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Sugarcane residue management impact soil greenhouse gas

Impacto do manejo do resíduo de cana-de-açúcar na produção potencial de gases do efeito estufa no solo

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ABSTRACT

Mechanized sugarcane harvest is replacing the historic practice of field burning, due to environmental concerns of the particulate and emissions during burning. However, the impact of these practices on soil greenhouse gas (GHG) production potential is not fully known. Thus, the present work quantified the potential production, in 1 g of soil, of greenhouse gases (GHG) in three systems of sugarcane management. The systems were: area with a history of burning sugarcane before harvest (B) and another with two systems of management of "green sugarcane" in two periods of implantation - 5 (G-5) and 10 years (G-10). A laboratory incubation experiment was used to assess the production potentials of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) in 1g of soil samples by the different sugarcane management systems. The results of this study demonstrate that the sugarcane management systems had an impact on the potential production of CO2 in the soil. In addition, when the results of gases were divided from convex and concave areas, differences in CO2 patterns between areas B and G-10 were observed, with greater emission in the G-10 area, probably due the residue on the soil surface.

Index terms: *Sacharium officinarium*; slope; CO_2; N_2O; CH_4.

RESUMO

O sistema de colheita mecanizado da cana-de-açúcar têm substituido o sistema de queima do canavial devido a preocupações ambientais como a emissão de partículas durante a queima e diversos malefícios ao solo. O impacto dessa prática no potencial de produção de gases do efeito estufa (GEE) no solo ainda demanda estudo. Assim, o presente trabalho quantificou a produção potencial, em 1 g de solo, de gases do efeito estufa em três sistemas de manejo de cana-de-açúcar. As áreas avaliadas foram: uma com histórico de queima do canavial antes da colheita (B) e outras com duas com sistemas de manejo de "cana crua" em dois períodos de implantação - 5 (G-5) e 10 anos (G-10). Um experimento de incubação em laboratório foi montado para avaliar os potenciais de produção de dióxido de carbono (CO_2), óxido nitroso (N_2O) e metano (CH_4) em de 1g de amostras de solo nos diferentes sistemas de manejo de cana-de-açúcar. Os resultados deste estudo demonstram que os sistemas de manejo de cana-de-açúcar apresentaram impacto na produção potencial de CO_2 no solo. Além disso, quando dividiu-se os resultados de gases oriundos de áreas convexas e concavas, observou-se diferenças nos padrões de CO_2 entre as áreas B e G-10, with greater emission in the G-10 area, possivelmente devido a presença de palhada na superífice do solo.

Termos para indexação: *Sacharium officinarium*; declividade; CO_2; N_2O; CH_4.

INTRODUCTION

The management of crop residues has significant implications on the agronomic and economic aspects of sugarcane production. The historic technique of burning sugarcane fields prior to harvest (to facilitate cutting) was popularized in the 1940s. The temperature during sugarcane burning is around 160-200 °C at the soil surface, causing volatilization of soil nutrients such as phosphorus, sulfur and nitrogen (Britts; Silva; Abrita, 2016). It has been estimated that each 1 Mg of sugarcane burned releases 0.004 Mg of black carbon aerosols, as well as additional organic contaminants into the atmosphere (Macedo; Nogueira, 2014). This can lead to harmful human health impacts in surrounding populations (Paraiso; Gouveia, 2015). In response to these detrimental environmental effects, since 2000 (São Paulo state law number 11.241/2002), there has been a shift toward what is known as "green sugarcane harvesting", which leaves the biomass residues in the field, thus burning should be gradually until 2021. Currently, the Sugarcane Industry Association of Brazil (UNICA) established a more aggressive target which will eliminate totally sugarcane burning in 2017 in the São Paulo state.

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In addition to the direct health and climate impacts, burning also reduces the amount of plant nutrients that are returned to the soil. Not only are large quantities of organic carbon (C) are lost in the burning process, it also leads to lower soil N content, reduced microbial biomass, which can decrease yields compared to the maintenance of the crop residues in the soil surface (Souza et al., 2012). Another benefit is the decreased greenhouse gas (GHG) footprint of green harvest systems, largely from reducing the aerosol and particulate emissions (Oliveira Bordonal; Figueiredo; La Scala, 2011).

