting system gradually depleting the C of the soil. Our results suggest that retaining the amount of trash necessary for maintaining soil organic C (balance = zero) is an approach that could be used as a criterion for avoiding soil-C depletion.

Key words Carbon sequestration, global warming, greenhouse gas emissions, mitigation

INTRODUCTION

Sugarcane (*Saccharum* spp.) is a high biomass crop used worldwide as a feedstock to produce sugar and bioethanol. This crop represents a source of energy of low carbon (C) emissions (IPCC 2014) that could be used for mitigating global warming generated by traditional fuels. At harvest, large amounts of trash provide a possible resource for cogenerate production of electrical energy in sugar mills. However, a sustainable criterion for trash extraction, based on its impact on soil and/or GHG emissions, is still required. Paradoxically, in-field burning of sugarcane trash - as in many sugarcane-producing countries - frequently occurs in Argentina. In fact, despite legal restrictions, post-harvest burning of trash still occurs.

Trash represents a substantial input of C and nitrogen (N) to the soil. Thus, trash burning or removal reduces the soil C/N ratio and increases N_2O emissions (Chalco Vera *et al.* 2017), modifying the potential mitigation of GHG emissions offered by sugarcane as a bioenergy crop (Beeharry 2001; Carvalho *et al.* 2017). In addition, 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 trash burning and N fertilization practices are needed in order to evaluate the sustainability of the sugarcane crop in Tucuman.

In order to enhance the sustainability of sugarcane trash management practices, the specific objectives of this study were to: i) Determine the effects of post-harvest trash burning and synthetic N fertilization on the emission rates of CO_2 and CH_4 and on a theoretical balance of soil C based on measured C emissions; and ii) Suggest and discuss a sustainable criterion for trash extraction and use based on the impacts evaluated in the first objective.

MATERIALS AND METHODS

General

A field experiment was carried out at the Famailla Experimental Station of the National Institute of Agricultural Technology (INTA) in Tucuman, Argentina, during three growing seasons (September 2012 to September 2015). The rainfall totals during the 2012/13, 2013/14 and 2014/15 crops were 1040, 1102 and 1638 mm, respectively.

The experimental area had a history of at least 50 years of sugarcane mono-cropping. The soil was classified as an Aquic Argiudoll and the content of sand, silt and clay on the top 20 cm layer was 15, 54 and 31%, respectively, with 2.6% of organic matter and a pH of 6 in the top 20 cm. The crop was harvested mechanically every year. At the beginning of the experiment (September 2012), the total amount of trash left on the soil surface postharvest was in average 12.23 t ha^{-1} of dry matter. After harvesting, the following treatments were applied in a strip-plot design: i) trash burning and N fertilization; ii) trash burning and no N fertilization; iii) no trash burning and N fertilization; and iv) no trash burning and no N fertilization. Each sugarcane plot consisted of six 100-m long rows, with 1.60 m row spacing.

Nitrogen fertilization (110 kg N ha^{-1}) was applied in furrows with solid urea incorporated to a depth of 10 cm in the plant row.

Sampling and measurements

Greenhouse gases were captured through closed-vented chambers. Chambers consisted of a rectangular polyvinyl chloride head (715 m^{-2} f area and 15 cm height) covered by a light-reflecting film and vented with a 10-cm-long stainless steel tube (Parkin and Venterea 2010) and an iron frame previously inserted to 8 cm-depth into the soil to couple the head during the deployment time. Gas samplings were conducted monthly throughout the growing season starting 12 days after harvest. The field sampling procedure was described by Chalco Vera *et al.* (2017). CO_2 and CH_4 concentrations were determined by gas chromatography.

In order to calculate CO_2 and CH_4 fluxes from the change in the concentration of each GHG by time in the chambers, a linear regression between gas concentrations and sampling time (Parkin *et al.* 2003) was used to determine GHG fluxes. 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.

