University of São Paulo
“Luiz de Queiroz” College of Agriculture

Crop prediction and soil response to sugarcane straw removal

Lucas Santos Satiro

Dissertation presented to obtain the degree of Master in Science: Area: Soil and Plant Nutrition

Piracicaba
2018

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Versão revisada de acordo com resolução CoPGr 6018 de 2011

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Prof. Dr. **CARLOS EDUARDO PELLEGRINO CERRI**

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In memoriam Bernardo Santos Satiro
I DEDICATE

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“The mind that opens to a new idea never returns to its original size”

Albert Einstein

"Take a chance, some follies worth it"

CONTENTS

RESUMO

Predição da produção e resposta do solo à remoção de palha de cana de açúcar

Preocupações acerca do aquecimento global e mudanças climáticas tem provocado uma crescente demanda por energias renováveis. Nesse cenário, tem aumentado o interesse em utilizar a palha de cana-de-açúcar como matéria prima para produção de energia. Contudo, a palha desempenha importante papel na manutenção da qualidade do solo. Aliado a isso, incertezas quanto a quantidade de palha produzida e o impacto da remoção da palha na produção de colmos tem levantado duvidas quanto ao uso dessa matéria prima. Nesse sentido, o objetivo desse estudo foi avaliar a curto prazo (2 anos) os impactos da remoção da palha de cana-de-açucar no solo, e modelar a produção de palha e colmo de cana-de-açucar utilizando atributos do solo de diferentes camadas. Para tanto, foram conduzidos dois experimentos nos municípios de Capivari (solo de textura média) e Valparaíso (solo de textura arenosa), estado de São Paulo, Brasil. Foram testados cinco taxas de remoção de palha (i.e., equivalentes a 0, 25, 50, 75 e 100 %). Amostras de solo foram coletadas nas camadas 0-2,5, 2,5-5, 5-10, 10-20 e 20-30 cm de profundidade para determinação de C, N, pH, P, K, Ca, Mg, densidade do solo e resistência do solo a penetração. Amostras de planta foram coletadas para determinar a produção de colmo e palha. Os impactos causados pela remoção da palha diferiu entre as áreas, no entato, se concentraram na camada mais superficial do solo. No solo de textura média a remoção da palha levou a depleção do carbono orgânico e a compactação do solo, enquanto que, no solo de textura arenosa os atributos químicos (i.e teores de Ca e Mg) foram os mais impactados. Os resultados indicam a possibilidade de remover cerca de metade da quantidade de palha depositada sobre o solo (8.7 Mg ha^{-1} palha remanecente) sem causar graves implicações na qualidade deste solo. Em contraste, no solo de textura arenosa, qualquer quantidade de palha foi suficiente para causar alterações na qualidade do solo, contudo, essas alterações foram menos intensas e não aumentaram com as taxas de remoção da palha. Foi possível modelar a produção de colmo e palha de cana-de-açucar utilizando atributos do solo. A camada 0-20 cm foi a mais importante na definição da produção de colmos, ao passo que a camada 0-5 cm, camada em que se concentra os impactos causados pela remoção da palha, foi menos importante. Assim, notamos que os impactos causados ao solo pela remoção da palha tem pouca influencia na produtividade da cultura. A predição da palha se mostrou mais complexa e possivelmente requer informações adicionas (e.g informações da cultivar e de clima) para que bons resultados sejam obtidos. No geral, os resultados sugerem que a remoção planejada da palha para fins energéticos pode ocorre de maneira susutentável, porém deve levar em conta condições locais, e.g propriedades do solo. Contudo, pesquisas de longo prazo com diferentes abordagens ainda são necessárias, tanto para acompanhar e confirmar nossos resultados, como para desenvolver soluções que atenuem os danos causados por esta atividade.

Palavras-chave: Manejo de resíduos; Predição da palha; Biocombustíveis; Atributos do solo

ABSTRACT

Crop prediction and soil response to sugarcane straw removal

Concerns about global warming and climate change have triggered a growing demand for renewable energy. In this scenario, the interest in using sugarcane straw as raw material for energy production has increased. However, straw plays an important role in maintaining soil quality. In addition, uncertainties as to produced straw amount and the straw removal impact on the stalk yield have raised doubts as to the use this raw material. In this sense, the objective this study was evaluate the short-term (2-year) the sugarcane straw removal impacts on soil and yield modeling of sugarcane stalk and straw, using soil attributes of different layers. Two experiments were carried out in São Paulo state, Brazil: one at Capivari (sandy clay loam soil) and another at Valparaíso (sandy loam soil). We have tested five rates of straw removal (i.e., equivalent to 0, 25, 50, 75 and 100 %). Soil samples were taken from 0-2.5, 2.5-5, 5-10, 10-20 and 20-30 cm layers to analyze pH, total C and N, P, K, Ca, Mg, bulk density and soil penetration resistance. Plant samples were collected to determine the straw and stalk yield. The impacts caused by straw removal differed between the areas, however, they concentrated on the more soil superficial layer. In sandy clay loam soil, straw removal led to organic carbon depletion and soil compaction, while in the sandy loam soil the chemical attributes (i.e. Ca and Mg contents) were the most impacted. In general, the results suggest that straw removal causes reduction more significant in soil quality for the sandy clay loam soil. The results indicate the possibility to remove about half-straw amount deposited on soil's surface (8.7 Mg ha^{-1} straw remaining) without causing severe implications on the quality of this soil. In contrast, although any amount of straw was sufficient to cause alterations the quality of the sandy loam soil, these impacts were less intense and are not magnified with the increase of straw removal. It was possible to model sugarcane straw and stalk yield using soil attributes. The 0-20 cm layer was the most important layer in the stalk yield definition, whereas the 0-5 cm layer, which the impacts caused by the straw removal were concentrated, was less important. Thus, we noticed that impacts caused to soil by straw removal have little influence on crop productivity. Straw prediction has proved more complex and possibly requires additional information (e.g crop and climate information) for good results to be obtained. Overall, the results suggest that the planned removal of straw for energy purposes can occur in a sustainable way, but should take into account site conditions, e.g soil properties. However, long-term research with different approaches is still necessary, both to follow up and confirm our results, and to develop ways to reduce damage caused by this activity

Keywords: Straw management; Straw prediction; Biofuels; Soil attributes

1. GENERAL INTRODUCTION

The world's population is growing and is expected to reach more than 9.7 billion people by 2050 (UN, 2013). This population growth, associated with changes in consumption patterns will increase energy demand by 60% (WEO, 2013).

Currently, about 87% of the energy produced in the world comes from non-renewable sources. Although this share is estimated to decline to 75 percent by 2035, fossil fuel consumption will continue to grow, emitting an additional 6 Gt of carbon in the form of CO_2 into the atmosphere (IEA, 2012). Reduce the emission of CO_2 and other greenhouse gases (GHG) is crucial to minimize the impacts caused by the planet's climate (ROGELJ et al, 2016). In the challenge of meeting growing energy demands and reducing GHG emissions, the bioenergy becomes a great promise for the near future (GOLDEMBERG, 2007, POP et al., 2014).

In Brazil, sugarcane is the main raw material used to produce bioenergy. The country stands out as the world's largest producer of this crop. In the 2016, 9 million hectares were planted and 657.1 million tons were produced. Half of this raw material was used for sugar production and the other half for ethanol production, culminating in the production of 27.81 billion liters. Despite this production, projections from the Brazilian government indicate that to meet the demands of the market, ethanol production is expected to increase by 16 billion liters by 2026 (BRAZIL, 2017). One way to increase ethanol production would be with the use of straw for production second generation ethanol (2G) (Graham-Rowe, 2011).

In energy terms, straw accounts for 1/3 of sugarcane potential energy, with the capacity to produce 283 L of ethanol per dry mass ton (SANTOS et al., 2012). The straw amount produced range from 4 to 32 Mg ha^{-1} (LEAL et al., 2013), depending on several factors, such as cultivar and crop's age (LANDELL et al., 2013). In this way, the use of this raw material can significantly increase ethanol production, reduce GHG emissions and the need for new cultivation areas, as well as increase profit per unit area.

Despite straw removal benefits for energy purposes, there is an environmental damage associated with this activity. This damage occurs due the discriminated straw removal which can lead to the depletion of soil organic carbon (OLIVEIRA et al., 2017), decreasing microbial activity (SOUZA et al., 2012), nutrient cycling and soil capacity to store water and nutrients (LIAO et al., 2014). Moreover, it can favor soil compaction, compromising the water and gases movement in the soil profile, increase soil resistance to penetration and the erosion risk. Thus, the combination of these factors can lead to soil degradation and decrease its ability to support plant growth.

Despite these implications, it is not yet established the straw amount which must be maintained on the field, to reach greatest economic and environmental benefit, and thus the sustainability of the sugarcane production chain. In this scenario, this work was developed with the following goals: i) to evaluate the impact caused on soil by sugarcane straw removal levels on different production environments and ii) to produce information that helps to understand the impacts caused by this activity to the soil and its relation with the crop productivity. These informations will be useful to support decision-making on how much straw can be removed from the field for renewable energy production in Brazil.

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2. SUGARCANE STRAW REMOVAL EFFECTS ON ULTISOLS AND OXISOLS IN SOUTH-CENTRAL BRAZIL

ABSTRACT

The maintenance of sugarcane straw on the field has an important role in preserving the soil properties and organic carbon content. However, there is a growing interest in removing part of this residue to use in bioenergy production. The effect of straw removal on soil quality is still poorly studied. The aim of this study was to evaluate the impact of short-term (2 years) straw removal from soil surface on soil quality. Two experiments were carried out in São Paulo state, Brazil: one in an Oxisol (sandy clay loam soil) and another in an Ultisol (sandy loam soil). We have tested five rates of straw removal (i.e., equivalent to 0, 25, 50, 75 and 100 %). Soil samples were taken from 0-2.5, 2.5-5, 5-10, 10-20 and 20-30 cm layers to analyze pH, total C and N, P, K, Ca, Mg, bulk density and soil penetration resistance. The effects of straw removal were limited to the soil surface layer and differed between the two types of soil. Under the Oxisol, the straw removal favored soil physical degradation (i.e., increased soil compaction and resistance to penetration) and depletion of soil C stocks. On the other hand, straw removal management only affected chemical properties in the Ultisol, reducing nutrient contents (e.g., Ca and Mg). Based on a multivariate analysis that involving all attributes, the sandy texture soil (Ultisol) showed more sensitivity to straw removal management, even over this short period (2 years), in which the removal of any amount of straw caused a negative impact on soil quality. In contrast, in the sand-clay-loam soil (Oxisol) the removal rate of up to 50% of the straw (i.e., the maintenance of ~ 8.7 Mg ha^{-1} of straw on soil surface) proved to be sustainable. Therefore, sugarcane straw removal should be site-specific, taking into account intrinsic soil properties and climate conditions, which preventing soil degradation and negative impacts on the provision of multiple ecosystem services. This guarantees the sustainability of the Brazilian bioenergy production.

Keywords: Crop residue management; Chemical attributes; Physical attributes; soil C; bioenergy

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2.1. INTRODUCTION

To support the growing demand for energy in recent years, much has been invested in technologies capable of using crop residues as a raw material for bioenergy production (Graham-Rowe, 2011; Rubin, 2008). In Brazil, sugarcane crop residue (straw) left in the field during harvest is now considered one of the main raw material for this purpose. Sugarcane straw, especially dry leaves, has high potential to produce cellulosic ethanol, as well as great heating value (i.e., high (HHV): 17.3 MJ kg^{-1} and lower (LHV): 15.61 MJ kg^{-1}) (Menandro et al., 2017).

Therefore, straw removal management is emergent in Brazilian sugarcane fields and will be intensified over the next few years (Franco et al., 2013). The use of sugarcane straw for energy purposes can potentially increase the productivity of ethanol and bioelectricity, reducing the need for expansion of planted areas and potential competition with food crops or natural ecosystems (Tilman et al., 2009). However, the indiscriminate straw removal can cause soil damage by reducing soil carbon, nutrient cycling, biological activity, resistance to compaction and erosion control. The combined action of these factors can lead to soil degradation and compromising its ability to support plant growth, reducing the sustainability of the sugarcane production (Blanco-Canqui and Lal, 2009; Carvalho et al., 2016; Cherubin et al., 2017).

Although C added via root system contributes significantly to soil C stocks, the straw is the main source of C added to soil in sugarcane areas, accounting for 70 to 80% of the soil carbon input (Carvalho et al., 2013; 2017). Thus, straw removal can negatively affect soil carbon balance (Cerri et al., 2011; Carvalho et al., 2017; Cherubin et al., 2017; Oliveira et al., 2017). The straw maintenance on the soil surface accumulates on average 1.5 Mg C ha^{-1} $year^{-1}$ at the 0 to 30-cm layer (Cerri et al., 2011). According to these authors, carbon accumulation varies according to soil texture, with clayey soils accumulating approximately three times more carbon than sandy soils. Moreover, Oliveira et al. (2017) estimated that SOC can decrease by 50 Tg in the next 30 years if straw removal will be adopted in Brazilian sugarcane producing areas. The straw maintenance on the soil surface also directly affects nutrient cycling through the gradual mineralization of the organic material during the decomposition process. Only part of these nutrients (mainly N) released during straw decomposition are recovered by the plants in the short term (Ferreira et al., 2016). However, the straw maintenance over successive years can reduce the need for input of mineral fertilizer in the long term (Fortes et al., 2013; Karlen et al., 2014; Trivelin et al., 2013).

The straw still has huge influence on soil physical quality (Cherubin et al., 2017; Tormena et al., 2017). When maintained on the field increases C and nutrients inputs, and thus the biological activity, which combined favor the aggregate formation and soil structuring (Six et al., 2000, 2002). Furthermore, the straw blanket protects the soil from the direct impact of the raindrops, increases soil roughness (Silva et al., 2012; Rocha Junior et al., 2016) and dissipates part of the pressure exerted by agricultural machinery (Braida et al., 2006). The combination of these effects reduces soil compaction, providing better soil structure (Tormena et al., 2017), with reduced impedance to root development (Otto et al., 2011) and a greater amount of water available for the plants (Tormena et al., 2017). Rosim et al. (2012) verified reductions up to 80% in the soil resistance to penetration and increases of about 17% in the soil moisture under wheel traffic in a soil covered with 15 Mg ha^{-1} of straw compared to a bare soil. However, the ability of the straw cover to reduce compaction may vary between different cultivation areas (Blanco-Canqui et al., 2006; Blanco-Canqui and Lal, 2007), since soil susceptibility to compaction depends on other factors such as texture and soil water content (Arvidsson, 1998; Braida et al., 2010).

Considering the multifunctionality of the straw on sustaining several soil functions and ecosystem services, studies that using integrated approach to assess soil chemical, physical and biological changes are crucial to better understand the straw removal effects on soil quality. The straw removal for energetic purposes is a recent activity in Brazil. Therefore, to our knowledge, there are no field studies that evaluated the impact of sugarcane straw removal management on soil quality, as well as the influence of soil texture in these conditions. This information is important because Brazilian sugarcane areas extend to great range of soil textural classes. In this way, we conducted a 2-year field study in two sites with different soil texture to quantify the changes in soil chemical, physical and biological properties and consequently, the soil quality induced by sugarcane straw removal. We have tested the hypothesis that straw removal induces soil degradation even in the short term, but the extension of these effects are dependent on soil texture.

2.2. Material and Methods

2.2.1. Study sites

The study was carried out in the state of São Paulo, Brazil, in the municipalities of Capivari (22°51'01"S 47°30'44"W, 571 m alt.) and Valparaíso (21°22'23"S 50°51'22"W, 385 m alt.) (supplementary material, Figure S1). In the experimental area of Capivari the soil was classified as Rhodic Kandiudox (Soil Survey Staff, 2014) with sandy clay loam texture (Table 1). The climate is subtropical humid (Köppen classification) with a hot summer (Cfa), average annual rainfall of 1236 mm and an average annual temperature of 20.1 °C. In the experimental area of Valparaíso the soil was classified as Kanhaplic Haplustults (Soil Survey Staff, 2014) with a sandy loam texture (Table 1).