The authors have discussed the important influence of topography on soil GHG potentials, specifically CO_2, N_2O and CH_4 (Braum et al., 2013). Topographically low areas (those with a concave structure) are likely to collect surface run-off and thereby increase the amount of infiltrating moisture to the soil microbial population, resulting in higher rates of carbon mineralization and CO_2 emissions (Brito et al., 2010). Greater N_2O emissions observed in the topographically low positions have primarily been linked to higher soil moisture increasing the number of anaerobic sites and higher denitrification rates, which is directly linked to higher N_2O production (Vilain et al., 2010). Topographically high regions are thought to have higher rates of CH_4 oxidation and footslopes (low regions) are generally regions of reduced oxidation, consequently, increases CH_4 production, again due the increase soil moisture (Ball et al., 2013). Topographic research on the variability of CH_4 emissions has primarily focused on bogs (Algan et al., 2015) and landfills (Di Trapani; Di Bella; Viviani, 2013), since arable soils are more commonly CH_4 oxidizing environments (Flessa et al., 2008).

The influence of management practices on GHG emissions associated with sugarcane production has been the focus of numerous studies comparing conventional to reduced tillage (Packer et al., 2015), increasing soil organic matter (Oliveira et al., 2013), fertilizer applications (Signor; Cerri; Conant, 2013) and crop rotations (Oliveira Bordonal et al., 2013). The current studies that have examined alterations in the GHG balances have used life-cycle approaches. Converting sugarcane areas from burned to green harvest could reduce GHG emissions by 310.7 (not considering soil C sequestration) to 1484.0 kg CO_2 equiv. ha^{-1} y^{-1} (considering C sequestration) (Figueiredo; La Scala, 2011).

With the phase out of sugarcane burning already underway, the objective of this study was to determine the effect of sugarcane fields under conventional burning and green sugarcane systems and the influence of slope (convex and concave) on GHG production potential.

MATERIAL AND METHODS

Study area and treatments

This study focused on three areas of sugarcane cultivation to compare burn vs. green harvest management practices and was conducted on a sugarcane (*Saccharum spp.*) plantation, located in the municipality of Pradópolis, São Paulo state, Brazil (21.362° S; 48.07° W). Three fields were selected with a different residue management history (Table 1), but the same soil type (Latossolo Vermelho – Brazilian Classification) at three fields (Haplustox, USDA Soil Taxonomy). The regional climate is classified as B_2rB’4a’ by Thornthwaite system, indicating a mesothermal

Table 1: Soil characterization in the three management areas of burned sugarcane (B), green sugarcane for five years (G-5) and green sugarcane for ten years (G-10).

Field Site	B	G-5	G-10
Average slope (%)	4.0	3.7	4.1
Year of conversion	--	2006	2001
	(>25 yr burned)	(5 years*)	(10 years*)
Convex area (m)	642	507	525
Concave area (m)	638	503	508
Organic carbon (g kg^{-1})	2.3	2.5	2.0
Cation exchange capacit ($cmol_c$ dm^{-3})	15.06	10.29	8.43
pH $CaCl_2$	5.2	4.8	4.9
Phosphorus (mg dm^{-3})	16.66	36.3	35.55
Sulfur (mg dm^{-3})	0.81	0.82	0.51
Calcium ($cmol_c$ dm^{-3})	9.0	4.21	3.44

region with rainy summers and dry winters. The mean annual precipitation is approximately 1425 mm and is concentrated between October and March. The three areas presented differentiated slopes, with convex (high altitude) and concave points (low altitude) as described in Table 1.

The burned sugarcane site (B) (slope = 4%), where plants were burned prior to harvest since the 1980s, was selected along with two green sugarcane harvest (without burn) sites; one that started the green sugarcane systems in 2006, called green sugarcane for 5 years (G-5) (slope = 3.7%) and the other cultivated green sugarcane since 2001, called green sugarcane for 10 years (G-10) (slope = 4.1%). Both G-5 and G-10 had previously used the traditional burning management practices prior to the switch to green harvesting. Besides the residue management, there were no other differences between these fields (i.e., fertilization, weed control, tillage).

To characterize spatial variability within each field, a 10,000 m^2 (1 ha) area was selected (100 x 100 m) and sampled with an 81-point grid was established in each field post-harvest (Figure 1). Soil samples were collected at 0-10 cm soil depths for all points on the grid to give a total of 243 individual soil samples (81 points x 3 areas). All samples were air dried outside for 1 week and sequentially stored in plastic bags.