Theoretical balance of soil C

This balance was estimated with the variability of soil organic carbon (SOC) content considering differential rates of C inputs and outputs. Carbon inputs were calculated from the C in the trash (our data) and the C contents reported by Digonzelli *et al.* (2011). Carbon in roots was estimated by Bolinder *et al.* (1999) and Carvalho *et al.* (2013). Soil CO_2-C emissions were considered to be C-outputs and CH_4 emissions were negligible in terms of mass.

The trash in unfertilized treatment plots was reduced by 20% annually due to an assumed N deficiency (Fogliata 1995). The average amount of trash in the treatment plots that received N fertiliser were maintained at levels found in the first crop. Any decreases in yield/trash due to trash burning were considered negligible in all three crops. Carbon emissions as GHG during trash burning were not considered a direct loss during the crop cycle as this C was previously produced by crop photosynthesis.

Statistical analysis

Analyses of variance (ANOVA) were performed on the CO_2 emission data and annual cumulative CO_2 emissions using an adjusted mixed model. One-way ANOVAs were used for estimations of annual C inputs and annual C balances by considering only the treatments as sources of variability and using growing seasons as replicates. A

Fisher's (*p-value*≤ 0.01) test was used for the comparison of means among treatments. InfoStat software (Di Rienzo *et al.* 2014) was used.

RESULTS

Emission rates of CO_2

There were positive emission rates of CO_2 from the sugarcane-soil system for the three growing seasons (Table 1). 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 in the 2014-2015 growing season that extends the period of high CO_2 emissions until May (Table 1).

Despite the large ranges of monthly fluxes, mean CO_2 emissions showed significant differences among treatments (F=4.2, p=0.0079), growing seasons (F=10.6, p=0.0001) and periods (F=18.4 p<0.0001). However, there were no significant interactions among them. The presence of trash increased CO_2 emission during the crop cycle: when N fertilizers were applied, the mean CO_2 emissions ranged from 20.8 ± 2.7 to 44.81 ± 16.7 and from 17.4 ± 4.0 to 59.2 ± 25.0 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 18.9 ± 6.0 to 62.3 ± 18.3 and from 22.7 ± 2.8 to 72.4 ± 16.3 mg CO_2-C m^{-2} h^{-1} for the burnt and unburnt treatments, respectively (Table 1). We note that the higher the rainfall during the growing season, the greater the differences among treatments.

Annual cumulative CO_2 emissions

The main cumulative C emissions (outputs) were not significantly different among treatments. However, there was a stronger influence of trash management on the cumulative CO_2 differences between burnt and unburnt treatments. However, the effect of trash on increasing the CO_2 emitted per growing season was much higher when N fertiliser was applied (Figure 1). Annual cumulative CO_2 emission was 12.4 to 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 to 51.5% higher than the burnt and unfertilized treatment.

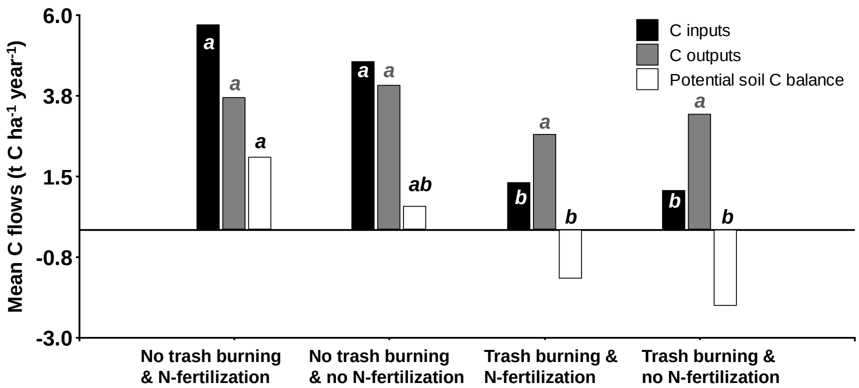

Figure 1. Average carbon flows and theoretical soil-Carbon balances generated with inputs and outputs of carbon into the soil under different sugarcane-soil management systems for three consecutive growing seasons in Tucuman. Different letters indicate significant differences among treatments according to one-way ANOVA and Fisher's test at 0.01 level. For C input and C balance, only treatments were considered as a source of variability (using growing seasons as replicates).

