University of São Paulo
"Luiz de Queiroz" College of Agriculture

Alterations in soil physical and hydraulic properties under sugarcane straw removal management: basis for assessment of ecosystem services related to water flow regulation and erosion control

Martha Lustosa Carvalho

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

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
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The LORD G-d formed man from the dust of the earth.

(Genesis 2.7a)

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RESUMO

Alterações nas propriedades físico-hídricas do solo sob manejo de remoção de palha de cana-de-açúcar: bases para avaliação dos serviços ecossistêmicos relacionados à regulação de fluxo de água e controle de erosão

A utilização da palha da cana-de-açúcar (*Saccharum officinarum* L.) como matéria-prima industrial é uma prática em crescimento nas usinas sucroalcooleiras brasileiras. A palha pode ser utilizada para produção de etanol celulósico e bioeletricidade, e pode gerar ganhos econômicos significativos. Todavia, a palha contribui para a regulação de diversos processos e funções do solo, e consequentemente, tem papel relevante na sustentação da provisão de serviços ecossistêmicos, como regulação de fluxo hídrico e controle de erosão. Removê-la do campo pode resultar em impactos sobre a provisão desses serviços. Portanto, o desafio reside em buscar o equilíbrio entre as implicações agroambientais e econômicas para estabelecer um manejo de remoção da palha que mantenha a sustentabilidade da cultura à longo prazo. Neste trabalho foram avaliados os efeitos da remoção de palha sobre a qualidade estrutural e funcional do solo, e a capacidade em prover serviços ecossistêmicos relacionados à regulação de fluxo hídrico e controle de erosão. Um experimento foi instalado e conduzido por seis anos com quatro níveis de remoção de palha em Iracemápolis – SP: remoção total (TR), alta (HR), baixa (LR), e sem remoção (NR). Utilizando amostras deformadas, indeformadas e avaliações de campo, foram determinados os seguintes indicadores: densidade do solo, infiltração de água e escoamento superficial, condutividade hidráulica saturada, capacidade de água disponível, Visual Evaluation of Soil Structure – VESS, e espaço poroso via micromorfologia do solo. Estes indicadores selecionados permitiram estudar os mecanismos pelos quais a remoção de palha influencia as funções do solo, e foram integrados em um índice de provisão de serviços ecossistêmicos do solo (I_{SES}) para examinar a capacidade do solo de prover regulação do fluxo de água e controle de erosão. No Capítulo 1, que avalia a provisão do serviço de regulação do fluxo de água, os resultados indicam que a manutenção da palha não minimiza a degradação física do solo por compactação causada pelo tráfego de máquinas. Foram encontrados valores de densidade, macroporosidade e capacidade de água disponível críticos para o crescimento de plantas, e o índices de regulação do fluxo de água indicam baixa provisão do serviço para todos os tratamentos. No Capítulo 2, que avalia a provisão do serviço de controle de erosão, em TR houve diminuição do carbono total, o VESS e a área total de poros indicam degradação estrutural em todos os tratamentos, mas os I_{SES} foram maiores do que 70%, o que sugere que a remoção de palha teve um impacto moderado a baixo no serviço de controle de erosão para este solo com alta estabilidade estrutural. Portanto, concluímos que no final do ciclo da cana-de-açúcar a palha não mitigou a degradação causada pelo tráfego de máquinas, teve pouco efeito sobre os indicadores avaliados, e, consequentemente, também pouco impacto sobre os serviços avaliados. A remoção moderada de palha pode ser uma oportunidade de aumentar a produção de bioenergia, porém, a gestão da remoção deve ser planejada considerando as funções da palha associada a outros serviços ecossistêmicos, como ciclagem de nutrientes, sequestro de carbono e conservação dos organismos do solo.

Palavras-chave: Qualidade do solo, Cobertura do solo, Funções do solo, Manejo de resíduos culturais

ABSTRACT

Alterations in soil physical and hydraulic properties under sugarcane straw removal management: basis for assessment of ecosystem services related to water flow regulation and erosion control