Table 1. Initial characterization of the soils in the experimental sites

Layer	C	pH_{water}	Ca	Mg	K	P	BS	AS	Clay	Silt	Sand
(cm)	g kg^{-1}	---	mmol$_c$ dm^{-3}			mg dm^{-3}	%		g kg^{-1}		
Oxisol - sandy clay loam soil											
0-10	11.3	5.2	26.1	7.7	9.3	29.3	68.8	0.8	330	60	610
10-20	11.0	4.8	19.0	5.9	5.1	24.9	54.7	3.5	330	70	600
20-30	9.4	4.5	12.5	2.9	3.3	22.1	36.8	4.2	335	65	600
Ultisol - sandy loam soil											
0-10	6.1	5.2	9.3	2.9	3.3	17.4	51.1	2.4	112	23	865
10-20	5.5	4.8	4.8	1.5	2.6	14.1	34.8	5.6	113	22	865
20-30	4.9	4.5	3.6	1.0	2.1	12.7	27.5	7.4	120	20	860

BS: base saturation; AS: aluminum saturation.

The climate is tropical with a dry winter (Aw), average annual rainfall of 1205 mm and an average annual temperature of 22.4 °C (Alvares et al., 2013).

Both experimental sites have been cultivated with sugarcane over 40 years, but in the last ten years the harvesting system was shifted from manual (with burning) to mechanized (without burning) (Figure S2). These areas were chosen because they presented flat topography and contrasting conditions of soil types. Therefore, the soil class and its texture were used to differentiate and designate the experiments, as "Oxisol" to Capivari site and "Ultisol" to Valparaiso site.

2.2.2. Experimental design

The experimental design was in randomized blocks with five treatments and four replications, totaling 24 experimental units (Figure S4). Each experimental unit consisted of 1250 m^2, with 10 double lines of sugarcane planted using alternated row spacing 1.5 m (trafficked area) and 0.90 m (non-trafficked area) between rows. The treatments consisted of different amounts of straw left on the soil surface (Table 2 and Figure S3) and were applied mechanically as described by Lisboa et al. (2017). To facilitate the presentation and discussion of the results, the treatments will be referred by their respective rate of straw removal, as shown in Table 2.

2.2.3. Soil sampling and the analyzed parameters

The experiments were established in October 2014, during the harvesting of sugarcane plant (first annual crop cycle). At that time, the treatments were applied and the soil was collected for initial characterization of the sites. In December 2015, during the first sugarcane harvesting after the experiment establishment, the respective treatments were applied again. In October 2016, after the

Table 2. Remaining quantities of sugarcane straw

Removal rate (%)	Oxisol - sandy clay loam soil			Ultisol - sandy loam soil		
	Sugarcane straw amount left on soil surface (Mg ha⁻¹)					
	1º yr§	2º yr‡	$\bar{X}$	1º yr	2º yr	$\bar{X}$
100	0.0	0.0	0.0	0.0	0.0	0.0
~75	3.4	3.2	3.3	5.1	4.1	4.6
~50	7.8	9.7	8.7	8.4	7.9	8.1
~25	13.0	11.4	12.2	11.4	9.6	10.5
0	16.6	14.7	15.6	15.0	12.4	13.2

§ 1ºyr: Straw amount added for each treatment at the experiment installation in October 2014 (first year); ‡ 2ºyr: Straw amount added for each treatment when the experiments were reinstalled in December 2015 (second year); $\bar{\boldsymbol{X}}$ Media of the two remaining quantities of straw.

second sugarcane harvesting, two years after the installation of the experiment, soil was sampled for assessing the potential effects of the treatments, even after the relatively short term of adoption.

Soil collection was performed on a transect within each experimental unit. Along each transect three trenches (approximately 30 x30 x 30 cm) were opened between the planted lines. Undisturbed soil samples were collected from all the trenches in the 0-2.5, 2.5-5, 5-10, 10-20, and 20-30 cm layers for the characterization of chemical attributes and soil C. In order to determine bulk density, undisturbed soil samples were collected using volumetric rings (~100 cm^{-3}) in the 0-5, 5-10, 10-20 and 20-30 cm layers from the central trench of each transect. Measurements of soil resistance to penetration (SRP) were also performed, and to minimize the inherent error of this assessment, four repetitions were carried out in each point (Figure S5).

The soil samples were air dried and sieved through a 2 mm mesh. The pH was determined in water at a soil:solution ratio of 1:2.5, and the levels of calcium (Ca), magnesium (Mg), phosphorous (P) and potassium (K) were extracted using an ion exchange resin method. P was determined in the molecular absorption spectrophotometer and the other nutrients in an atomic absorption spectrophotometer (Raij et al., 2001). A sub-sample was ground to a fine powder and sieved with 100 mesh (0.149 mm), prior to the total C and N determination by dry oxidation, using an elemental analyzer (Nelson and Sommers, 1996). The soil bulk density was determined by dividing the soil dry mass by the volume of the ring, whereas SRP was determined using an impact penetrometer (Stolf, 1983), and calculated for specific layers according to the equation proposed by Stolf et al. (2014).

The C and N stocks (Mg ha^{-1}) were calculated according to equation 1:

$$Stock = C \times BD \times W \qquad \text{Equation 1}$$

Where, **C** is the concentration of carbon or nitrogen (%), **BD** is the bulk density (Mg m^{-3}) and **W** is the width of the soil layer (cm). As the samples were collected in fixed layers, the stocks were corrected for the same mass of soil (Lee et al., 2009), the reference treatment was without straw removal.

It should be highlighted that the soil attributes were selected because they are included in the minimum dataset suggested by Cherubin et al., (2016a) for soil quality assessment of sugarcane areas in Brazil.

2.2.4. Statistical Analysis

The statistical analyses were carried out using the software R (R Core Team, 2017). To analyze the response of each attribute to the straw removal rates, the data were submitted to an analysis of variance (ANOVA) and when significant (F test $p<0.05$), the means were compared using the Tukey test ($p<0.05$). Subsequently, in order to obtain an integrated assessment of the straw removal effects on soil quality, the data were subjected to a multivariate analysis of variance (MANOVA) and to canonical discriminant analysis (CDA) using the Candisc package (Friendly and Fox, 2013). From the CDA data, a biplot graphic was generated to evaluate the multivariate differences between the treatments and to hierarchize the contribution (weight) of each soil attributes for distinguishing the straw removal rates. The center of the circles plotted on the graph represent the mean value of the first two canonical variables and the radius is calculated using Equation 2:

$$Radius = \sqrt{((\chi_{0.95}^{2}(\mathrm{v}))/\mathrm{n}\,)} \qquad \text{Equation 2}$$

Where, χ_0.95^2 is the chi-square distribution value for 95% confidence, v is the number of canonic variables used in the representation and, n is the number of samples in the treatment. When the circles overlap, the treatments are not statistically different. The size of the arrow represents the importance of each attribute in the distinction of the treatments and its direction indicates the positive or negative effect of the attribute on the treatments. Further explanation and examples of CDA can be found in Gittins (1985). Considering that soil samples for BD determination were collected under a different experimental design (1 sample per plot) and its results are very collinear to SRP, BD was not included in the CDA analysis.

2.3. RESULTS

2.3.1. Carbon and nitrogen

The straw removal management modified the C stocks only for the Oxisol (Figure 1). However, significant differences were only observed in the soil surface layer (0 – 2.5 cm) and in the accumulated within the first two soil layers (0 – 5 cm). In this site, soil C stock of the 0-5 cm layer under no straw removal (11.9 Mg C ha^{-1}) was 20 % higher than when the straw was completely removed (9.8 Mg C ha^{-1}). Under intermediate removal rates the soil C stocks were statistically similar to those values found under total straw removal or no straw removal plots; however, C stocks tended to reduce with higher removal rates. The mean C stock for the 0-30 cm layer in this area was 54.7 Mg C ha^{-1}.

In contrast, sugarcane straw removal did not significantly affect C stocks in the Ultisol. For that site, soil C stocks average was 5.6 and 29.1 Mg C ha^{-1} in the 0-5 cm and 0-30 cm layers, respectively (Figure 1). At both locations, sugarcane straw removal did not significantly alter soil N stocks (Figure 2), and thus, none pattern of response to the treatments was identified.

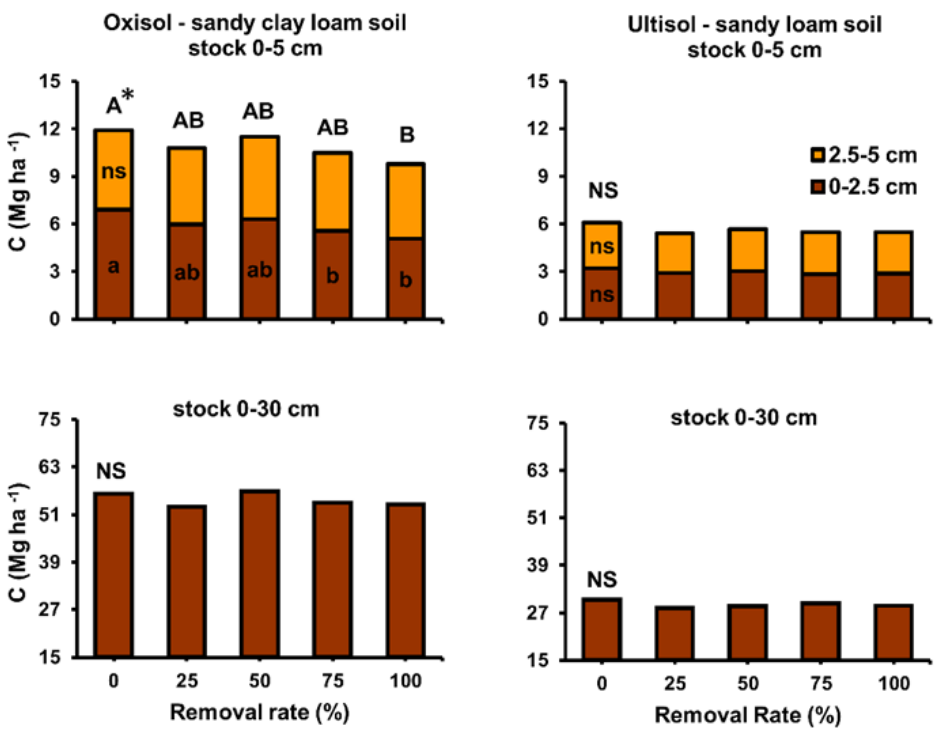

Figure 1. Average carbon stocks under the different management systems and the soil layers analyzed in the experimental areas. *Carbon stock values followed by the same letter did not significantly differ according to Tukey's test ($p<0.05$).

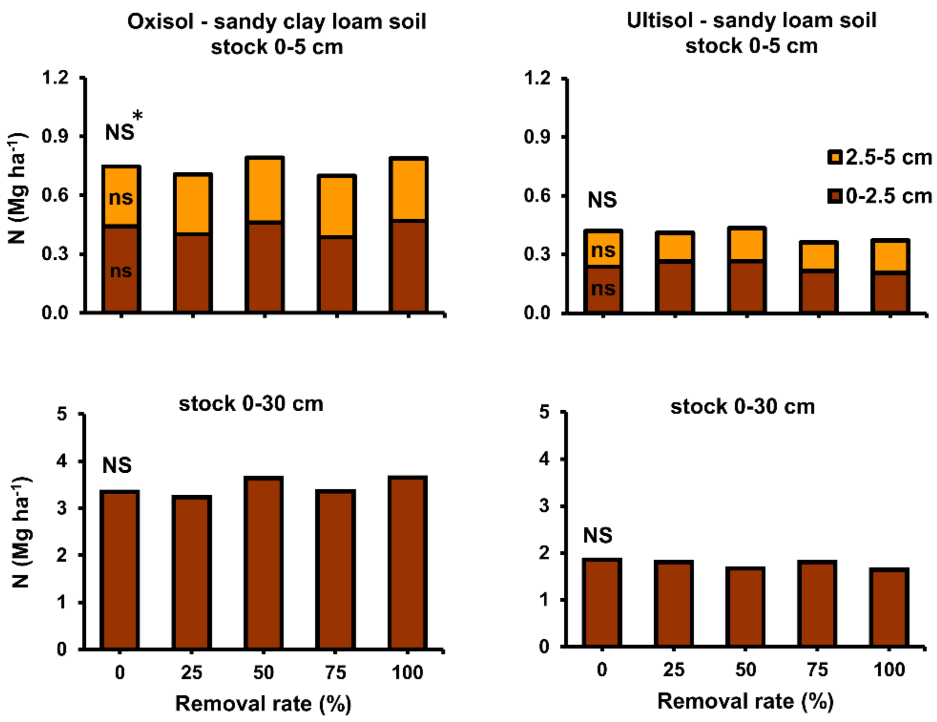

Figure 2. Nitrogen stocks under the different management systems and the soil layers analyzed in the experimental areas. *Nitrogen stock values followed by the same letter did not significantly differ according to Tukey's test ($p<0.05$).

2.3.2. Chemical attributes

At the Ultisol, straw removal management modified the soil chemical attributes at the surface layer (Table 3). The levels of Ca and Mg were 40 and 60%, respectively; lower when total straw was removed, compared to those found under no straw removal. Similar to observed for soil C, there was a tendency to reduce the levels of these nutrients with an increase in the level of straw removal, although intermediate straw removal rates (25, 50 and 75 %) did not induced significant difference in Ca and Mg levels compared to total removal or no straw removal treatments. Although no significant difference was observed, the levels of K tended to reduce with depth (5 to 30 cm) under higher straw removal rates. For the other attributes analyzed, no significant difference was observed. In the Oxisol, no significant difference was observed for any of the chemical attributes analyzed.