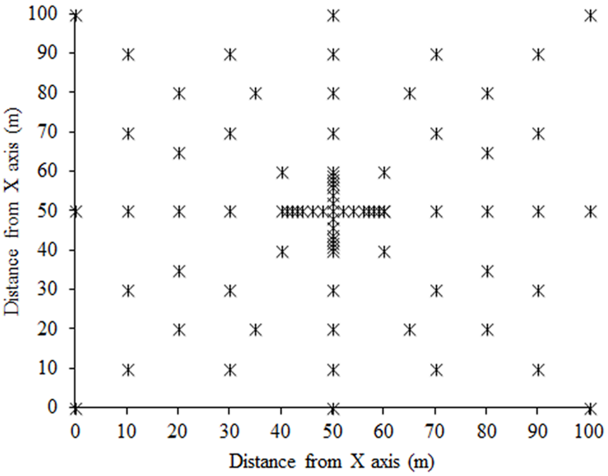

Figure 1: Sampling grid with 81 point spaced in 1, 2 and 10 m.

CO_2 flux measurement in field

CO_2 flux measurement in field was simultaneously performed in all areas using three chambers at all sampling grid points, during 10 days in August, 2011 at the mornings (7-11 a.m.) to standardization using soil chambers manufactured by LI-COR® model LI-8100 (Nebraska, USA).

Soil incubation

Soil samples were then shipped to the USDA-ARS lab in Saint Paul, Minnesota (USA) for GHG production assessment. CO_2, N_2O and CH_4 production potentials were assessed through laboratory incubations using 243 soil sample (3 areas x 81 points). The incubation consisted of 1 g soil at 80% field capacity (1 cm^3 of distilled water addition) in a previously oven-sterilized 25 cm^3 serum vial (Wheaton Glass, Millville, NJ, USA). The soil was allowed to pre-incubate (unsealed) for a period of 24 h to avoid the irreproducible initial GHG production. The vials were then sealed with red butyl rubber septa (Grace, Deerfield, IL, USA) and analyzed on a headspace-gas chromatography GC, model 7694 (Foster City, USA) system to quantify gas production over a 3-d incubation period, which was sampled daily. This period of 3 d was selected based on initial incubations which were run for 21 d and there was no significant difference observed in the calculated GHG production rates from 3 to 21 d.

Analysis

A customized headspace-gas chromatograph system with 3 detectors (flame ionization, thermal ionization, and electron capture detector) was used (Spokas et al., 2009). Briefly, the GC system consisted of a headspace sampler that was modified to allow the injection of 3 separate gas samples unto 3 different analytical columns, which permitted the analysis of O_2, N_2, CO_2, CH_4, and N_2O, simultaneously from the same incubation. The system was calibrated against NIST traceable gas standards (Minneapolis Oxygen, Minneapolis, MN).

The total GHG impact over a 100 year time span was estimated using the emission factor proposed by IPCC for a 100 yr horizon (Myhre et al., 2014):

$$\text{Total GHG Production Impact} = CO_2\text{Production Potential} + 298{*}N_2O\text{ Production Potential} +, 25{*}CH_4\text{ Production Potential}$$

where total GHG production impact is in $\mu g\ CO_2\ eq.\ g_{soil}^{-1} d^{-1}$.

soil microbial biomass was measured using the fumigation-extraction method (Vance; Brookes; Jenkinson, 1987), where soil moistures were adjusted to 70% field capacity and samples were incubated 24 h at 22 °C. Soil organic carbon and microbial C determination were performed according to the Walkey-Black method (Nelson; Sommer, 1982).

Statistics

Values of GHG production potential were the averages of triplicates runs for each soil sample. Descriptive statistics of CO_2, N_2O and CH_4 emissions were obtained with the SAS program (Version 9.4) and was used the Dunn's test 5% to multiple comparisons among means. The results from the fields were initially compared based on local topography (convex vs. concave) within each area. Geospatial kriging was used as an interpolation method for the measured variables. The spatial variability models were derived (GS+ 9 software; Gamma Design Software, Version 9) and kriging maps were produced (Surfer; Version 9.0, Golden Software). The studied properties were submitted to one-way analysis of variance (ANOVA) and means were compared by t test at 5% probability (SAS, Version 9.4).