Table 1. Mean CO_2-C and CH_4-C emission rates and standard errors for the September to November, November to March and April to August periods in the 2012–2013, 2013–2014 and 2014–2015 growing seasons of sugarcane in Tucuman, Argentina. CO_2 and CH_4 rates were expressed in mg CO_2-C m^{-2} h^{-1} and µg CH_4-C m^{-2} h^{-1}, respectively.

Growing season	Period	No trash burning & N-fertilization		No trash burning & no N-fertilization		Trash burning & N-fertilization		Trash burning & no N-fertilization	
		CO_2-C	CH_4-C	CO_2-C	CH_4-C	CO_2-C	CH_4-C	CO_2-C	CH_4-C
2012-2013	September to November	-	-	34.6 ± 11.6	-6.7 ± 4.8	-	-	18.9 ± 6.0	-35.4 ± 27.4
	November to March	48.2 ± 3.9	27.9 ± 4.8	53.1 ± 12.6	-5.9 ± 2.9	37.4 ± 4.5	-27.22 ± 12.6	25.1 ± 5.6	-21.6 ± 15.1
	April to August	17.4 ± 4.0	10.8 ± 13.1	22.7 ± 2.8	5.9 ± 9.6	20.8 ± 2.7	-4.5 ± 6.9	20.6 ± 2.8	-6.5 ± 12.3
2013-2014	September to November	-	-	33.3 ± 9.7	0.2 ± 30.1	-	-	33.8 ± 7.4	-62.7 ± 2.7
	November to March	57.5 ± 14.6	23.8 ± 8.2	43.2 ± 11.3	-27.0 ± 12.5	33.7 ± 3.4	-31.2 ± 15.4	40.0 ± 1.0	-27.1 ± 10.7
	April to August	35.3 ± 7.6	-1.9 ± 1.7	33.9 ± 4.4	0.9 ± 2.6	20.8 ± 1.8	-5.5 ± 1.6	35.1 ± 1.1	-4.0 ± 0.9
2014-2015	September to November	59.2 ± 25.0	12.8 ± 6.2	72.4 ± 16.3	-14.1 ± 1.8	44.8 ± 16.7	-2.9 ± 4.6	62.3 ± 18.3	-10.9 ± 3.9
	November to March	51.2 ± 11.7	28.4 ± 11.3	71.5 ± 13.0	14.7 ± 8.5	37.3 ± 5.4	-4.3 ± 12.7	55.1 ± 6.4	15.3 ± 5.5
	April to August	45.8 ± 10.4	-5.8 ± 4.2	41.0 ± 7.9	18.4 ± 11.0	29.5 ± 6.5	-6.4 ± 5.3	36.3 ± 4.7	-0.7 ± 11.4

Emission rates of CH_4

There were negative and positive rates (uptakes and emissions, respectively) of CH_4 from the sugarcane-soil system for the three growing seasons (Table 1). There was no clear dynamic for CH_4 emission rates across the treatments; significant CH_4 emissions were found only for the unburnt and fertilized treatment from November to March in all growing seasons, coinciding with the period of high temperatures (soil and air temperatures) and rainfalls. During winters (April to August period), CH_4 emissions were low (nearby to zero) and steady in all sugarcane treatments.

Annual cumulative CH_4 fluxes

Cumulative CH_4 flows were negligible in term of C mass: mean cumulative fluxes ranged from -1.79 ± 0.08 to 1.18 ± 0.1 kg CH_4-C ha^{-1} yr^{-1} for sugarcane treatments and differences among them were inconsistent throughout all growing seasons studied (data not shown).