Table 3. Chemical attributes of soils evaluated two years after the adoption of straw management in the two study areas

Removal rate (%)	Oxisol - sandy clay loam soil					Ultisol - sandy loam soil				
	pH_{water}	Ca	Mg	K	P	pH_{water}	Ca	Mg	K	P
	---	mmol$_c$ dm^{-3}			mg dm^{-3}	---	mmol$_c$ dm^{-3}			mg dm^{-3}
Layer 0 – 2.5 cm										
100	5.81 a*	22.43 a	12.21 a	2.47 a	29.56 a	6.18 a	10.14 b	5.85 b	1.69 a	15.64 a
75	5.89 a	30.42 a	14.29 a	3.25 a	31.06 a	5.91 a	10.71 ab	6.43 ab	1.82 a	17.83 a
50	5.80 a	29.69 a	14.17 a	3.29 a	29.37 a	6.02 a	12.54 ab	6.50 ab	1.92 a	16.14 a
25	5.89 a	28.59 a	13.70 a	3.07 a	25.51 a	6.15 a	13.30 ab	6.59 ab	1.66 a	14.22 a
0	5.89 a	31.86 a	15.74 a	3.71 a	27.94 a	5.91 a	14.22 a	7.85 a	1.71 a	17.31 a
Layer 2.5 - 5 cm										
100	5.94 a	23.13 a	11.12 a	1.70 a	28.31 a	6.15 a	11.43 a	4.73 a	1.44 a	20.29 a
75	6.09 a	29.22 a	13.12 a	1.98 a	33.18 a	6.05 a	10.56 a	4.59 a	1.57 a	16.38 a
50	6.04 a	29.85 a	14.71 a	2.10 a	28.96 a	5.98 a	12.23 a	5.22 a	1.63 a	13.01 a
25	6.10 a	26.10 a	12.17 a	1.70 a	27.02 a	6.23 a	13.92 a	6.04 a	1.26 a	17.01 a
0	5.90 a	30.30 a	14.57 a	1.97 a	29.25 a	6.24 a	14.53 a	6.92 a	1.39 a	19.71 a
Layer 5 - 10 cm										
100	5.93 a	24.54 a	10.93 a	1.24 a	27.03 a	6.12 a	15.27 a	4.48 a	0.89 a	18.73 a
75	6.05 a	32.94 a	14.37 a	1.42 a	33.76 a	6.14 a	14.37 a	4.23 a	0.89 a	13.65 a
50	6.27 a	37.63 a	16.00 a	1.29 a	32.01 a	6.19 a	16.45 a	3.75 a	0.84 a	9.52 a
25	6.05 a	30.66 a	12.96 a	1.17 a	29.34 a	6.33 a	16.04 a	3.84 a	0.86 a	15.41 a
0	6.03 a	37.80 a	16.12 a	1.16 a	29.89 a	6.41 a	18.89 a	5.64 a	1.01 a	15.91 a
Layer 10 - 20 cm										
100	5.77 a	25.18 a	12.65 a	0.96 a	25.87 a	5.77 a	8.27 a	1.92 a	0.49 a	9.37 a
75	5.91 a	27.99 a	11.93 a	0.98 a	27.12 a	5.60 a	6.88 a	1.95 a	0.54 a	6.93 a
50	5.88 a	24.57 a	12.15 a	0.87 a	27.34 a	5.87 a	8.12 a	3.62 a	0.50 a	6.88 a
25	5.93 a	32.87 a	14.21 a	0.99 a	30.70 a	6.00 a	7.35 a	2.18 a	0.56 a	6.95 a
0	5.80 a	25.94 a	11.94 a	1.24 a	26.87 a	6.09 a	10.31 a	3.46 a	0.70 a	10.88 a
Layer 20 - 30 cm										
100	5.00 a	9.87 a	6.01 a	0.83 a	25.17 a	5.48 a	5.80 a	1.45 a	0.48 a	6.27 a
75	5.02 a	7.48 a	4.53 a	0.78 a	22.81 a	5.50 a	6.81 a	1.42 a	0.53 a	5.68 a
50	5.15 a	9.54 a	5.13 a	0.78 a	22.26 a	5.40 a	5.59 a	1.32 a	0.50 a	5.80 a
25	5.00 a	9.08 a	5.54 a	0.73 a	35.78 a	5.49 a	6.62 a	1.69 a	0.57 a	8.94 a
0	5.10 a	7.80 a	4.48 a	0.87 a	31.04 a	5.65 a	7.44 a	1.88 a	0.62 a	6.36 a

*Mean values followed by the same letter within each soil layer did not differ from each other according to Tukey's test (p<0.05).

2.3.3. Physical attributes

In the Oxisol the lowest values of BD were observed (1.60 to 1.79 Mg m^{-3}) and the highest SRP (2.5 to 12.8 MPa), compared to the Ultisol, where BD varied from 1.78 to 1.97 Mg m^{-3} and SRP from 0.9 to 5.1 MPa (Figures 3 and 4).

The values of BD and SRP in the area with a Oxisol increased with the rates of straw removal. In the 0-5 and 5-10 cm layers, lower BD values were observed for no-removal (1.60 and 1.63 Mg m^{-3}) compared to 75% (1.68 and 1.73 Mg m^{-3}) and 100% straw removal (1.75 and 1.79 Mg m^{-3}), respectively.

At 2.5 cm depth, the RP of total removal (8.3 MPa) was up to three times greater than the treatment without straw removal (2.5 MPa) (Figure 4). This relationship decreased along the profile, reaching 1.5 MPa at 30 cm depth, where no difference was found between the straw removal levels. In the Ultisol, any influence of the straw management was observed on the physical attributes (Figure 4).

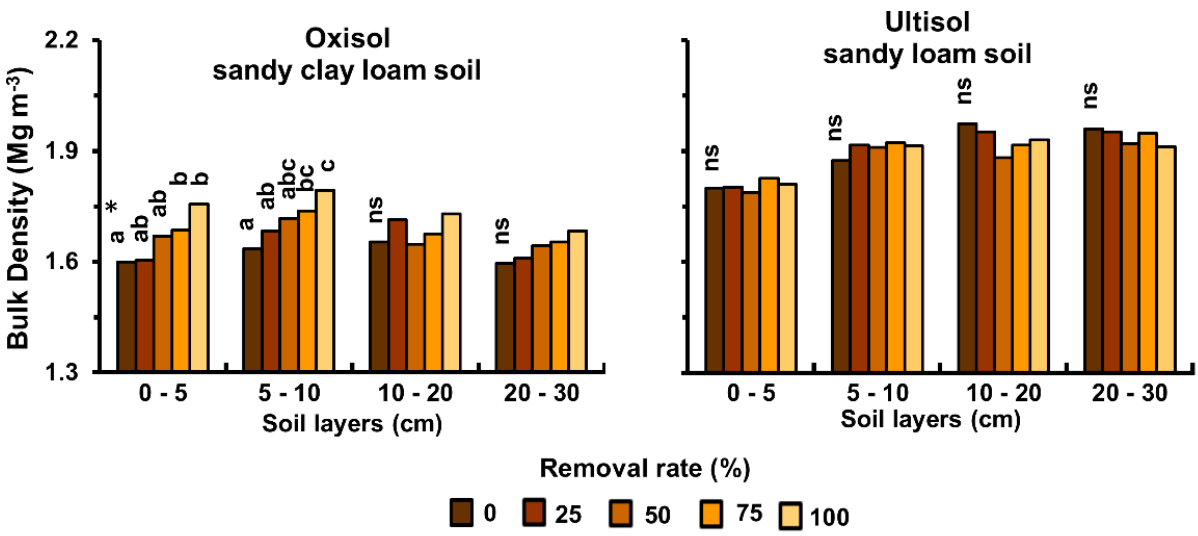

Figure 3. Average bulk density values under the different management systems and the soil layers analyzed in the experimental areas. *Mean values followed by the same letter did not significantly differ according to Tukey's test ($p<0.05$).

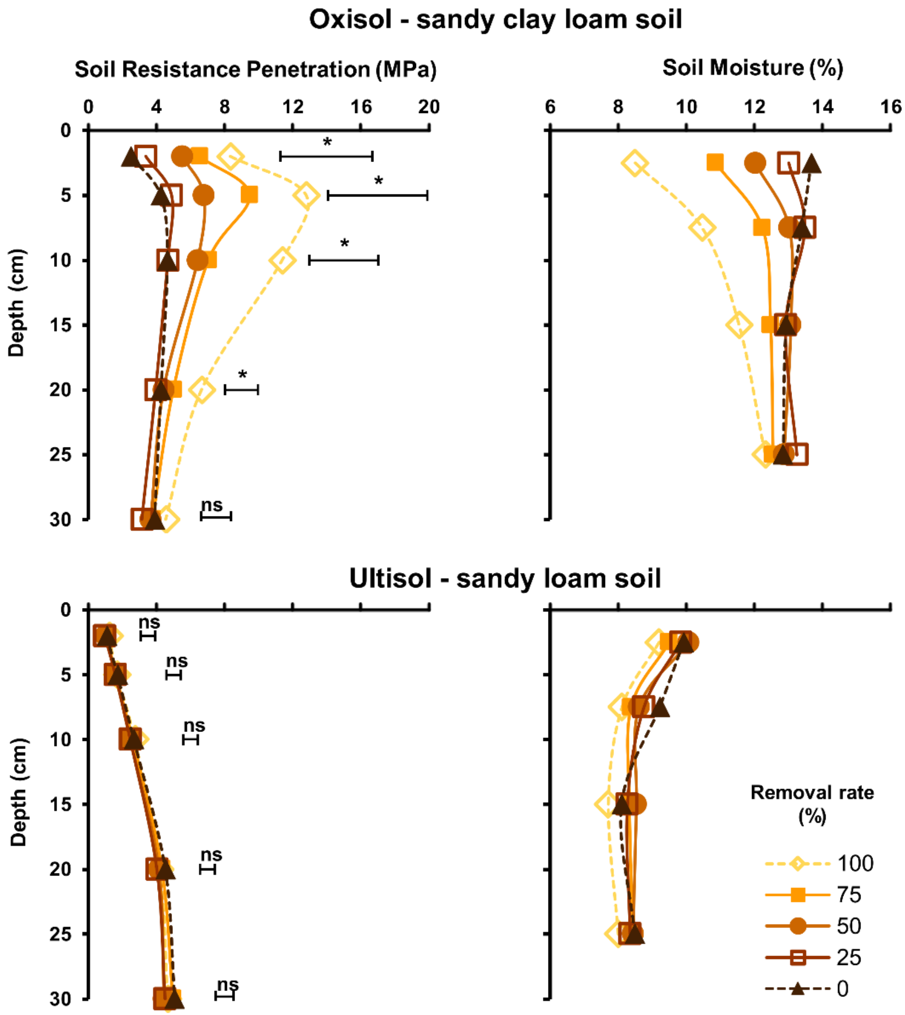

Figure 4. Soil resistance to penetration and moisture content by depth for the sandy clay loam soil and sandy loam soil. The horizontal bars indicate the least significant difference calculated by the Tukey test ($p<0.05$) and the comparison of the averages for the treatments in each layer. ns not significant. *significant.

2.3.4. Integrated analysis (Canonical discriminants)

The multivariate approach allowed an integrated assessment of straw removal effects on the soil quality, evaluating the effect of each soil attribute in the integrated results of straw removal management rates (Table 4 and Figure 5).

In the 0-2.5 cm layer, CDA showed that the first two canonical variables (CV) together were responsible to explain 97.8 and 86.9% of the data variance induced by straw removal in the Oxisol and Ultisol, respectively (Figure 5A-C). In the Oxisol, the straw removal resulted in the depletion of C, Ca, Mg and K and increased the RP, while the pH and P were weakly influenced by the treatments (Figure 5, A). In the Ultisol, C and pH presented more importance to distinguish the treatment in the CV1, while SRP and Ca were, respectively, the most relevant attributes in the CV2 (Figure 5 C).

In the 0-30 cm layer, the first two canonical variables explained 96.2 and 89.1% of the variability of the straw management systems in the in the Oxisol soil and Ultisol, respectively (Figure 5B-D). The SRP was the most important in the distinction of the treatments in the Oxisol, with weight three times higher than any other soil attribute in the VC1. In the VC2, C, N and SRP were the attributes that presented greater contributions. In the Ultisol, the influence of the attributes in the distinction of the straw management systems was more balanced, with C, Mg and Ca being more important in the VC1 and pH, Ca, P and Mg in the VC2.

Table 4. Values of the canonical discriminant coefficients

Soil attributes	Oxisol - sandy clay loam soil				Ultisol - sandy loam soil			
	0-2.5 cm		0-30 cm		0-2.5 cm		0-30 cm	
	VC1§	VC2‡	VC1	VC2	VC1	VC2	VC1	VC2
C	0.82	0.16	-0.14	-0.50	0.45	0.27	0.48	-0.15
N	0.16	0.47	0.12	-0.35	-0.10	0.22	0.14	0.10
Ca	0.56	-0.29	-0.25	-0.08	0.16	0.48	0.37	0.39
Mg	0.52	-0.01	-0.19	-0.21	0.29	0.19	0.46	0.21
K	0.60	-0.08	-0.13	-0.07	-0.04	-0.06	0.08	-0.18
P	-0.22	0.03	-0.17	0.24	0.02	-0.13	0.22	0.34
pH	0.14	-0.11	-0.11	0.03	-0.46	-0.08	0.29	0.78
SRP	-0.70	0.04	0.78	0.36	0.04	-0.72	0.29	-0.04

§ First canonical variable; ‡ two canonical variable.

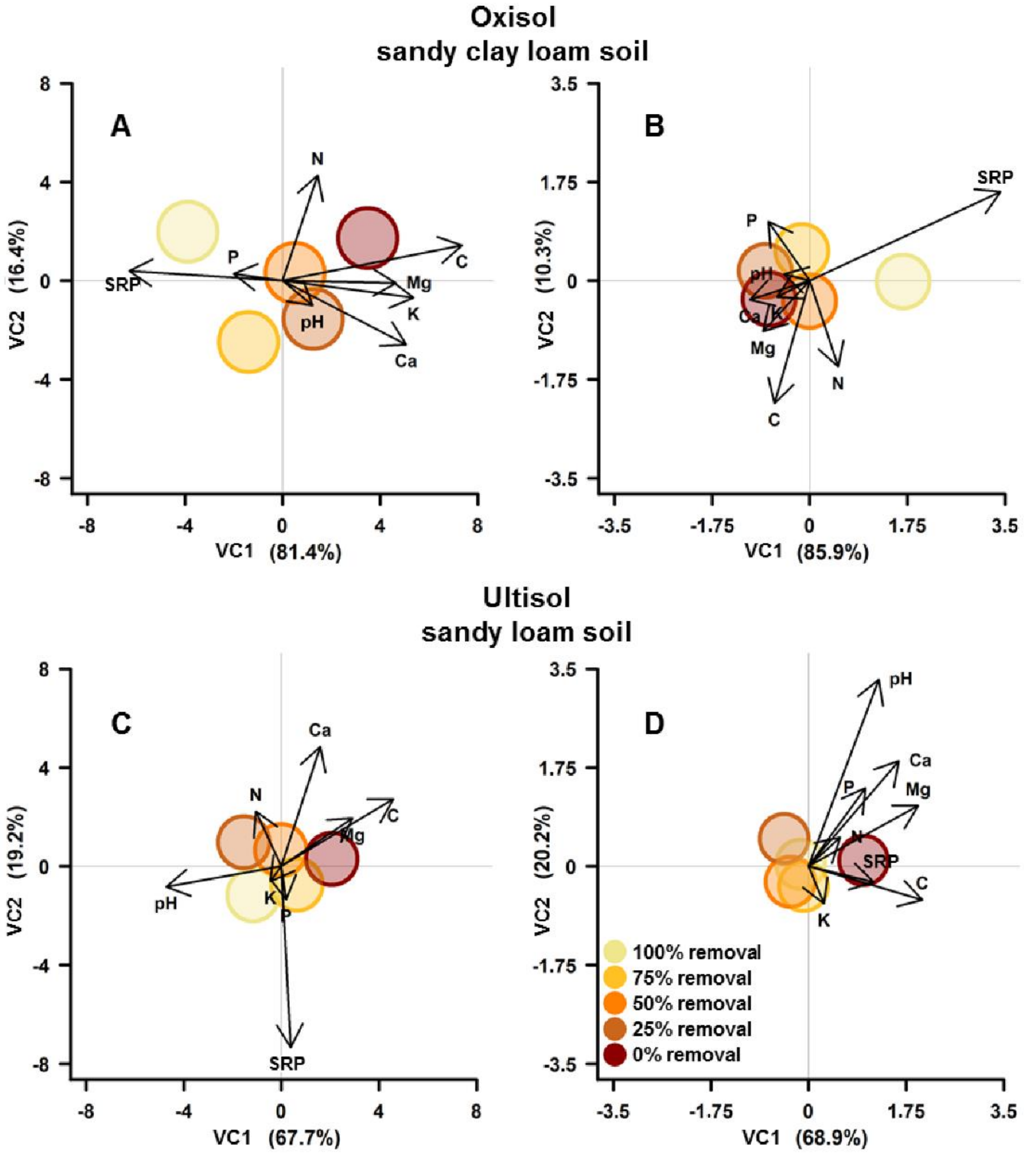

Figure 5. Biplot containing the means of the scores with 95% confidence ellipses and the loadings of the original variables in the first two canonical variables. When the ellipses overlap the straw management systems are not statistically different. The percentage of total variance explained by each canonical component is indicated in parentheses. A and C represent the layer of 0-2.5 cm and B and D the layer of 0-30 cm.