Removing sugarcane (*Saccharum officinarum* L.) straw to use as an industrial feedstock is a growing practice in Brazilian sugar mills. Straw can be used to produce cellulosic ethanol and bioelectricity and can generate significant income. However, straw contributes to the regulation of various soil processes and functions and consequently has a relevant role in supporting the provision of ecosystem services, such as water flow regulation and erosion control. Removing straw from the field may cause negative impacts on the provision of these services. Therefore, the challenge lies in seeking the balance between the agri-environmental and economic implications to establish a straw management strategy that maintains the sustainability of the crop in the long run. In this dissertation were evaluated the effects of straw removal on soil structural and functional quality, and the soil's capacity to provide ecosystem services related to water flow regulation and erosion control. The evaluations were done in a six-year experiment in Iracemápolis - SP with four levels of straw removal: total (TR), high (HR), low (LR), and no removal (NR). Using disturbed and undisturbed samples from four soil depths and field evaluations the following indicators were determined: soil bulk density, water infiltration and runoff, hydraulic conductivity, available water capacity, Visual Evaluation of Soil Structure (VESS), and porous space via soil micromorphology. These selected indicators were used to study the mechanisms by which straw removal influences soil functions, and were integrated into two soil-related ecosystem services provision indexes (I_{SES}) to examine the soil's capacity to provide water flow regulation and erosion control. In Chapter 1, which examines the provision of the water flow regulation service, the results indicate that the maintenance of straw does not minimize the physical degradation of the soil by compaction caused by field traffic. Soil bulk density, macroporosity, and available water capacity showed critical values for plant growth, and water flow regulation indexes indicate low service provision for all treatments. In Chapter 2, which examines the provision of the erosion control service, TR showed a decrease in total carbon, and VESS scores and total area of pores values indicate structural degradation in all treatments, but the I_{SES} were all above 70%, which suggests that straw removal had a low-to-moderate impact on the erosion control service for this soil with high structural stability. Therefore, we concluded that at the end of the sugarcane cycle the straw did not mitigate the degradation caused by machine traffic, had little effect on the indicators evaluated, and consequently also little impact on the evaluated services. Moderate straw removal may be an opportunity to increase bioenergy production, however, removal management should be planned considering the roles of straw associated with other ecosystem services such as nutrient cycling, carbon sequestration, and conservation of soil organisms.

Keywords: Soil health, Soil cover, Soil functions, Crop residue management

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1. INTRODUCTION

The importance of bioenergy for the global energy matrix had been growing significantly over the last decades, as a report by the International Energy Agency (IEA, 2018) on renewable energy sources highlighted. In 2017, the energy obtained from biomass and derivatives represented half of the renewable energy consumed in the world, and the IEA report projected that it would be responsible for 30% of the growth in energy consumption generated by renewable sources until 2023. However, in the wake of the global paralysis in 2020, the IEA (2020) reported that biofuel use dropped the most of all renewable energy sources, as a combination of lower demand for transportation, and falling oil prices. Brazil is part of the global bioenergy production scene as the second-largest producer and exporter of ethanol and derivatives in the world. The 2019/2020 agricultural season registered a historical 35.6 billion liters of ethanol produced (CONAB, 2020), the largest-ever recorded in the country. However, the demand for hydrated ethanol and the real price of the liter fell significantly during 2020, as a result of the broader global economic scenario (ANP, 2020; CEPEA, 2020). In the Brazilian case, the main bioenergy crop is sugarcane, used as a feedstock for over 90% of the ethanol produced, and for the production of other commodities such as sugar and bioelectricity.

Sugarcane and bioenergy production in Brazil has gone through an intensification process in the last decade. In the Center-South region, which concentrates over 90% of total Brazilian production (CONAB, 2021), the burnt cane harvest system has been substituted by a system with mechanized harvesting of unburnt or "green" cane. In addition to the agronomic, environmental, and human health benefits, the transition to mechanized harvesting opened the possibility of using crop residues as raw material for cogeneration of electricity or production of cellulosic ethanol (Carvalho et al., 2017; Carvalho et al., 2019; Aguiar et al., 2021), in addition to the already-used sugarcane bagasse. As the majority of sugarcane mills in the Center-South region are already energy-independent, and a growing number has been sending their surplus electricity to the national grid since 2013 (UNICA, 2020), the use of sugarcane straw to produce bioelectricity for commercialization is an interesting possibility to increase the financial sustainability of mills facing an economic crisis. In terms of bioelectricity, in the state of São Paulo alone, the use of sugarcane straw in addition to the bagasse has the potential to generate up to an additional 45.8 TWh, which would correspond to 37% of the state's electricity demand (Cervi et al., 2019).

The challenge in this scenario lies in establishing an adequate management strategy for straw removal, as several studies reveal that indiscriminate straw removal promotes degradation of soil physical quality (Castioni et al., 2018; Castioni et al., 2019; Lisboa et al., 2019) and depletion of carbon stocks (Bordonal et al., 2018; Tenelli et al., 2021), which diminishes the soil's capacity to function (Carvalho et al., 2017; Cherubin et al., 2018) and provide ecosystem services, such as water flow regulation and erosion control. Straw is related to several mechanisms that regulate the physical functions of the soil (Ranaivoson et al., 2017). It provides physical protection to the soil surface and disperses the kinetic energy of raindrops, which reduces the disaggregation of soil particles by splashing, and the formation of soil crusts (Fernández-Raga et al., 2017; Silva et al., 2012). Straw has a moderate effect in dispersing the pressure exerted by machinery wheels that cause soil compaction (Hamza & Anderson, 2005; Cherubin et al., 2021c). Straw also regulates the carbon stock, and the abundance and activity of soil organisms (Bordonal et al., 2018; Cherubin et al., 2018; Menandro et al., 2019; Morais et al, 2019), which in turn regulate the aggregation and strength of the soil structure (Six et al., 2002). With indiscriminate straw removal and depletion of soil organic carbon stocks, the degree of aggregation and the resistance and structural