RESULTS AND DISCUSSION

CO_2 production and emission rates

CO_2 production rates from the different management treatments were tightly clustered, within one order of magnitude of one another. The average CO_2 production potentials of all 81 points across the treatments were 101, 105 and 148 µg C-CO_2 g soil^{-1}d^{-1}, respectively for B, G-5, and G-10 (Figure 2). The average CO_2 production rates in this study was significantly higher in the G-10 field, potentially influenced by longer term sugarcane residue being incorporated into the soil. This practice would provide higher amounts of organic carbon and stimulate microbiology activity, thus increasing soil CO_2 emissions.

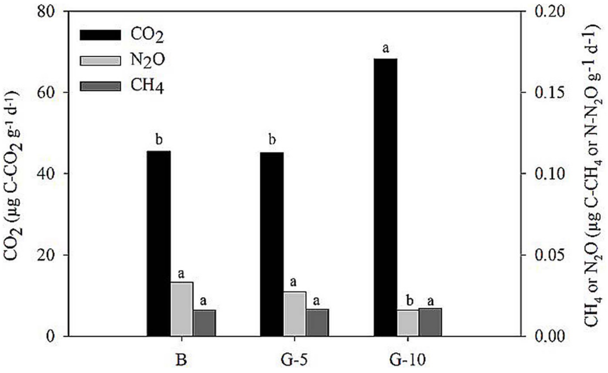

Figure 2: Total predicted average production rate of CO_2, N_2O, and CH_4 in the burned sugarcane (B), green sugarcane for 5 years (G-5), and green sugarcane for 10 years (G-10) (n: 81). Means were evaluated across the treatments, and those followed by the same letter are not statistically different (P<0.05).

We also compared field CO_2 emissions data with the laboratory production potentials (Table 2) with greater CO_2 emission in both methodology in the G-10 area. These instantaneous measurements have been well correlated to the longer term static chamber flux measurements in studies comparing different soil managment in southern Brazil (Chavez et al., 2009).

Since the field sites were not identical (i.e., not paired blocks), results from fields were initially compared based on local slope (convex vs. concave) within each area for normalization (Table 3). When analyzing the results from convex and concave terrains the results showed different trends in each management system as a function of slope. For the convex areas in each field, CO_2 production rate were 35.4, 39.8 and 94.8 µgC-CO_2 gsoil^{-1}day^{-1} for the B, G-5 and G-10, respectively. In concave area, CO_2 production were 61.5, 48.2 and 63.8 µgC-CO_2 gsoil^{-1}day^{-1} for the B, G-5 and G-10, respectively. However, no significant differences between B and G-10 were found.

In the convex areas, CO_2 was statistically different in the B and G-10 areas, with higher CO_2 emissions in the G-10 area, probably due to the presence of residue in soil surface that maintains soil moisture and to microbial activity. This is in agreement, with the observations of higher CO_2 emissions in high position-shaped landforms when compared to the linear-shaped ones from a Brazilian green sugarcane soil field (10yr) (Brito et al., 2010). However, in the area B, without residue, soil water tends to migrate to favorable areas of accumulation (concave positions), stimulating CO_2 emissions in these specific locations. Soil moisture is known to increase CO_2 production by the stimulates microbial activity (Schimel; Bilbrough and Welker, 2004). In the concave area, had significate difference only between G-5 and G-10 with more CO_2 production in the G-10 due the more straw in this area. However, some conclusion of CO_2 flux in G-5 is precipitated because this area can be considerate a transition of B to G-10.

Table 2: Comparison of field measured CO_2 emissions and comparison to the laboratory derived CO_2 production rates.

Treatments	Field measurement	Laboratory production rate
	(µg CO_2 m^{-2}s^{-1})	(µgC-CO_2 g soil^{-1}day^{-1})
B	455 b	100.9 ± 25.7 b
G-5	647 b	105.1 ± 32.0 b
G-10	791 a	148.4 ± 35.2 a

SD: standard desviation for laboratory production rate data. Mean followed by the same letter within a column do not differ from each other by Student's t-test at the 5% probability level.

Table 3: Descriptive statistics of soil CO_2, N_2O and CH_4 production rates from field sites at high and low topography in 0-10 cm soil depth for burned sugarcane (B), green sugarcane for 5 years (G-5) and green sugarcane for 10 years (G-10) sites.