2.4. DISCUSSION

2.4.1. Impact of straw removal on soil C and N

In the sugarcane crops, C incorporation via deposition of plant residues is the most important factor to control and maintain the soil organic carbon (SOC) stocks (Carvalho et al., 2017; Cerri et al., 2011; Galdos et al., 2009; Oliveira et al., 2017). Assuming that the experimental sites have not reached their dynamic equilibrium, the maintenance of straw in the field would increase the soil C level. However, as soil C accumulation is strongly influenced by local conditions (Brandani et al., 2015; Carvalho et al., 2017; Cerri et al., 2011), a direct response between C incorporation (via maintenance of plant residues) and soil C accumulation may not be found (Mthimkhulu et al., 2016; Thorburn et al., 2012), as verified in the present study (Figure 1).

Similar pattern was observed by Thorburn et al. (2012) in a study established in Australia, where total removal and non-removal were compared. The authors reported that at the site where straw was kept for six years, carbon accumulated six-fold more than the site where straw was kept for 17 years. According to the authors, this difference was due to a site-specific factor, such as soil type and climate, which had a great influence on carbon dynamics.

Soil texture is recognized as one of the main factors associated with the protection and stabilization of soil C (Dieckow et al., 2009; Hao and Kravchenko, 2007). This property could explain the alterations in C stocks observed between the two experimental sites. Clay soils naturally accumulate more carbon because they are more efficient in stabilizing organic compounds (Six et al., 2002) due to their elevated reactivity that permits a higher number of bonds between the organic compounds and the mineral phase. These organo-mineral bonds favor the formation of micro and macro-aggregates, which chemically and physically protect the organic compounds against microbial action, increasing the residence time of soil C (Dieckow et al., 2009; Six et al., 2000). Through a review of related studies, Cerri et al. (2011) verified that sandy soils accumulate on average three times less C than clay soils. These values are compatible with those presented in this study, where the C stock (0-30 cm) in the Oxisol (sandy clay loam texture) was almost twice higher than the Ultisol (sandy loam texture).

Carbon depletion is one of the main trade-off associated with the straw removal for bioenergy production. Therefore, great efforts have recently been made to identify the rate of straw removal that causes the least impact on soil C stocks (Adler et al., 2015; Carvalho et al., 2017; Johnson et al., 2014; Tan and Liu, 2015a). In this study, the data shows that in Oxisol, the removal of straw more than 50 % cause the depletion of C stocks. In contrast, in the Ultisol, two years of management was not enough time to induce alterations in C stocks due to straw removal. Although the C stocks for the 0-30 cm layer had no statistical differences, we observed that the C stocks increased at a rate of 1.33 and 0.75 Mg ha^{-1} $year^{-1}$ in the Oxisol and Ultisol, respectively, comparing no removal and total straw removal treatments.

To our knowledge, there are no field studies available in the literature that measured the effects of sugarcane straw removal rates on SOC. Carvalho et. al. (2017) showed that C depletion increased with straw removal rates over the years, however these results were obtained through modeling, which requires field data to validate the findings. Cerri et al. (2011) evaluated soil carbon changes from burnt to unburnt sugarcane harvest management and found that when sugarcane straw was kept on field, the SOC increased at a rate of 1.5 Mg ha^{-1} $year^{-1}$, close to the value found here.

The potential decrease in soil C (especially in the long-term) (Carvalho et al., 2017; Liska et al., 2014; Oliveira et al., 2017) has aroused many discussions about the sustainability of bioenergy production, since C losses and their negative implications on soil quality may outweigh the environmental benefits offered by bioenergy production (Liska et al., 2014).

No reductions were observed in N stocks due to straw removal, similar to that reported by Thorburn et al., (2012) in a study carried out in Australia. These results may be associated with the relatively small amount of N released from the straw during this short period (Fortes et al., 2012), losses by leaching and volatilization (Otto et al., 2016), absorption by the crop (Ferreira et al., 2016), or those lost in the sampling and analytical processes (Oliveira et al., 2017). Despite this, studies have shown that in the long term, the management of straw can increase soil N stocks (Thorburn et al., 2012; Trivelin et al., 2013) to situations of reducing the use of nitrogen fertilizers by approximately 40 kg ha^{-1} yr^{-1} (Robertson and Thorburn, 2007; Trivelin et al., 2013).

2.4.2. Impact on the chemical quality of the soil

Sugarcane straw can contribute significantly to the cycling and supply of nutrients to plants (Fortes et al., 2013; Menandro et al., 2017; Trivelin et al., 2013). Approximately 35% of the nutrients extracted from the aboveground biomass is accumulated in the leaves (de Oliveira et al., 2010), and therefore, the removal of this residue over many years implies the extraction of large amounts of nutrients from the field (Menandro et al., 2017). In a study carried out in the same region of this study, Trivelin et al. (2013) observed in four cycles of sugarcane that the amount of N, P, K, Ca and Mg accumulated in straw corresponded to 227, 21, 408, 173, 60 and 41 kg ha^{-1}, respectively. Although many of the nutrients contained in straw are not readily available to the plants, their contribution should be accounted for fertilization management. According to Franco et al. (2013), when the straw is maintained in the field, the K2O application for the subsequent cultivation could be reduced by approximately 96 kg. For other nutrients such as N, the effects can only be observed in the long-term, however, up to 40 kg ha^{-1} year of N can be save (Trivelin et al., 2013).

In the present study, the straw's ability to alter the soil nutrient content varied according to the site conditions. This could be associated with the natural fertility of these soils. In the Oxisol (sandy clay loam texture), the higher initial values made the amount of mineralized nutrients derived from the straw insufficient to increase the availability of these nutrients or to interfere the soil acidity. On the other hand, since the area with Ultisol (sandy loam texture) is naturally poorer in nutrients the effect of straw removal was detected, even if subtly (Table 3).

Sugarcane straw removal is expected to alter more significantly K levels in the soil rather than Ca or Mg, since K is present in greater quantity in the straw and is readily released from residue to soil, once this chemical element is not part of any plant-structural compound. However, these results can be explained by factors that control the dynamics of these nutrients associated to the characteristics of the areas under study. The higher valence and smaller hydrated radius induce a stronger attraction between soil negative charges and Ca and Mg, compared to the K, increasing the adsorption and accumulation of these elements in the superficial layers of the soil. The increase in competition for the soil adsorption sites associated with the good soil drainage favored the K leaching in the upper layers (Werle et al., 2009). In this way, K released from the straw is diluted among the deeper layers, resulting in no significant differences between the straw removal levels.

Several studies evaluated soil chemical changes from burnt to unburnt sugarcane harvest management (e.g., Liao et al., 2014; Souza et al., 2012); however, studies with field measurements of the impacts of sugarcane straw removal rates on soil chemical properties are inexistent in the literature. The only study available was recently performed in laboratory conditions by Aquino et al. (2015), who observed that after 60 days, sugarcane straw removal rates subtly modified Ca and Mg contents, while K content and pH were not affected, corroborating with the results found in this study.

Although the alterations in chemical quality were subtle in the short-term, the removal of straw in the long-term could prejudice the plant development. In addition to the reduction of soil nutrient contents, there may be a depletion of organic material (OM), which has a great influence on the nutrient storage capacity of tropical soils.

The impact caused by straw removal on the soil chemical attributes can be minimized by the replacement of nutrients through the application of mineral fertilizers (Adler et al., 2015; Tan and Liu, 2015a, 2015b). However, the viability of nutrient replacement should be better evaluated, since there is an environmental cost associated with the production of fertilizers (i.e. residue production and the emission of GHGs) and the fertilizer raw materials and reserves are limited in the future (Isherwood, 2000). On the other hand, the use of organic residues from sugarcane industry [e.g., vinasse (in nature or concentrated) and filter cake] could be offset part of nutrient removal by straw management, recycling nutrients and increasing the sustainability of sugarcane production system.

2.4.3. Impact on the physical quality of the soil

Several studies have shown that the maintenance of crop residues on the soil surface has an important role in maintaining or improving the physical quality of the soil (Cherubin et al., 2017; Reichert et al., 2016; Tormena et al., 2017). The positive effects of the straw maintenance are associated with three main aspects: i) the layer of straw formed on the soil surface protects against the direct impact of rain drops and increases the roughness of the terrain, thus reducing the intensity of any erosive processes (Rocha Junior et al., 2016; Silva et al., 2012); ii) the contribution of organic matter, which not only increases the aggregates stability in the soil, but also promotes higher resilience and structural resistance of soils (Six et al., 2002, 2000); iii) the mechanical characteristics of straw such as low density, elasticity and susceptibility to deformation, allows to dissipate part of the pressures applied to the soil, such as the ones from agricultural machinery (Braida et al., 2006).

In the present study, only the Oxisol (sand clay loam soil) had the physical attributes affected by the levels of straw removal (Figure 3 and 4). At this site, the BD and SRP increased with the levels of straw removal, mainly in the superficial layers. According to Blanco-Caqui et al. (2006; 2007) the alteration for these attributes may occur not only due to the straw removal, but also in combination with local conditions (e.g., soil type).

Bulk density and SRP are measurements used to infer about the soil compaction. However, SRP is strongly influenced by soil moisture, i.e., its values are lower when the soil is more moist (Moraes et al., 2013; Otto et al., 2011). According to the results, straw removal induces soil compaction and increases impedance to root development, which may be even more limiting to plant development due to lower available water content under this type of management. We did not correct the SRP values to equivalent soil moisture, because the variation of soil moisture is an inherent effect of straw management adopted, and therefore, it cannot be overlooked. It is important to highlight that high SRP values observed in this study are not commonly found in the literature. However, the results can be explained due to the fact that this evaluation was carried out between the rows of sugarcane, an area that soil is under intense pressure caused by the agricultural traffic (Roque et al., 2010; Souza et al., 2015, 2014). Additionally, the soil SRP was measured in low moisture conditions resulting in measurement with higher values (Moraes et al., 2013; Otto et al., 2011).

Soil compaction is one of the biggest concerns in the cultivation of sugarcane, especially after the introduction of mechanical harvesting in the last few decades. Successive traffic of machines intensifies the soil compaction, directly affecting the physical quality of soils (Cherubin et al., 2016b; Otto et al., 2011; Souza et al., 2015, 2014). According to Cherubin et al. (2016b), the compaction in sugarcane fields occur to such a magnitude that physical functions of soil can be reduced to 58% of its capacity, limiting plant development and other processes that take places in the soil, such as gas exchange and water movement.

In general, the results suggest that straw removal induces soil physical quality degradation, however, the damage caused by this processes depends on the local conditions of cultivation. In the Oxisol, straw removal of more than 25 % caused soil physical quality reduction, making it less favorable to plant development. On the other hand, no differences were observed in the Ultisol (sandy loam soil). In this way, managing the straw in the system could mitigate the impact caused by the intense traffic of machines.

2.4.4. Removal of sugarcane straw vs. soil quality

When comparing the areas, it was observed that some soil attributes had different weights under distinct management systems. We believe that this result is also related to soil texture. In the superficial layer of the Ultisol with sandy loam texture, the lower cation exchange capacity coupled with the lower preference for adsorption caused K leaching along the profile, thus reducing its contribution to distinct the treatments. However, the pH was more important because the soil in this area has a lower buffering capacity. Therefore, this soil likely was more sensitive to the alterations of pH caused by the decomposition of crop residues. In the 0-30 cm layer of the Ultisol, the importance of each attribute in treatment distinction was more balanced due to mainly two reasons: the lack of effect of the straw removal on soil physical quality and the greater sensitivity of the chemical dynamics to the same management.

In general, the removal of sugarcane straw induced degradation of soil quality. The magnitude of this degradation varied with the site conditions. Greater impact was observed in the more superficial soil layers. It is noteworthy that although changes in soil C were observed more intensely in the superficial layers, when the entire profile was analyzed, this attribute was shown to be important in the distinction between management systems (Figure 5, C and D). The integrated evaluation reiterates that in areas with greater amount of clay, the physical quality is more affected by the removal of straw, whereas in areas with sandy texture, the chemical attributes are more influenced.

Our findings also showed that sandy loam soils were more sensitive to straw removal when compared to soils with a higher clay content. In the Ultisol the removal of any amount of straw altered the environment (Figure 5, D), while in the Oxisol the removal of 25 and 50 % of the straw was not significantly different from the no-removal treatment (Figure 5, B). However, total straw removal caused greater damage to soil quality in Oxisol, since the multivariate mean for the total straw removal was more distant from the multivariate means for the other treatments (Figure 5B-D).

Based on the soil attributes analyzed in this study, the straw removal of up to 50 % (8.7 Mg ha^{-1} of remaining straw) in the Oxisol did not affect soil quality. This value is close to that reported by Carvalho et al. (2016), where most agronomic and environmental benefits are achieved when at least 7 Mg ha^{-1} of straw is maintained in the field. In the Ultisol, the impact caused by the straw removal rates were less intense, however, any amount was enough to alter the quality of the soil.

The adoption of more conservative management practices (e.g., cover crop cultivation during the fallow before sugarcane replanting, no-tillage, organic residues application) have been proposed as potential solutions to minimize the negative impact of straw removal on soil functions (Cherubin et al., 2017). When straw removal management is conducted coupled with some best management practices, the benefits achieved may be even greater. Oliveira et al. (2017) predicted a potential soil C accumulation of 0.25 Mg ha^{-1} $year^{-1}$ by maintaining only 3 Mg ha^{-1} of straw on the soil's surface(i.e., 75% of straw removal), if a no-tillage system is adopted together with the application of organic fertilizers (filter cake and vinasse).

In this way, long-term studies that involve and monitoring other indicators of sustainability such as water dynamics, biodiversity, soil losses through erosion and plant yield, are fundamental for expanding the scope of results reported here.

2.5. CONCLUSION

The impact caused by short-term sugarcane straw removal are concentrated in the soil surface layers. The magnitude of alterations is influenced by the site conditions and therefore, this factor should be better studied and taken into account in the sugarcane straw management. In the Oxisol with sandy clay loam texture, the straw removal induced C stock depletion and lead to the physical degradation of soil. In contrast, the straw removal impacts on soil chemical attributes were more significant in the Ultisol with sandy loam texture.

In general, the results suggest that straw removal causes reduction more significant in soil quality for the sandy clay loam soil. In the short-term, the results indicate the possibility to remove for bioenergy production about a half of the straw amount deposited on soil's surface (8.7 Mg ha^{-1} straw remaining) without causing severe implications on the quality of this soil. In contrast, although any amount of straw was sufficient to cause alterations the quality of the sandy loam soil, these impacts were less intense and are not magnified with the increase of straw removal. Nevertheless, we do not recommend the indiscriminate straw removal in these soils, which are highly depend on soil organic matter to storage water and nutrient to plants.

2.6. Acknowledgments

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3. PREDICTION OF SUGARCANE YIELD BY SOIL ATTRIBUTES UNDER STRAW REMOVAL

ABSTRACT

Concerns about global warming and climate change have boosting the global demand for renewable energy. In Brazil, the sugarcane straw left on the field after harvest has been indicated as the main solution to increase the bioenergy productivity. However, uncertainties about the amount of straw produced per hectare, as well as the effects of straw removal on the soil quality and plants yield, make difficult to plan a sustainable industrial use of this raw material, justifying field investigations to clarify these doubts. In this sense, this study aimed to develop a model capable to estimate sugarcane yield (stalk and straw) by soil attributes in two sites managed with straw removal (i.e., 0, 25, 50, 75 and 100 % of straw removal rates, and straw piled in the inter-row position). Soil samples were collected and straw and stalk yield were quantified after two years of straw removal effect. The soil attributes evaluated were C, N, Ca, Mg, P, K, pH, BD and soil penetration resistance, in the 0-5, 0-10, 0-20, and 0-30 cm soil layers. The data were subjected to descriptive statistical, geostatistical, simple linear correlation and a multiple linear regression analyses. Our findings showed the straw and stalk yield can be efficiently predicted using soil attributes in sites where straw removal is practiced. The best modelling coefficients for stalk yield were obtained using soil data from the 0-20 cm layer (mean of $r^2 = 0.52$). Likely, it explains why the soil changes induced by straw removal at least in short term (which is limited to superficial layer) have little, or no influence on sugarcane stalk yield. Straw yield modeling, although possible, seems to be more complex, requiring the use of additional information (e.g., cultivars characteristics and meteorological variables) to obtain more accurate models. We also found that Meteorological conditions is an additional factor that influences in the straw/stalk ratio and therefore the amount of straw produced per hectare. The results obtained in this study provided science-based information that will help the sugarcane sector in decision making and planning of the industrial use this raw material, contributing for a more sustainable production of the bioenergy in Brazil.