Theoretical soil-C balance

There were significant differences among treatments for the soil-C balance ($p< 0.01$) (Figure 1). It appeared that application of N fertiliser promoted soil-C gain, with the unfertilized treatments producing the worst scenarios (particularly when trash was burned; soil-C loss of 2.11 Mg C ha^{-1} yr^{-1}). In N-fertilised treatments, trash burning practice led to mean net C loss of 1.35 (Mg C ha^{-1} yr^{-1}). Conversely, trash conservation promoted a net C gain of 2.03 and 0.66 (Mg C ha^{-1} yr^{-1}) for fertilized and unfertilized treatments, respectively (Figure 1). When trash was retained without burning (without considering C emissions at the moment of burning), C output during the growing season were 38 and 25% higher than when the trash was burnt for the fertilized and unfertilized treatments, respectively. In comparison to unfertilized treatments, N fertilization resulted in decreases of 8.5 and 17% in CO_2-C output in the unburnt and burnt treatments, respectively.

DISCUSSION

Our results showed that the main CO_2 fluxes were higher between November and March (the rainy and warm period). The CO_2 emissions were steady and lower during the dry and cold period (April to August) and moderately higher prior to summer (September and November). This probably was associated with the strong influence of the seasonal soil temperature on CO_2 formation processes (Kirschbaum 1995) and with the soil moisture variations (Moitinho *et al.* 2015). In addition, the differences in CO_2 emissions between burnt and unburnt treatments were boosted by the C availability due to sugarcane trash decomposition mainly from November to March of each year. However, we demonstrated that C outputs did not always offset C inputs. This means that it is possible to determine the minimal amount of trash necessary for keeping or increasing soil C. Thus, management practices that avoid burning or an indiscriminate extraction of trash could be effective for mitigating the global emissions of GEI by anthropogenic sources. In addition, our results showed that unfertilized treatments had higher annual cumulative CO_2 emissions than N-fertilized treatment. Hence, the application of N fertilizer could have an effect of reducing CO_2 losses or increasing C storage. However, its impact on N_2O emissions should be considered when selecting the rate of N to be applied (Chalco Vera *et al.* 2017).

The C balance of the treatment with no trash burning and application of N fertilizer was 2.03 Mg of C ha^{-1} yr^{-1}, similar to those reported when soil-C stocks were assessed in Brazil (Cerri *et al.* 2011; Oliveira *et al.* 2016). Our results suggest that performing C flow measurements could be viable short-term alternatives to determining soil-C balances in agro-ecosystems. However, this methodology does not replace studies that assess the dynamics of the SOC in the long-term rather they complement it. Moreover, there are reports that show that C gains in sugarcane soils without burning would be lower than those reported here (Razafimbelo *et al.* 2006; Galdos *et al.* 2009). However, it is important to note that the balance of C that we present could be underestimating the losses of C as CO_2 when performing soil management practices and by assuming a fixed combustion efficiency of trash (80%, recommended value by the IPCC). Therefore, the values of the potential loss of SOC estimated in our study could be higher or lower depending on the efficiency of trash burning.

CONCLUSIONS

Our results demonstrate the importance of considering management practices when measuring CO_2 fluxes in soil-C balance studies during the crop cycle. We mainly showed that the burning of trash can cause negative soil-C balance. Avoiding trash burning results in a positive soil-C balance, which can maintain, restore or increase SOC, respectively. This criterion could reduce C losses during the agricultural phase of the bioethanol production by restoring or avoiding the gradual loss of soil C.

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Effets du brulage du paillis de canne à sucre et de la fertilisation en azote sur les équilibres sol-carbone en Argentine