	Convex position			Concave position		
	B	G-5	G-10	B	G-5	G-10
CO_2 (μg C-CO_2 g soil^{-1} day^{-1})						
Mean	35.4 b	39.8 b	94.6 a	61.5 ab	48.2 b	63.8 a
SD	6.7	11.4	23.0	13.0	20.4	14.5
N	13	13	11	10	21	38
CI	31 - 39	32 - 46	78 - 111	52 - 70	38 - 57	60 - 67
Dunn's test 5%			P < 0.001			P < 0.001
N_2O (ηg N-N_2O g soil^{-1} day^{-1})						
Mean	42.4	10.2	29.8	33.6	14.5	12.9
SD	42.8	6.9	34.4	40.7	20.8	15.0
N	13	13	11	10	21	38
CI	16 - 68	6 - 14	6 - 53	0 - 67	3 - 25	9 - 16
Dunn's test 5%			P = 0.278			P = 0.207
CH_4 (ηg C-CH_4 g soil^{-1} day^{-1})						
Mean	16.7 a	17.0 a	17.6 a	15.9 a	16.5 a	17.1 a
SD	0.8	0.3	0.5	2.1	0.8	1.6
N	13	13	11	10	21	38
CI	16 - 17	16 - 17	17 - 18	14 - 17	16 - 16.8	16 - 17.5
Dunn's test 5%			P = 0.002 P < 0.001			P < 0.001
Soil microbial activity (μg C g^{-1} kg^{-1})						
Mean	197.6	187.83	212.82	237.09	181.9	179.25
SD	53.5	123.89	58.47	56.4	67.84	126.1

SD: standard desviation; CI: confidence interval.

A possible explanation for the variation in the CO_2 production with change in slope could be related to the soil microbial biomass (SMB). In the G-10 treatment both (convex and concave) CO_2 production and SMB were correlated to slope (Table 3).

CO_2 production potential in G-10 may be influenced by the crop residues left from previous harvests, which increased soil organic carbon contents and stimulated microbial activity and in turn increased microbial respiration (i.e. CO_2 production) (Varella et al., 2004). The soil organic carbon maps (Figure 3) possess the same spatial tendency as CO_2 production potential and SMB, which supports the hypothesized linkages.

At the burned field, SMB and CO_2 production rates were elevated at the concave position (compared to the convex in the green harvest areas) (Table 3, Figure 4A). Because the B treatment effectively removes the residues, the soil in this field has greater erosive potential, which means that water and nutrients will collect in concave position more quickly than with either green sugarcane management (residues hinder erosion and water flow). Thereby, this results in altering the spatial distribution of soil organic matter with time, with more soil carbon in the concave in the B and convex in the G-10 (Figure 3).

N_2O production rates

The greater value of N_2O emission was 118,7 ηg gsoil^{-1} day^{-1} (0,11μg gsoil^{-1} day^{-1}), this is very low rates (Figure 2) and can be explained by anaerobic processes occurring to reduce the amount of N_2O in the headspace.

Oliveira et al. (2013) reported negative values for N_2O (meaning a larger consumption rate of N_2O than production pathways) from soil with green harvest (7 yr) compared to burned sugarcane treatments.

It has been reported that N_2O emissions from soil are related to the C:N ratio of residues. Residues with a C:N ratio less than 25 are less stable in soil, meaning they are mineralized more quickly promoting the N in the soil and N_2O production (Dambreville et al., 2006; Figueiredo; La Scala, 2011), but the sugarcane crop residues, on average, have a C:N ratio close to 100, an immobilization of soil N is expected (Trivelin et al.,

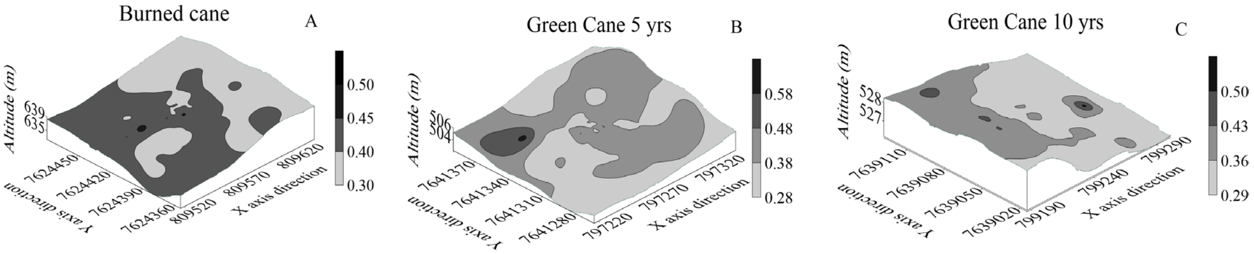

Figure 3: Spatial distribution of soil carbon (g C kg^{-1}) in burned sugarcane (A), green sugarcane 5 years (B) and green sugarcane 10 years (C) at 0-20 cm soil depth (n: 81).