Keywords: Yield modelling; Straw management; Stalk yield

3.1. INTRODUCTION

In order to mitigate climate change, government actions have been adopted to replace the use of fossil fuels by renewable energies, e.g. ethanol (Rogelj et al., 2016). Using sugarcane as raw material, Brazil produced 27.81 billion liters of ethanol in 2017 (Conab, 2017), consolidating as the world's second largest ethanol producer. Even with this production, Brazilian government projections point out that to meet market demands, ethanol production is expected to increase by 16 billion liters by 2026 (Brasil, 2017). To achieve this growing bioenergy demand is necessary not only expand the sugarcane cultivated area, but also increase the productivity of current areas (Marin et al., 2016).

Using sugarcane straw left on the soil for second generation ethanol and bioelectricity production has been pointed out as one of the main ways to increase bioenergy production in this short term (Ferreira-Leitão et al., 2010; Cardoso et al., 2013; Losordo et al., 2016). The amount of straw yield can range to 4.1 to 32 Mg ha^{-1} per crop cycle (Menandro et al., 2017), and each ton of dry matter can produce 283 L of ethanol (Santos et al., 2012). Therefore, with the use of this raw material, the markets demands can be reached without need to expand the cultivated area and still contributing to greenhouse gases mitigation (Tilman et al., 2009; Ferreira-Leitão et al., 2010).

However, there is an environmental cost associated with this activity (Carvalho et al., 2017; Cherubin et al., 2018). Straw removal, even in short term, can reduce soil organic carbon, nutrient cycling and compact the soil, especially in the more superficial layer (~ 5 cm) (Satiro et al., 2017). The association of these factors can compromise the ecosystem services provided by soil, and its capacity to sustain plant growth (Aquino et al., 2017a,b) Nevertheless, little or even none straw removal influence on sugarcane productivity has been was observed (Olivier and Singels, 2012; Lisboa et al., 2018). It may be associated with some factors, such as: i) ideal edaphic-climatic conditions for the crop development; ii) efficient use of solar radiation associated with the long sugarcane cycle that allows the recovering of crop from adverse conditions (Inman-Bamber, 2013); iii) soil surface layer affected by straw removal has little representative on the soil volume explored by root system, and thus, it has no influence on crop yield, at least, in short term.

The uncertainties regarding the straw management impact on the sugarcane yield and on the amount of straw produced per hectare, makes it difficult to plan the industrial use of this raw material. In this sense, we preformed this study to test the following hypotheses: i) soil changes induced by the short-term straw removal have no influence on sugarcane yield; ii) model based on soil attributes can efficiently predict sugarcane yield (straw and stalk). The objective was to develop models capable of estimating sugarcane yield (straw and stalk) using soil layers from sites managed with different intensity of straw removal.

3.2. MATERIAL AND METHODS

3.2.1. Characterization of the experimental areas

The study was carried out in the municipalities of Capivari (22° 51'01" S 47° 30' 44" W, 571 masl) and Valparaíso (21° 22' 23" S 50° 51' 22" W, 385 masl), state of São Paulo, Brazil (Figure S1). At Capivari soil was classified as Rhodic Kandiudox with sandy clay loam texture while at Valparaíso the soil was classified as Kanhaplic Haplustults with a sandy loam texture (Soil Survey Staff, 2014). The climatic classification of the sites follows the Köppen classification for Brazil, proposed by Alvares et al. (2013). In Capivari was classified as humid subtropical climate with hot summer (Cfa) and in Valparaíso as tropical climate with dry winter season (Aw).

Additional meteorological information of these sites, such as precipitation, global radiation and solar radiation at the top of atmosphere are shown in Figure 1. At Capivari sugarcane variety cultivated was CTC 14 and at Valparaíso was RB 86-7515. In both sites, sugarcane has been cultivated for more than 40 years. In the last ten years, the harvest system has been changed from manual (burned harvest) to mechanized harvest (green harvest), and since 2014 experiments of straw removal rates have been conducted (Figure S2). The experimental design adopted in the studies, as well as the different removal rates are described in Satiro et al. (2017) and in the supplementary material (Figure S3, S4 and Table S2).

3.2.2. Sampling and analysis

In order to have a suitable spatial representation of the site, 72 sampling points were demarcated with global positioning system (GPS) in each experimental area of approximately 3 ha (Figure 2). In August 2016, two years after the treatments application, in two thirds of the points marked, 4 m of biomass were harvested manually before the mechanized harvest, to determine straw and stalk yield.

After harvest, a soil sampling was performed as illustrated in Figure S5. At each point, a trench of approximately 30 x 30 x 30 cm was opened to collect disturbed soil samples in the 0-2.5, 2.5-5, 5-10, 10-20, and 20-30 cm layers, to characterize chemical attributes and soil C. Four measurements of soil resistance penetration (PR) were carried out 1 meter to side each trench.

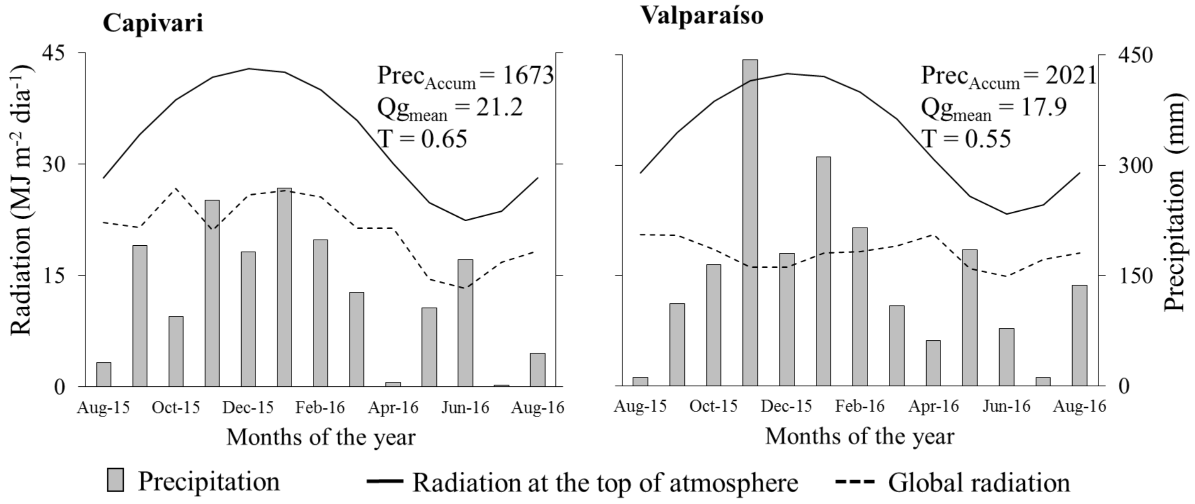

Figure 1. Precipitation, global radiation and solar radiation at the top of the atmosphere along second sugarcane ratoon (August/2015 to August/2016) in the two study areas. T: transmittance (without unit); Qg_{mean}: annual average of global radiation (MJ m^{-2} dia^{-1}); $Prec_{accum}$: accumulated precipitation (mm). Sources: CEPAGRI (http://www.cpa.unicamp.br) and ESALQ (http://www.leb.esalq.usp.br/posto).

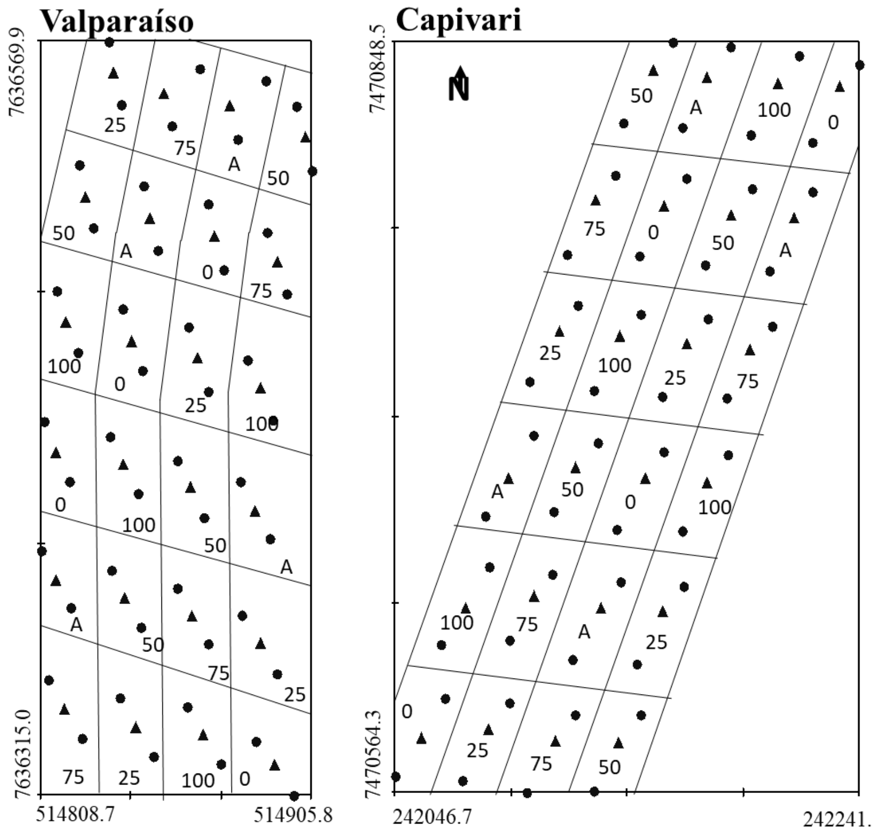

Figure 2. Experimental sites with georeferenced sampling points. Each rectangle represents an experimental plot; the numbers represent the treatments (straw removal rate - %); **A:** straw mulched in the inter-row position; ●▲: point for characterization of C, chemical attributes and PR; ●: points for characterization of BD, straw and stalk yield.

For reducing the inherent variation of this evaluation, four-measurement average was used to represent the composite PR value. In same 2/3 of points utilized for biomass determination, undisturbed soil samples (volumetric rings) were taken in the 0-5, 5-10, 10-20, and 20-30 cm layers to determine bulk density (BD) (Figure S5). Within each experimental site, it was used 72 samples to quantify soil C, PR and chemical attributes as well as 48 points to quantify BD and productivity parameters (stalk and straw) (Figure 2).

All plant biomass contained in the four meters of line were separated in stalk and leaves straw (composed by dry and green leaves) for later weighing. Subsamples of each component were oven-dried at 65 °C for dry mass quantification. Soil samples were air dried and sieved on a 2 mm mesh to obtain: total organic carbon (C), total nitrogen (N), pH, calcium (Ca), magnesium (Mg), phosphorus (P) and potassium (K) according to the methodology described by Raij et al. (2001); the BD was determined by volumetric ring method (EMBRAPA, 2011); PR was directly measured in the field using an impact penetrometer (Stolf, 1983) and the PR data in the soil profile was obtained through the equation proposed by Stolf et al. (2014). Based on results for each soil layer, the weighted averages for the 0-5, 0-10, 0-20 and 0-30 cm soil layers were calculated.

3.2.3. Statistical analysis

The data was subjected to descriptive statistical analysis to verify position and dispersion measurements. The statistical parameters determined were: minimum; mean; median; maximum and coefficient of variation (CV). The CV values were classified according to Pimentel Gomes & Garcia (2002), being: low ($CV \leq 10\%$), medium ($10\% < CV \leq 20\%$), high ($20\% < CV \leq 30\%$) and very high ($CV > 30\%$).

In order to verify the importance of each soil layer (0-5, 0-10, 0-20, 0-30 cm) in the sugarcane yield (stalk and straw) and establish relationships among sugarcane yield and soil attributes, the data were correlated using Pearson's linear correlation matrix and multiple regression analysis (MRA) using the R software (R Core Team, 2017). Previously to MRA, collinearity among soil attributes was verified, eliminating those that presented correlations greater than 0.85.

The spatial analysis was performed with the MRA-predicted and real yield data with the aim to evaluate the map similarities. The spatial dependence analysis was performed through the construction of semivariograms in Software Gamma Design 7.0 (Robertson, 2008). When spatial dependence was found, the theoretical mathematical model was adjusted by initial selection of: lower residual squared sums (RSS), higher coefficient of determination (R^2) and spatial dependency index (SDI). It was obtained following parameters of the adjusted mathematical models: range (a), nugged effect (C0), contribution (C1) and sill (C0 + C1). The SDIs were calculated using the equation:

$$SDI = [C0 / (C0 + C1)] \times 100$$

Based on the SDIs, the spatial dependence evaluation (SDE) was classified according to Cambardella et al. (1994), being: weak (SDI $\geq$ 0.75), moderate (0.25> SDI <0.75) and strong (SDI $\leq$ 0.25). The parameters that did not present spatial dependence were interpolated by inverse distance weighted (IDW).

3.3. RESULTS

3.3.1. Descriptive analysis

All soil attributes evaluated at Valparaíso (except pH) presented smaller averages than Capivari (Tables 1 and 2). In both sites, soil C and soil chemical attributes decreased in depth. In Capivari, BD and PR increased from 0-5 cm layer to intermediate layers (0-10 and 0-20 cm) and decreased again in the 0-30 cm layer, whereas, these values increased according to increase the soil layer thickness in Valparaiso.

The data dispersion was lower in the thicker soil layers. In other words, the attributes of layer 0-5 cm had greater dispersion than the attributes of layer 0-10 cm, and so on. For all dataset, mean and median values were similar, indicating that data frequency followed a normal distribution curve (Pimentel-Gomes and Garcia, 2002). The CV values were low for pH and BD in the two sites; medium for C and PR at Valparaiso and P at Capivari. The other soil attributes presented CV ranging from high (i.e., N at Valparaiso; Ca and Mg at Capivari) to very high (i.e., Ca, Mg, K and P at Valparaiso; PR and K at Capivari).

Sugarcane stalk and straw yields in Valparaiso were respectively 37.96 and 11.20 Mg ha^{-1}. In Capivari, stalk and straw average yields were 72 and 20 % higher than those observed in Valparaíso, being respectively 65.30 and 13.44 Mg ha^{-1} (Tables 1 and 2). At both sites, yield data presented median dispersion (10% <CV $\leq$ 20%) following a normal distribution curve.