Résumé. La canne à sucre laisse une énorme quantité de paille dans les champs au moment de la récolte, qui pourrait être utilisé pour générer de l'énergie et éviter de la brûler dans les champs. Cependant, un critère durable pour l'extraction du paillis basé sur son impact sur le C du sol et / ou les émissions GES est nécessaire. La dynamique des émissions de C sous forme de dioxyde de carbone (CO_2) et de méthane (CH_4) provenant du système terre-canne à sucre a été évaluée afin de quantifier les émissions de C et de déterminer et discuter un bilan théorique C-sol. Une expérience sur le terrain pendant trois saisons de pousses consécutives de canne à sucre a été réalisée à Tucuman, en Argentine. Les mesures des flux de CO_2 et de CH_4 du système canne à sucre-sol ont été effectuées par la méthode des chambres statiques (fermées - ventilées). Les bilans théoriques du sol en carbone ont été estimés à partir de la différence entre le carbone retourné au sol, principalement par le paillis de canne à sucre, et le carbone qui quitte le système sous forme d'émissions cumulées de carbone. Les principaux flux de CO_2 étaient plus élevés entre novembre et mars (période pluvieuse et chaude), allant de 25,1 ± 5,6 à 71,5 ± 13,0 mg CO_2-C m -2 h -1, amplifiés par la présence du paillis. Des flux positifs et négatifs de CH_4 ont entraîné des valeurs cumulatives négligeables pour tous les systèmes de production de canne à sucre. Le brulage du paillis a entraîné des bilans négatifs en carbone du sol: -1,35 et -2,11 t C ha^{-1} an^{-1} respectivement pour les traitements fertilisés et non fertilisés. Ainsi, le brulis du paillis transforme la capacité de séquestration du carbone du système canne à sucre-sol de Tucumán en un système émetteur de carbone qui épuise progressivement le carbone du sol. Nos résultats suggèrent que la conservation de la quantité de paillis nécessaire au maintien du carbone organique du sol (solde = zéro) pourrait être utilisée comme critère pour éviter l'épuisement du carbone dans le sol.

Mots-clés: Séquestration du carbone, réchauffement de la planète, émissions de gaz à effet de serre, atténuation

Efectos de la quema de caña de azúcar y la fertilización nitrógenada en los balances de carbono del suelo en Argentina

Resumen. En la cosecha, la caña de azúcar deja una alta cantidad de rastrojo que se promueve para ser utilizada en la cogeneración de energía adicional y evitar la práctica de quema de rastrojo. Sin embargo, todavía se requiere un criterio sostenible para la extracción del rastrojo en función de su impacto en el contenido de carbono (C) del suelo y/o las emisiones de gases con efecto invernadero (GEI). El objetivo de este estudio fue evaluar la dinámica de las emisiones de C, en forma de dióxido de carbono (CO_2) y metano (CH_4), del sistema suelo-caña de azúcar, con el fin de cuantificar las salidas de C y determinar y discutir los balances teóricos del C del suelo. Se llevó a cabo un experimento a campo durante tres ciclos consecutivos de caña de azúcar en Tucumán, Argentina. Las mediciones de los flujos de CO_2 y CH_4 del sistema suelo-caña de azúcar se realizaron a través del método de cámaras estáticas (con ventilación cerrada). Los balances teóricos del C de suelo se estimaron por la diferencia entre el C que retorna al suelo principalmente por el rastrojo de la caña de azúcar y el C que sale del sistema en forma de emisiones acumuladas de C. Los flujos medios de CO_2 fueron más altos en el período de noviembre a marzo (el período de lluvias y cálido) oscilando entre 25,1 ± 5,6 y 71,5 ± 13,0 mg C-CO_2 m^{-2} h^{-1}, potenciado por la presencia de rastrojo. Hubo flujos positivos y negativos de CH_4 que dieron lugar a valores acumulativos insignificantes para todos los sistemas de caña de azúcar. La quema de rastrojo produjo balances negativos de carbono en el suelo: -1,35 y -2,11 t C ha^{-1} $año^{-1}$ para los tratamientos fertilizados y no fertilizados, respectivamente. Por lo tanto, se demostró que la quema de rastrojo transforma la capacidad de secuestro de C del sistema suelo-caña de azúcar de Tucumán en un sistema de emisión de C que empobrece gradualmente el C del suelo. Nuestros resultados sugieren que mantener la cantidad de rastrojo necesaria para mantener el C orgánico del suelo (balance= cero) es un enfoque que podría utilizarse como criterio para la extracción y uso sostenibles del rastrojo, mitigando las emisiones de C y evitando el agotamiento de C del suelo.

Palabras clave: Calentamiento global, emisiones de gases de efecto invernadero, mitigación, secuestro de carbono