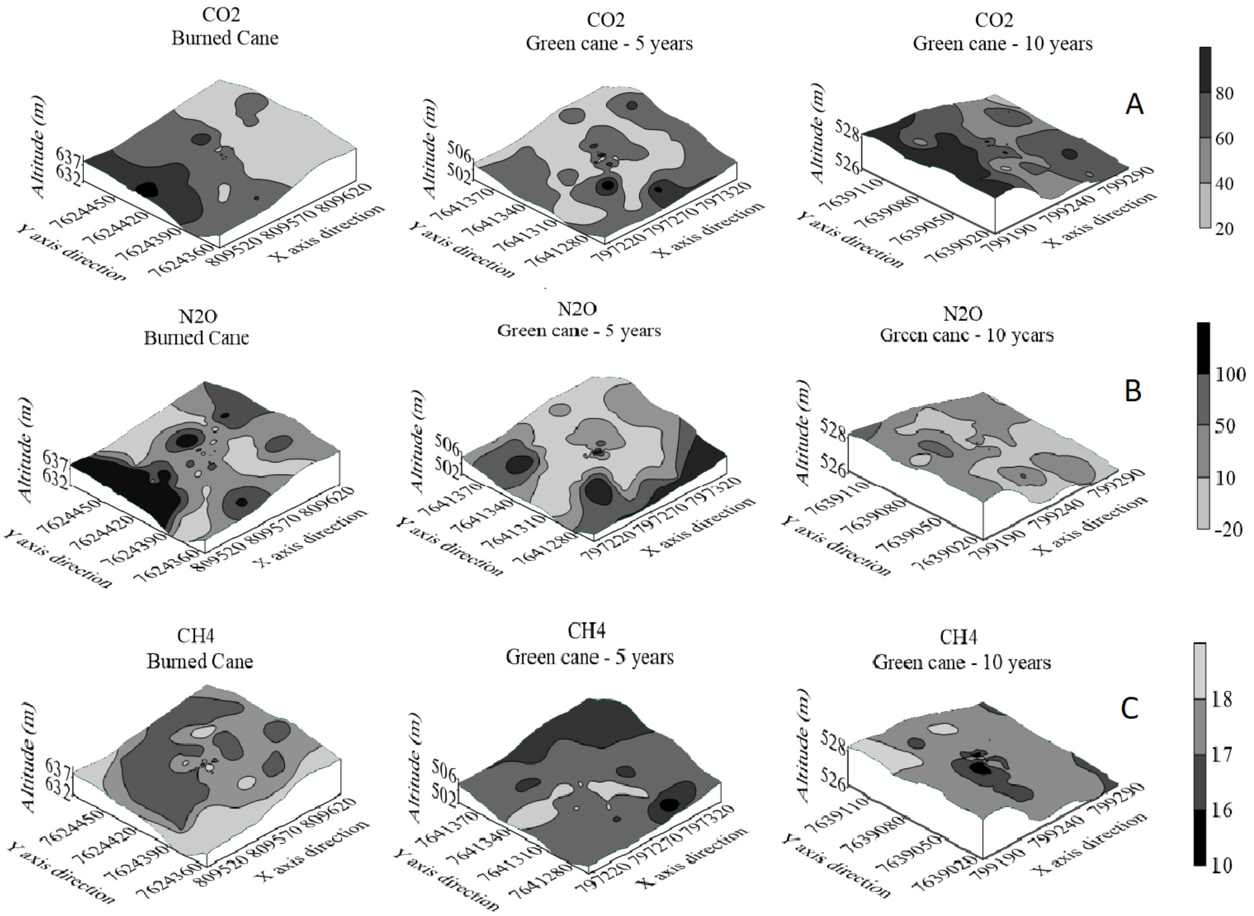

Figure 4: Spatial distribution of soil A - CO_2 emission (ηgC-CO_2 gsoil^{-1} d^{-1}); B - N_2O emission (ηgN gsoil^{-1} d^{-1}) and C - CH_4 emission (ηgC gsoil^{-1} day^{-1}) (C) in burned sugarcane, green sugarcane 5 years and green sugarcane 10 years (n: 81).

2002; White et al., 1988), which consequently leads to lower N_2O emissions.