Table 1. Descriptive statistics of soil attributes and yield of straw and stalk in the Valparaíso site

Statistical parameter	C	N	Ca	Mg	K	P	pH_{water}	BD	PR	Stalk	Straw
	$g\ kg^{-1}$		$mmol_c\ dm^{-3}$			$mg\ dm^{-3}$	unitless	$Mg\ m^{-3}$	MPa	$Mg\ ha^{-1}$	
						0-5 cm					
Mean	0.66	0.04	12.95	6.44	1.68	15.30	6.07	1.84	1.39	37.96	11.20
Median	0.63	0.04	12.72	6.14	1.31	14.88	6.10	1.87	1.38	38.20	11.10
Minimum	0.48	0.03	3.18	1.99	0.81	8.34	5.32	1.50	0.56	30.60	7.07
Maximum	1.22	0.07	24.13	15.59	5.07	26.87	6.47	1.99	1.93	49.40	14.45
C.V	19.60	22.81	38.25	43.12	58.24	27.52	4.57	6.06	13.23	11.14	16.35
						0-10 cm					
Mean	0.61	0.04	14.50	5.71	1.44	14.52	6.12	1.88	1.84		
Median	0.60	0.04	14.45	5.59	1.14	13.70	6.18	1.90	1.82		
Minimum	0.47	0.03	3.62	1.94	0.66	7.93	5.23	1.66	1.45		
Maximum	0.83	0.06	37.72	10.06	4.14	30.94	6.57	1.99	2.44		
C.V	12.73	20.39	38.87	38.37	56.92	33.30	5.27	4.25	11.41		
						0-20 cm					
Mean	0.55	0.03	11.74	3.79	0.93	10.61	6.02	1.93	3.24		
Median	0.53	0.03	11.69	3.57	0.84	9.60	6.03	1.94	3.23		
Minimum	0.46	0.02	3.25	1.11	0.43	5.69	5.07	1.81	2.35		
Maximum	0.73	0.07	27.12	6.59	2.15	18.97	6.57	2.01	4.42		
C.V	11.67	28.13	39.23	38.98	41.28	31.99	5.79	2.35	12.36		
						0-30 cm					
Mean	0.51	0.03	9.69	3.18	0.79	10.13	5.84	1.94	3.76		
Median	0.51	0.03	9.50	3.04	0.72	9.10	5.85	1.94	3.69		
Minimum	0.44	0.02	3.33	1.09	0.41	5.30	5.10	1.80	2.80		
Maximum	0.66	0.05	15.75	7.20	1.66	23.91	6.38	2.02	4.86		
C.V	8.98	19.11	31.57	39.89	31.70	36.46	4.94	2.29	12.37		

Table 2. Descriptive statistics of soil attributes and yield of straw and stalk in the Capivari site

Statistical parameter	C	N	Ca	Mg	K	P	pH_{water}	BD	PR	Stalk	Straw
	g kg^{-1}		mmol$_c$ dm^{-3}			mg dm^{-3}	unitless	Mg m^{-3}	MPa	Mg ha^{-1}	
						0-5 cm					
Mean	1.40	0.10	26.67	13.05	3.32	30.24	5.79	1.64	5.96	65.30	13.44
Median	1.35	0.09	26.42	13.19	3.13	30.16	5.84	1.64	4.99	61.10	12.79
Minimum	0.88	0.05	12.26	6.98	1.58	22.41	5.12	1.48	1.79	42.40	7.88
Maximum	2.61	0.25	43.32	20.81	6.41	43.49	6.20	1.89	14.26	85.70	19.16
C.V	18.87	30.74	25.22	22.43	35.52	15.22	4.35	5.87	64.65	19.02	19.42
						0-10 cm					
Mean	1.29	0.09	28.58	12.92	2.50	29.62	5.88	1.68	6.16		
Median	1.26	0.08	28.66	13.25	2.43	29.90	5.95	1.66	5.31		
Minimum	1.02	0.06	13.75	6.50	1.26	19.33	4.97	1.57	2.04		
Maximum	1.93	0.16	50.21	22.55	4.78	39.49	6.34	1.91	14.00		
C.V	12.45	20.71	27.15	25.18	33.74	14.53	4.42	4.58	58.05		
						0-20 cm					
Mean	1.20	0.08	26.21	11.78	1.92	27.92	5.83	1.68	5.41		
Median	1.19	0.08	26.29	11.68	1.85	27.96	5.91	1.69	4.62		
Minimum	0.97	0.06	10.94	6.31	1.13	17.38	4.95	1.60	2.58		
Maximum	1.50	0.11	47.81	18.68	3.64	40.30	6.34	1.79	10.74		
C.V	10.06	17.06	29.17	27.06	33.14	16.19	4.85	3.06	43.80		
						0-30 cm					
Mean	1.12	0.07	20.74	9.54	1.61	27.22	5.59	1.67	4.85		
Median	1.12	0.07	20.19	9.04	1.51	26.94	5.62	1.68	4.24		
Minimum	0.95	0.05	10.37	5.14	0.98	16.43	4.94	1.56	2.61		
Maximum	1.40	0.10	34.74	14.71	2.73	39.35	5.96	1.76	9.07		
C.V	8.78	15.75	25.56	24.98	29.57	16.31	3.61	3.07	36.03		

3.3.2. Linear correlation between soil attributes and yield (stalk and straw)

In Valparaiso, BD, PR and P presented significant linear correlation with stalk yield (Table 3). In all layers, PR obtained significant correlation with stalk yield, being the highest coefficient observed in 0-20 cm layer (r = -0.49). For BD, only layers 0-20 (r = -0.42) and 0-30 cm (r = -0.37) were significant. The other attributes did not present significant correlation. In Capivari, stalk yield correlated significantly with pH in the 0-20 cm (r = 0.47) and 0-30 cm layers (r = 0.39), and with K content in the 0-30 cm layer (r = 0.38).

Only N content in the 0-30 cm layer was correlated (r = 0.39) with straw yield in Valparaíso (Table 3). In Capivari, C and N content presented direct correlation with straw yield, with coefficients varying from 0.39 to 0.59; BD, PR and pH presented inverse correlation, with coefficients varying from -0.38 to -0.59. Among these attributes, only PR was significant in all layers; however, the highest coefficients were observed for N content and BD in the 0-5 cm layer (r = 0.59).

3.3.3. Yield prediction with multiple regression analysis

Stalk yield predictions based on soil attributes presented determination coefficients (R^2) ranging from 0.28 to 0.58 in Valparaíso and from 0.14 to 0.47 in Capivari (Table 4). In both sites, the highest determination coefficients were obtained using soil data from the 0-20 cm layer. In Valparaiso, C, Mg, P, PR and BD values from the 0-20 cm layer explained 58% of stalk yield whereas in Capivari N, Ca, Mg and pH values from the 0-20 layer cm explained 47%.

In Valparaíso, it was not possible to build a significant model to explain straw yield using soil attributes (Table 4). In Capivari, models that used 0-5 and 0-20 cm layers data obtained the highest R^2. The combined use of N and BD values from the 0-5 cm layer explained 44% of the straw yield, while the N, Ca, Mg, P and PR values from the 0-20 layer explained 42% of the straw yield.

Table 3. Linear correlation coefficients between soil attributes and production parameters (straw and stalk) in two areas in different soil layers

Soil layer	C	N	Ca	Mg	K	P	pH_{water}	BD	PR
cm	g kg^{-1}		$mmol_c$ dm^{-3}			mg dm^{-3}	---	Mg m^{-3}	MPa
Valparaíso									
Stalk									
0-5	-0.17^{ns}	-0.06^{ns}	0.03^{ns}	-0.08^{ns}	0.14^{ns}	-0.26^{ns}	-0.31^{ns}	-0,11^{ns}	-0,44*
0-10	-0,19^{ns}	-0,06^{ns}	0,06^{ns}	-0,08^{ns}	0,09^{ns}	-0,30^{ns}	-0,27^{ns}	-0,14^{ns}	-0,40*
0-20	-0,21^{ns}	-0,19^{ns}	0,09^{ns}	0,00^{ns}	-0,02^{ns}	-0,38**	-0,08^{ns}	-0,42*	-0,49*
0-30	-0,26^{ns}	-0,31^{ns}	0,09^{ns}	-0,02^{ns}	-0,02^{ns}	-0,34^{ns}	-0,05^{ns}	-0,37**	-0,47*
Straw									
0-5	0.18^{ns}	0.00^{ns}	0.23^{ns}	0.25^{ns}	0.20^{ns}	-0.07^{ns}	0.27^{ns}	0.06^{ns}	0.21^{ns}
0-10	0.21^{ns}	0.13^{ns}	0.26^{ns}	0.29^{ns}	0.17^{ns}	-0.09^{ns}	0.28^{ns}	0.07^{ns}	0.16^{ns}
0-20	0.30^{ns}	0.26^{ns}	0.20^{ns}	0.23^{ns}	0.18^{ns}	-0.11^{ns}	0.21^{ns}	0.31^{ns}	0.28^{ns}
0-30	0.26^{ns}	0.39**	0.21^{ns}	0.26^{ns}	0.27^{ns}	-0.15^{ns}	0.22^{ns}	0.31^{ns}	0.31^{ns}
Capivari									
Stalk									
0-5	-0.08^{ns}	-0.05^{ns}	0.01^{ns}	-0.19^{ns}	0.28^{ns}	-0.08^{ns}	0.11^{ns}	-0.08^{ns}	0.01^{ns}
0-10	0.06^{ns}	-0.18^{ns}	0.03^{ns}	-0.09^{ns}	0.33^{ns}	0.07^{ns}	0.28^{ns}	0.01^{ns}	0.03^{ns}
0-20	0.25^{ns}	0.11^{ns}	0.25^{ns}	0.13^{ns}	0.30^{ns}	0.00^{ns}	0.47*	-0.01^{ns}	-0.02^{ns}
0-30	0.24^{ns}	0.11^{ns}	0.27^{ns}	0.04^{ns}	0.38**	0.22^{ns}	0.39**	-0.01^{ns}	-0.03^{ns}
Straw									
0-5	0.47*	0.59*	-0.01^{ns}	-0.02^{ns}	0.32^{ns}	0.08^{ns}	-0.38**	-0.59*	-0.43*
0-10	0.35**	0.39**	-0.10^{ns}	-0.14^{ns}	0.26^{ns}	0.00^{ns}	-0.28^{ns}	-0.54*	-0.47*
0-20	0.28^{ns}	0.35**	0.09^{ns}	0.03^{ns}	0.23^{ns}	0.20^{ns}	-0.02^{ns}	-0.35**	-0.48*
0-30	0.18^{ns}	0.24^{ns}	0.10^{ns}	0.05^{ns}	0.17^{ns}	0.23^{ns}	0.04^{ns}	-0.23^{ns}	-0.47*

*$P \leq 0.05$.

**$P \leq 0.10$.

ns, no significant at $P \leq 0.05$

Table 4. Models based on multiple linear regression for predicting sugarcane straw and stalk yield using soil attributes from different layers

Layer (cm)	Model	R^2	*p*-value
Predictions of stalk yield			
	Valparaíso		
0-5	Y= 68.2 – 30.7C + 0.7Ca – 0.4P – 9.6PR	0.28	<0.03
0-10	Y= 73.8 – 39.4C + 0.8Ca – 0.7P – 7.2PR	0.42	<0.00
0-20	Y= 121.0 - 51.1C + 2.0Mg - 0.8P - 2.4PR - 24.5BD	0.58	<0.00
0-30	Y= 112.1 - 47.6C + 2.2Mg – 0.9P – 2.7PR – 19.7BD	0.43	<0.00
	Capivari		
0-5	Y= 72.2 + 4.4Ca – 10.9Mg + 5.1K	0.31	<0.01
0-10	Y= 80.6 + 4.2Ca – 10.5Mg	0.14	<0.07
0-20	Y= -226.8 + 345.7N + 3.8Ca -13.6 Mg +55.4 pH	0.47	<0.00
0-30	Y= -207.8 + 43.4C + 4.6Ca -15.1Mg + 48.8 pH	0.45	<0.00
Predictions of straw yield			
	Valparaíso		
0-5	Y= 4.0 - 94.5N + 0.3Ca + 5.3PR	0.13	<0.12
0-10	Y= 9.1 + 0.1Ca	0.07	<0.65
0-20	Y= -2.1 + 7.0BD	0.05	<0.14
0-30	Y= 5.9 + 165.5N	0.11	<0.16
	Capivari		
0-5	Y= 28.2 + 56.8N - 12.4BD	0.44	<0.00
0-10	Y= 78.9 + 69.3N + 0.7Ca – 1.5Mg – 0.8K – 5.8pH –20.0BD	0.39	<0.01
0-20	Y= 1.09 + 138.5N + 0.5Ca - 2.0Mg + 0.5P - 0.5PR	0.42	<0.00
0-30	Y= 1.1 + 87.5N + 0.3P - 0.7PR	0.24	<0.03

3.3.4. Spatial modelling

The sugarcane stalk and straw yields showed a structured spatial distribution pattern in Valparaiso (Table 5). Nevertheless, the semivariograms of the stalk predictions, which used the soil layers of 0-5 and 0-10 cm, have showed pure nugget effect (PNE). The mathematical models that best fitted the data spatial distribution were exponential and spherical.

The semivariograms of stalk yield that presented spatial dependence obtained strong SDE, with R^2 ranging from 0.72 to 0.93 and range varied from 38 to 76 m. The real and predicted straw yield using soil data from the 0-20 cm layer presented moderate SDE, while the other semivariograms presented strong SDE. The R^2 for straw yield ranged from 0.72 to 0.93 and, the range varied from 26 to 100 m. The spatial representation through maps confirmed that yield predictions using the soil data from 0-20 and 0-30 cm layers were more similar to the map built by the measured (real) yield data. This result was clearer observed in Valparaíso (Figure 3), possibly because only this site presented a spatial dependence pattern of the measured variables.

Table 5. Geostatistical parameters of measured (real) and predicted stalk and straw yields

Geostatistical parameter	Stalk yield Mg ha^{-1}					Straw yield Mg ha^{-1}				
					Valparaíso					
Prediction	Real	0-5†	0-10†	0-20†	0-30†	Real	0-5†	0-10†	0-20†	0-30†
Model	Exponential	PNE	PNE	Exponential	Spherical	Spherical	Spherical	Exponential	Spherical	Spherical
Nugget	0.01	PNE	PNE	0.01	0.01	0.01	0.001	0.0001	0.001	0.001
Sill	19.68	PNE	PNE	13.25	10	3.39	0.86	0.23	0.36	4.98
Range	38.1	PNE	PNE	43.100	75.6	56	69.20	26.20	99.80	77.1
R^2	0.73	PNE	PNE	0.93	0.73	0.72	0.91	0.71	0.83	0.93
SDI	0.05	---	---	0.08	0.10	0.29	0.12	0.04	0.28	0.02
SDE	Forte	---	---	Strong	Strong	Moderate	Strong	Strong	Moderate	Strong
					Capivari					
Prediction	Real	0-5p	0-10p	0-20p	0-30p	Real	0-5p	0-10p	0-20p	0-30p
Model	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE
Nugget	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE
Sill	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE
Range	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE
R^2	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE	PNE
SDI	---	---	---	---	---	---	---	---	---	---
SDE	---	---	---	---	---	---	---	---	---	---

† Predicted production.

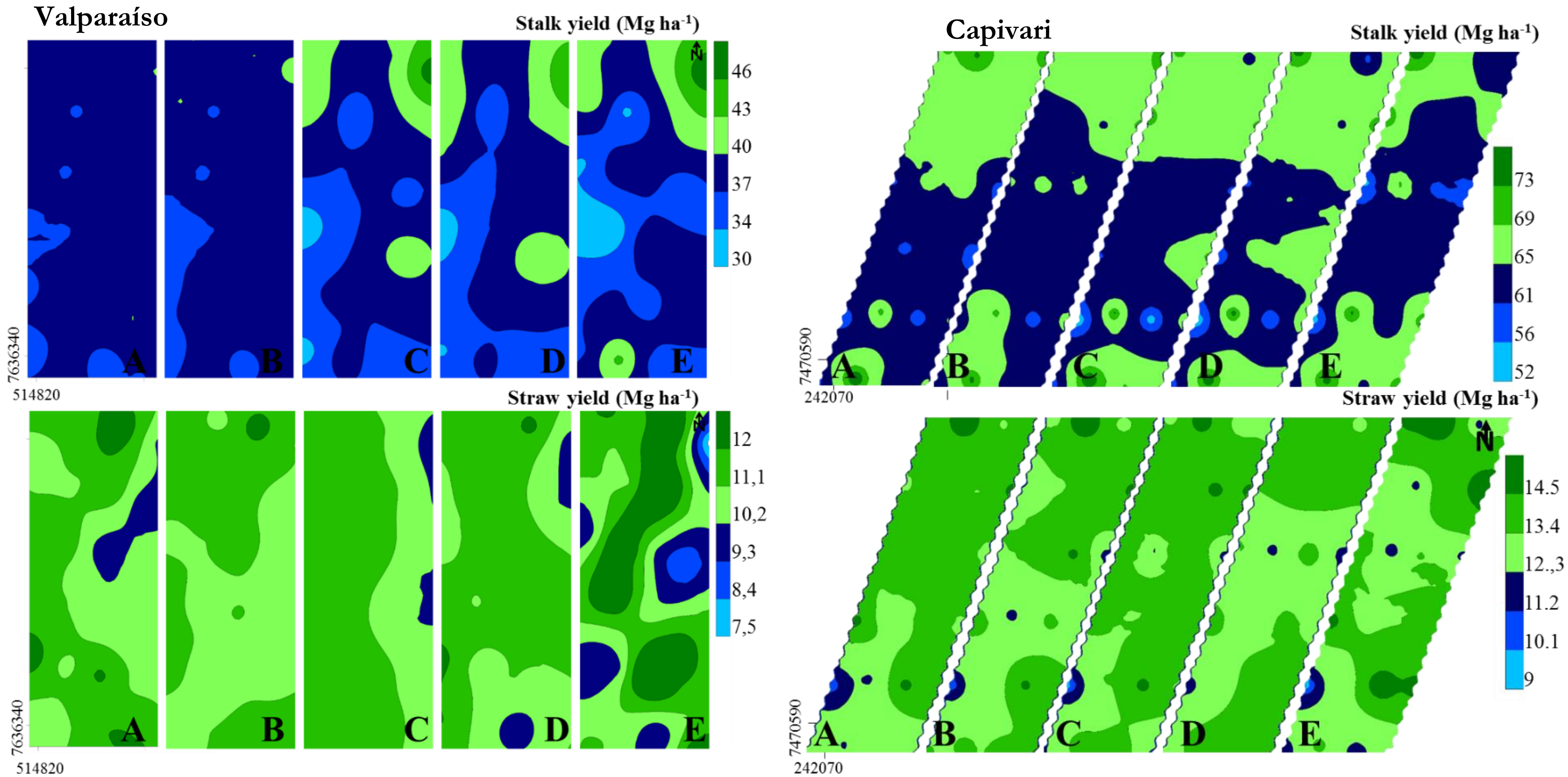

Figure 3. Maps of sugarcane stalk and straw yield in Valparaíso and in Capivari predicted by soil data from 0-5 cm layer (**A**); 0-10 cm layer (**B**), 0-20 cm layer (**C**) and 0-30 cm layer (**D**); and maps created using measured (real) yield data (**E**).

3.4. DISCUSSION

3.4.1. Soil attributes and sugarcane yield parameters

In Valparaíso, the soil K and P contents of the 0-20 cm layer were below the critical level required by the crop, indicating a poor fertility in this soil (Table 1). On the other hand, Capivari site presents a more fertile soil, since all the nutrients were within the range considered satisfactory for sugarcane development (Table 2) (Raij et al., 1997).

The decrease in soil fertility with increased layer thickness may be related to the following reasons: firstly, due to the natural nutrient cycling process, where subsurface elements are absorbed by the roots and deposited on the soil surface by crop residues (Maluf et al., 2015a,b). The decomposition of these residues increases C stocks in the soil surface (Satiro et al., 2017), which plays a key function on nutrient storage for tropical soils (Signor et al., 2016). Finally, due to fertilizer application, which in sugarcane crop usually occurs on surface for N and K, and incorporated within soil arable layer for Ca, Mg and P (Demattê, 2005).

The soil physical degradation is one of the main problems that occurs in sugarcane areas in Brazil. The advent of mechanized harvesting, which intensified the machinery traffic in the field has led to a serious status of soil compaction (Cherubin et al., 2016). In this study, both sites presented physical limitations to plant growth, according to the classification described by Reichert et al. (2003). According to these authors, soils with loamy or sandy texture with BD values above 1.6, as well as PR greater than 2 MPa, are limiting to suitable root growth. However, this reference values must be used with caution in sugarcane areas (de Sá et al., 2016), since high yields are commonly obtained on soils that have BD and PR above the critical values reported in the literature (Ceddia et al., 1999; De Souza et al., 2005; Costa et al., 2007). This may be related to intense growth of sugarcane root system (Smith et al., 2005), which can develop even in BD and PR values considered critical for other crops; and the fact that root growth of successive ratoon cane is facilitated by bio-pores formed by the decomposition of roots from previous cycles (Reichert et al., 2003).

The stalks yield in both sites were below the regional average of 80 Mg ha^{-1} (Conab, 2017). We can attribute part of the lower sugarcane yield to the cycle of cultivation (second ratoon cane), once sugarcane yield normally decrease over cycles (Lisboa et al., 2018). As reported by Lisboa et al. (2018), sugarcane yield decreases along crop cycles can be associated with: i) mechanical damage to the root system during harvesting, which reduces plant vigor in the following cycles, causing crop failure and increasing weed infestation; ii) reduction of the plant-available nutrients in the soil along crop cycles, mainly for Ca, Mg and P, which are applied only during planting or replanting

(~ every 5 years); iii) soil compaction that increases throughout the crop cycles due to successive machinery traffic.

The lower sugarcane yield found in Valparaiso can be associated to the poor inherent quality of this sandy loam soil (i.e., 12% of clay). Greater capacity of the clay soil to store and supply water and nutrients to plants impacts directly on crop growth, sustaining higher yields compared to a sandy soil (Costa et al., 2007).

Straw yield in Capivari (13.74 Mg ha^{-1}) was higher than in Valparaiso (11.20 Mg ha^{-1}). Studies have shown that straw amount produced by sugarcane widely vary from 4 to 32 Mg ha^{-1} (Carvalho et al., 2013; Franco et al., 2013; Menandro et al., 2017), and that the straw/stalk ratio vary from 0.08 to 0.23 (Romero et al., 2007; Franco et al., 2013; Landell et al., 2013). According to the literature, there are three factors that can influence straw yield: firstly, there is a direct relationship between stalk and straw production; thus greater stalk yield results in greater straw yield (Leal et al., 2013); secondly, the ratio straw/stalk changes between sugarcane varieties (Landell et al., 2013); finally, the straw/stalk ratio decreases throughout the crop cycles (Menandro et al., 2017).

In Capivari the straw/stalk ratio was 0.20, within the values reported in literature. However, in Valparaíso this ratio was 0.30, being above the values previously mentioned. The high straw/stalk ratio found in Valparaíso (0.30) may be associated to lower atmosphere transmittance during the crop cycle caused a lower incident radiation in the plants canopy (Wild, 2009) (Figure 1). Thus, the plants underwent morphological changes (greater leaf growth), optimizing the absorption of solar radiation (Friml and Sauer, 2008; Pedmale et al., 2016). However, the limited soil capacity to provide water and nutrients to plants did not allow that the "investment" in leaf growth were reversed in stalk yield. Therefore, likely climatic condition may be directly influence straw/stalk ratio in sugarcane crops, although this hypothesis cannot be totally tested in this study.

3.4.2. Correlations between yield parameters and soil attributes

In Valparaíso, the physical attributes (BD and PR) presented inverse relationship with stalk yield. It occurs because the increment of BD induced a reduction in the soil macroporosity, limiting water fluxes and oxygen diffusion into the soil (Cherubin et al., 2016). In addition, compacted soil presents higher PR values (Roque et al., 2010). The combination of these factors hinders root growth, reducing the volume of soil explored by roots and, consequently, the plant access to water and nutrients (Otto et al., 2011). Some studies performed with sugarcane (de Medeiros et al., 2005) and grasses (Lima et al., 2007; e.g. Cavallini et al., 2010) have also found negative correlation between soil physical attributes (BD and PR) and plant yield, corroborating to the results found in our study.

The negative correlation between stalk yield and P in Valparaiso was unexpected, once the soil content of this nutrient was not high enough to cause plant toxicity or to inhibit absorption of other nutrients. In Capivari site, the chemical attributes K and pH were those that best correlated with stalk yield. The pH is an attribute of great importance in crop development, since it is related to the nutrients availability (Lima et al., 2016). Although sugarcane is tolerant to acidity and alkalinity, developing under pH range from 4 to 8.5, the pH around 6.5 is ideal for its development (Marin, 2017). As the pH values in Capivari site varied from 4.94 to 6.34, its increase was beneficial to stalk yield. For K nutrient, the same above explanation can be adopted. The values for this nutrient (K) varied from 1.13 to 3.64 $mmol_c\ dm^{-3}$ in the 0-20 cm layer, with values below the range considered critical to the sugarcane development (Raij et al., 1997). For this reason, K increase in the soil may have resulted in higher stalk yield.

In the literature, several studies have been tried to correlate soil chemical attributes and stalk yield (Anderson et al., 1999; Dias et al., 1999; Landell et al., 2003; Cerri and Magalhães, 2012; Dalchiavon et al., 2013). For instance, Landell et al. (2003) verified that pH, K and P were directly correlated with sugarcane yield in 43 varietal competition trials. On the other hand, Cerri and Magalhães (2012) did not observe significant correlation between stalk yield with pH and K contents. However, these authors also obtained unexpected inverse correlation for P.

Studies correlating soil attributes with sugarcane straw yield are few or even inexistent. However, the influence of the soil attributes on plant development can help explain the results found in this study. Soil N content was directly correlated with straw yield in Valparaíso site. This nutrient is absorbed in greater quantity by plants being related to important physiological processes (Taiz et al., 2015).

In Capivari, a greater number of correlations were observed between soil attributes and straw. The inverse correlation found for the physical attributes (BD and PR), and the positive correlation observed for N, may be related to the facts cited above. The direct correlation between straw yield and carbon may be related to the fact that C is the main constituent of the soil organic matter, an attribute that has great influence on the soil capacity to sustain plants growth. Soil organic matter increases the soil's capacity to store and supply water and nutrients, besides being an energy source for the microorganisms, which favors the soil structural quality (Lehmann and Kleber, 2015). The well-structured soil facilitates gas exchange, infiltration and movement of water, as well as the root growth (Cherubin et al., 2016).

The plant "investment" to sustain growth of leaves observed in Valparaíso may have interfered on relationships between straw yield and soil attributes, resulting in the less significant correlation for this site. However, as observed for stalk yield, different relationships between soil attributes and productivity parameters can be established when edaphoclimatic and/or cultivar conditions changes (Landell et al., 2003; Bastos et al., 2007; Costa et al., 2007), supporting the results found in this study.

3.4.3. Yield prediction

Plant yield depend on complex interaction of many factors (e.g., plant characteristics, climate and soil) (Monteiro and Sentelhas, 2014; Dias and Sentelhas, 2017). Therefore, using only one soil attribute to explain production can lead to misunderstandings (Cerri and Magalhães, 2012). In contrast, using multiple regressions analysis we allows to observe the integrated effect of more than one variable to explaining a phenomenon (Landell et al., 2003). With this approach, we obtained a yield models based in soil attributes that explained more than 42% of the sugarcane production (lowest R^2 obtained in this study), what is highly satisfactory.

A few studies were performed to model sugarcane stalk yield using soil attributes. Dalchiavon et al. (2013), for example, were able to explain 24 % of stalk yield using data from the 0-20 cm soil layer, while Landell et al. (2003) explained 47% of stalk yield using data from the subsurface soil layer (0.8 to 1 m). However, to our knowledge, no studies have used similar approach to predict sugarcane straw yield.

Through the results obtained, we observed that the 0-20 layer was the best option to explain stalks yield in both areas. Similarly, a satisfactory curve adjust (i.e., high R^2) was also obtained for straw yield using the 0-20 cm layer in Capivari. However, in Valparaiso none model was adjusted for this variable. This result is possibly due to the unbalance of the straw/stalk ratio for this area, caused by a complex interaction between soil, climate and plant (see item #4.1), which made difficult to construct a model using only soil attributes.

The highest model performance obtained in the 0-20 cm layer may be related to architecture and distribution of sugarcane root system. The majority of sugarcane roots is concentrated on the soil surface and decreases exponentially in depth (Smith et al., 2005; De Aquino et al., 2015; Clemente et al., 2017). Furthermore, there is tendency for the root system to become more superficial over sugarcane harvest cycles (Bacchi, 1983). Otto et al. (2009) for instance, found that about 65 % of the sugarcane roots are contained within the 0-20 cm soil layer, which may increase to 70 %, depending on the fertilization management.

Possibly, the combination of root, water and nutrient distribution in the soil profile makes the 0-20 cm soil layer the one that best represents the sugarcane yield environment. As the soil volume explored by the root system is not limited to the soil volume or layer affected by straw removal, soil changes caused by straw removal may have little influence on the yield of sugarcane. This result helps to explain the relationship lack (at least short-term) between straw removal effects on soil and sugarcane yield, as reported by Satiro et al. (2017) and Lisboa et al (2018).

It was clearly confirmed in the sugarcane yield maps of Valparaiso site (Figure 3). The maps constructed using soil data from the 0-5 and 0-10 cm layers has little similarity with the map derived from the measured stalk yield data. In contrast, maps derived of yield predicted using soil data from the 0-20 and 0-30 cm presented greater similarity with measured-data map. For straw yield, it was less evident, possibly due to the imbalance in the straw/stalk ratio caused by edaphoclimatic conditions.

3.5. CONCLUSIONS

Sugarcane straw and stalk yield can be efficiently modelled using physical and chemical soil attributes in sites managed with sugarcane straw removal. However, modelling straw yield is more complex than stalk, requiring additional information (e.g., cultivar characteristics and climatic variables) to obtain more accurate models. The best sugarcane yield predictions were obtained from soil data from the 0-20 cm, showing that this soil layer best represents the soil volume explored by sugarcane root system. Our findings helps to explain that any influence caused by short-term straw removal on soil surface layer has little or none interference on crop yield. We also found that climatic conditions have a great influence on the straw/stalk ratio, and this possibly it is more evident in soils with less capacity to sustain suitable nutritional and hydric conditions to plant growth. In this sense, our study provided science-based information that can help the sugarcane sector in decision making and planning of the industrial use this raw material, contributing for a more sustainable production of the bioenergy in Brazil.

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4. SUPPLEMENTARY MATERIAL

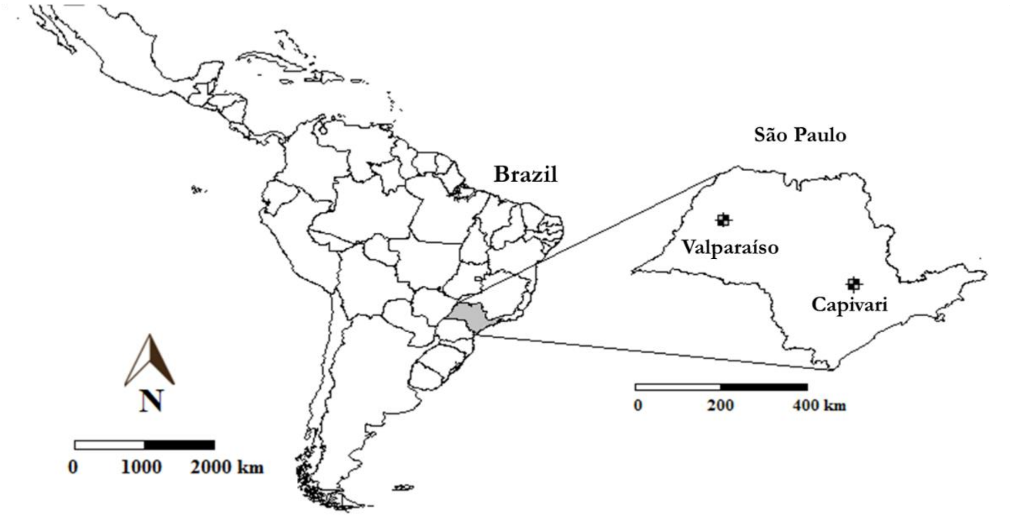

Figure S1. Geographic location of the study areas.