It is important to note that in this experiment no manure or fertilizers is applied to the field. This may have influenced the low emissions measured because the input of N into the soil from applications of organic or synthetic fertilizer has been found to stimulate the denitrification processes (Oliveira et al., 2013; Signor; Cerri; Conant, 2013).

Analyzing the convex and concave area, was no possible to compare the N_2O production rate between areas due the P value was > 5% of probability by Dunn's test, this means that the difference in the median values among the treatments groups are not great enough to exclude the possibility that the difference is due to random sampling variability, there is not a statistically significate difference. Despite this, the maps of N_2O production showed that the little gas concentration was similar with CO_2 production (Figure 4). However, this does not universally hold across all field measurements, with some studies showing no relationship with topography (Paré; Haughn, 2012).

CH_4 Production Rate

Overall, CH_4 production rates were not statistically different between treatments with an overall average of 15 ng C $g_{soil}^{-1}day^{-1}$ across the three sites (Table 3; Figure 4C). One explanation for the low CH_4 concentrations observed and the similarity of data among the three sites may be related to the natural tendency of these iron-rich soils to absorb CH_4 (Oliveira et al., 2013). No significant trends between convex and concave topography with CH_4 production were observed, consistent with the results obtained in a study by (Paré; Haughn, 2012). Soil CH_4 emissions are more frequent in flooding areas (anaerobic conditions), because the gas is produced by the methanogenic microorganisms during anaerobic decomposition of organic substances (Thangarajan et al., 2013). As already mentioned, the soil properties at these sites do not promote anaerobic conditions.

Estimated net GHG impact

GHG production impact was the highest in the G-10 field in the convex position and the burned management had the highest GHG in the concave (Table 3). However, this was mainly due to the higher CO_2 emission, due to the increased microbial mineralization activity. The more interesting observation is that the B field had the highest non-CO_2 GHG contribution in both landscape positions (Table 4). It is important to note that in this study, the CO_2 emission is correlated to soil biological activity. Sugarcane can return about 15-20 Mg ha^{-1} of organic matter, containing 6-8 Mg ha^{-1} of carbon to the soil surface (Thangarajan et al., 2013). Cultivation methods affect the magnitude and pattern of CO_2, N_2O and CH_4 emissions, by influencing the supply of organic C and N to soil microorganisms (Wang; Bettany, 1995). And in this case, residue management imposed this control on the field sites. Management practices that result in changes in soil organic matter and influence the physical and chemical soil directly affect microbial activity and hence GHG emissions.

Contradicting this result, the study of Figueiredo and La Scala (2011) calculated more CO_2eq. emission in burned sugarcane (3103.9 kg CO_2eq $ha^{-1}year^{-1}$) compared with green sugarcane (1619.8 kg CO_2eq ha^{-1} $year^{-1}$), but considered the carbon sequestration from soil. Similar to our results, elevated CO_2 emission (1331 kt CO_2 $year^{-1}$) was observed in green residue sugarcane treatments in Australia when compared with bare sugarcane soil (1058 kt CO_2 $year^{-1}$) (Blair et al, 1998). In Brazil, a study showed that the sugarcane trash increased CO_2 emission rate by 380% compared to the bare soil (Weier, 1996). Therefore, since CO_2 production and emission are highly temporally dynamic these relationships will change as a function of soil moisture and temperature as well as timing of field operations.

Table 4: Greenhouse gases impact of soil in burned sugarcane (B), green sugarcane for 5 years (G-5) and green sugarcane for 10 years (G-10).

	Convex position			Concave position			Total	% Non-CO_2
	CO_2	Non-CO_2	Total	CO_2	Non-CO_2	Total		
		µg CO_2eq g_{soil}^{-1} d^{-1}			µg CO_2-equiv g_{soil}^{-1} d^{-1}			
B	35.37	13.05	48.42	61.50	38.34	99.83	148	35%
G-5	38.85	3.47	43.32	48.23	16.15	64.37	108	18%
G-10	94.75	9.34	104.08	63.88	4.29	68.17	173	8%

CONCLUSIONS

The conventional burning and green harvest practices have significantly different GHG soil production profiles. The slope area was observed to have a significant influence on the distribution of GHG emissions. Higher CO_2 production from the G-10 soils were presumably related to soil microbial activity, and therefore indicate improved soil quality in the G-10 compared to the B field. On the other hand, the B management had the highest contribution of non-CO_2 GHG to the total GHG impact. Despite the higher numeric GHG impact of the green harvest (10 year).

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