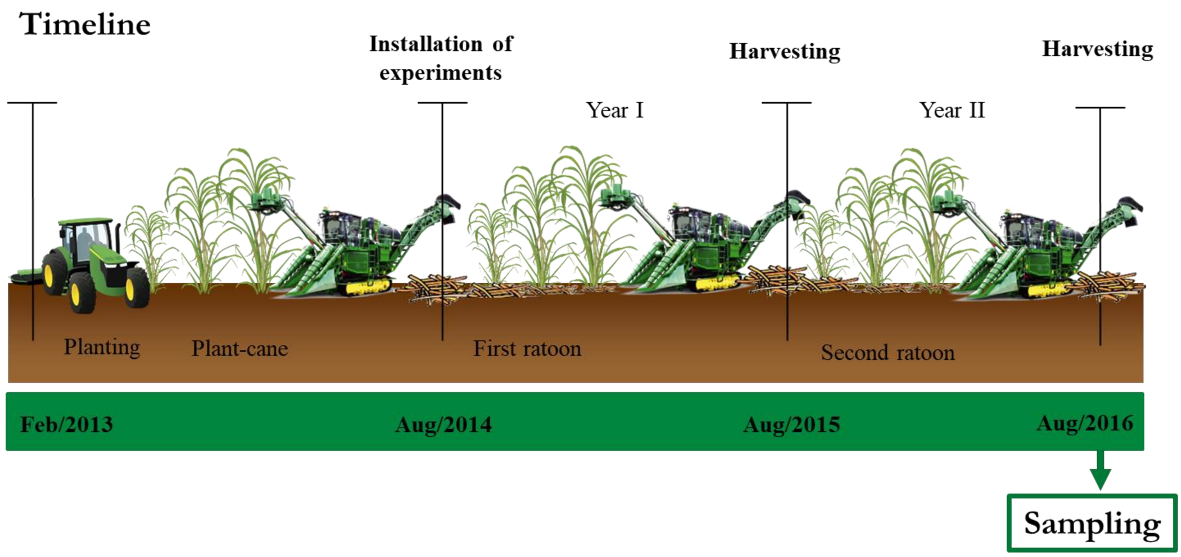

Figure S2. Timeline of the experiment, highlighting the soil and plant sampling after harvesting of second ratoon. The sugarcane was planted in February/2013 and the treatments were applied at the time of cane-plant harvesting in August/2014. The treatments were applied again in the first ratoon harvest. In the second ratoon harvest, two years after the first treatments application, were performed soil and plant sampling. Source: Adapted from Lisboa et al. (2018).

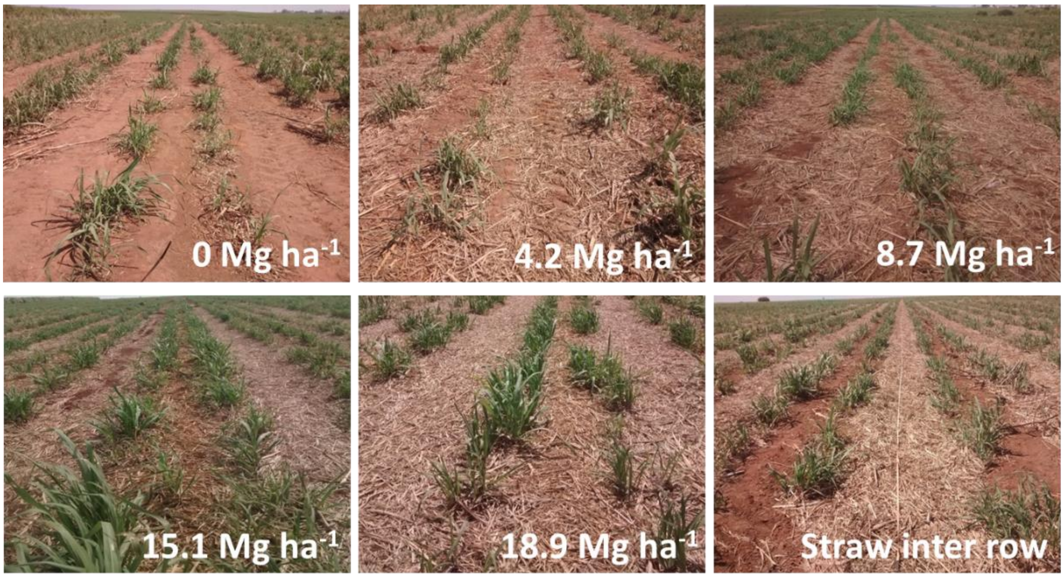

Figure S3. Field view of the plots with rates of straw removal in the Capivari experiment. In straw inter row treatment the 0.90 m row straw was transferred to row 1.50 m. Treatments were applied according to methodology proposed by Lisboa et al (2017). The treatment "straw inter row" was not used in Chapter 1.

Table S1. Soil characterization before implementation of the experiments

Layer	pH	C	P	K	Ca	Mg	BS†	AS‡	Clay
(cm)	---	g kg^{-1}	mg dm^{3}	mmol$_c$ dm^{-3}			%		
Capivari									
0-10	5.2	11.3	29.3	9.35	26.1	7.7	68.8	0.8	33
10-20	4.8	11.0	24.9	5.1	19.0	5.9	54.7	3.5	33
20-30	4.5	9.4	22.1	3.3	12.5	2.95	36.8	4.2	34
Valparaíso									
0-10	5.2	6.1	17.4	3.3	9.3	2.9	51.1	2.4	11
10-20	4.8	5.5	14.1	2.6	4.8	1.5	34.8	5.6	11
20-30	4.5	4.9	12.7	2.1	3.6	1.0	27.5	7.4	12

†BS: base saturation; ‡AS: aluminium saturation.

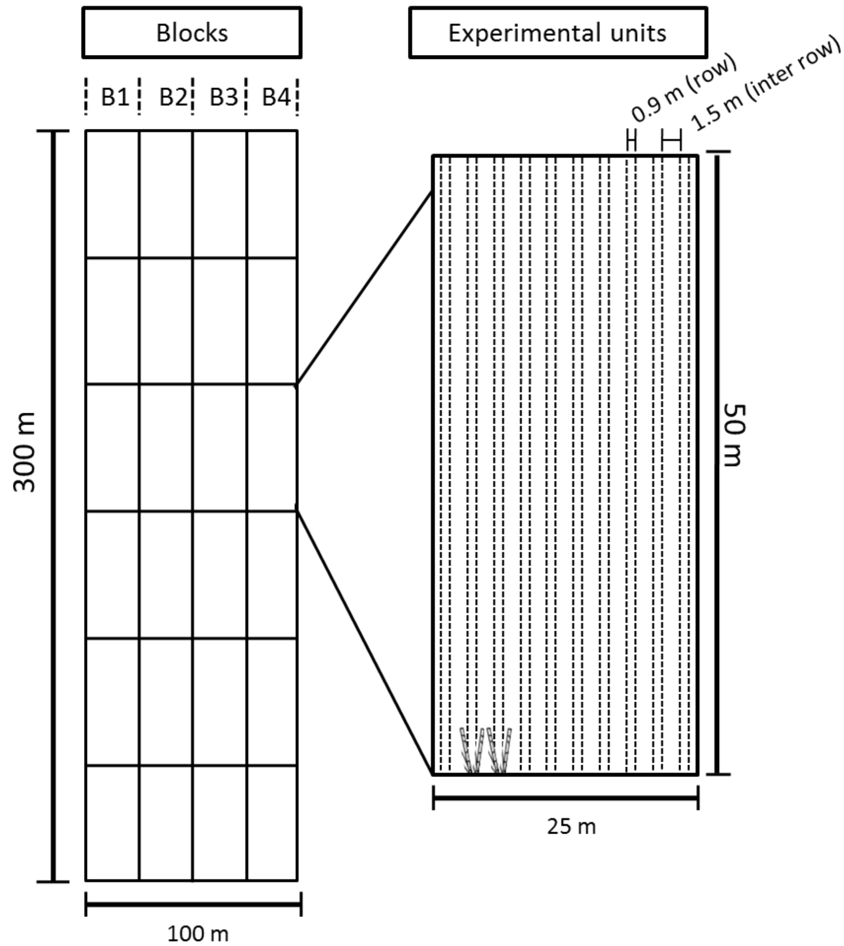

Figure S4. Trial design with the blocks layout and experimental units location. The experimental design was in randomized blocks with six treatments and four replicates, totaling 24 experimental units. Each experimental unit had 1250 m², with 10 double row of sugarcane, planted using an alternating double row spacing of 1.5 and 0.9 m. The borders areas were composed of two double rows of sugarcane located between blocks, and 5 meters of sugarcane line between experimental units of the same block.

Table S2. Amount of sugarcane straw left on soil surface in each removal rate.

Straw removal rate (%)	Capivari			Valparaíso		
	Sugarcane straw amount left on soil surface (Mg ha^{-1})					
	1ª yr†	2ª yr‡	$\overline{X}$	1ª yr	2ª yr	$\overline{X}$
100	0.0	0.0	0.0	0.0	0.0	0.0
~75	3.4	3.2	3.3	4.2	4.1	4.1
~50	7.8	9.6	8.7	8.7	7.9	8.3
~25	13.0	11.4	12.2	15.1	9.6	12.3
0	16.6	14.7	15.6	18.9	12.3	15.6
Straw inter rows§	16.6	14.7	15.6	18.9	12.3	15.6

The treatments were applied mechanically, according to methodology described by Lisboa et al. (2017). † 1ºyr: Straw amount added in the experiment installation (August 2014); ‡ 2ºyr: Straw amount added for when the experiments were reapplied (August 2015); $\overline{\boldsymbol{X}}$: average for the two applications of treatments; § Soon after sugarcane harvest, the straw was removed from above rows and piled inter rows. The farmers commonly adopt this management in order to remove the straw that is covering the sugarcane plants, preventing potential disturb on the crop sprouting.

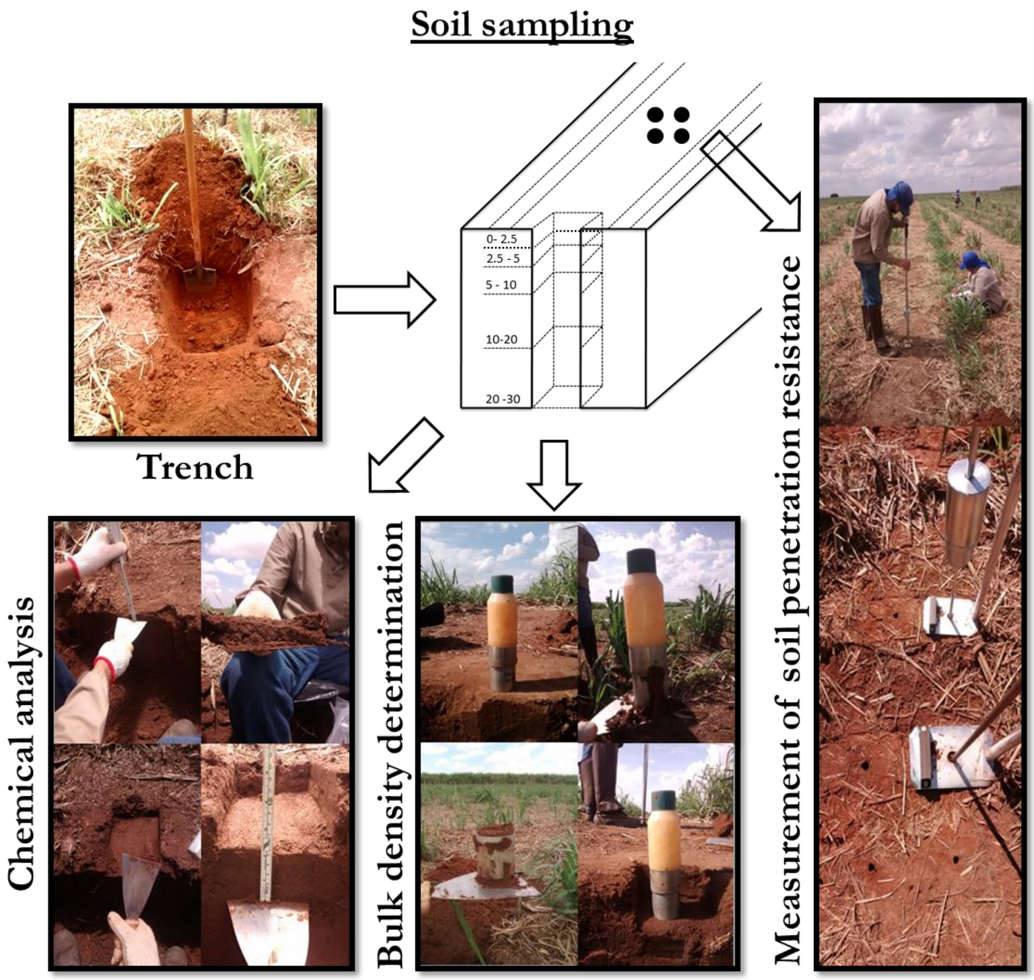

Figure S5. Soil sampling for quantification of chemical attributes (C, N, Ca, Mg, K, P, pH), bulk density and soil penetration resistance.

5. FINAL REMARKS

Brazil is the world's largest sugarcane producer and the second largest ethanol producer. However, to meet future demand, ethanol production is expected to increase considerably. In this scenario, the use of sugarcane straw for ethanol production appears with an alternative potential. Although, the implementation of plants to produce 2G ethanol is a recent reality and therefore still requires information for its planning. In this sense, our study provided science-based informations that can help sugarcane producers as well as mills in decision making and planning the use his raw material.

In Chapter II we evaluated the straw removal impact on soil. We observed that impact caused by straw removal is concentred on soil surface and is influencied by soil texture. In clayey soil the straw removal induced C stock depletion and lead to the soil physical degradation. On the other hand, in the sandy texture soil, the straw removal affected only soil chemical attributes. The results indicate the possibility to remove about half-straw amount deposited on soil's surface (8.7 Mg ha^{-1} straw remaining) without causing severe implications on the quality of this soil. In contrast, any straw amount was sufficient to cause alterations the quality of the sandy loam soil, however these impacts were less intense and are not magnified with the increase of straw removal.

In Chapter III, stalks and straw yield of sugarcane was modeled using different soil layers, from areas where the straw removal was practiced. We found that is possible to model the straw and stalk yield using physical and soil chemical attributes. However, straw production modelling is more complex and possibly requires additional information (like cultivar characteristics and climatic variables) to obtain more precise and accurate models. The 0-20 cm layer it showed the most important layer in the production definition, while the 0-5 cm layer (layer where straw removal impacts are concentrated), showed to be inefficient in stalk production explain. This result helps to explain the little or even none straw removal influence on sugarcane productivity. We also found that climatic conditions have a great influence on the straw/stalk ratio, and this possibly it is more evident in soils with less capacity to provide plant growth.

Overall, our study showed that it is possible to model sugarcane straw production in areas where straw removal is practiced. We also showed that it is possible to remove a straw amount without causing soil damage, while indiscriminate removal, even in the short term, may compromise soil quality. However, the impacts caused to the soil by straw removal, do not reflect in yield losse. Thus, we believe that the sugarcane straw planned removal for energy purposes can increase ethanol production in a sustainable way. However, long-term research with different approaches are necessary, both to follow the impact caused by the straw removal, as for develop ways to mitigate the damages caused by this activity.