resilience of the soil decrease, leaving the exposed soil more susceptible to surface sealing and erosion (Silva et al., 2012; Johnson et al., 2016), as well as the compression caused by the pressure of the wheels (Castioni et al., 2018; Castioni et al., 2019). The deterioration of the soil structure impacts the porous space of the soil, reducing the size, continuity, and functionality of the pores, and consequently negatively impacting the dynamics of water in the soil. With the increase in surface sealing and the reduction of porosity, water infiltration is restricted, water runoff increases, and, consequently, water retention in the soil declines (Mualem & Assouline, 1996; Hillel, 1998; Gmach et al., 2019).

Balancing the trade-off between the industrial and agri-environmental applications of straw, therefore, implies identifying the amount of straw that can be removed from the field for the production of bioenergy without compromising the proper functioning of the soil. As the amount of straw required to fully cover the soil surface is 7 ton ha^{-1} (Silva et al., 2019), and recent studies in Central-South Brazil have shown that keeping up to 10 ton ha^{-1} of straw on the field is sufficient to sustain productivity levels (de Aquino et al., 2018, Lisboa et al., 2018) and mitigate soil structure degradation (Castioni et al., 2018; Castioni et al., 2019), in areas with high productive potential that result in a large amount of straw left on the soil surface, moderate removal for the production of bioenergy may be a viable alternative. However, the intensity of the changes catalyzed by straw removal management is site-specific (Bordonal et al., 2018; Carvalho et al., 2019: Tenelli et al., 2021) and depends on variables such as soil texture, and tillage (Tenelli et al., 2019). Therefore, it is still necessary to understand how soil functions and soil ecosystem services provision capabilities are affected by the straw removal management to develop appropriate recommendations.

Modifications to soil functions correlated with straw removal can be monitored using soil parameters used as indicators/proxies related to the soil structure since the physical degradation mechanisms are strongly linked to the soil structure (Rabot et al., 2018). By this approach, it is possible to correlate the indicators with soil functions and finally infer about services provided by the soil, e.g., support for plant growth, flow regulation and water retention, and erosion control (Bünemann et al., 2018; Rabot et al., 2018), as outlined in Figure 1.1.

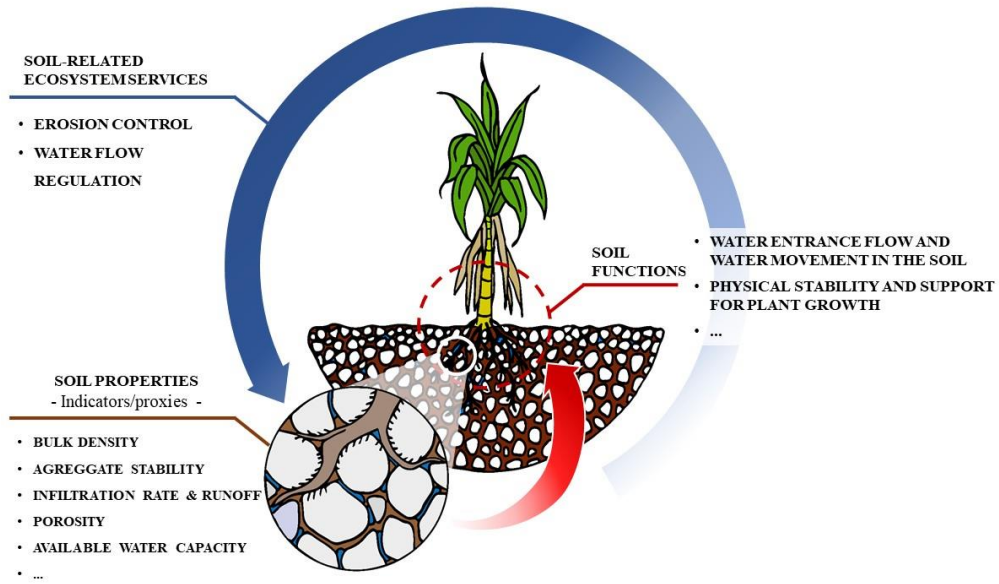

Figure 1.1. Theoretical framework applied in this study, which links soil physical and hydraulic properties to soil physical functions and then to soil-related ecosystem services (water flow regulation and erosion control).

Different strategies have been widely used to assess changes in soil structure and water flow induced by management practices. Water movements in the soil can be assessed by specific indicators for each process. The infiltration of water is inferred by the infiltration rate, runoff by the runoff rate, the movement of water inside the soil by hydraulic conductivity, water retention by the parameters of the water retention curve, such as field capacity and the permanent wilting point. Soil structure can be assessed by two distinct and complementary approaches, as discussed by Rabot et al. (2018). The most common approach is to use indirect methods, such as soil bulk density, porosity, resistance to penetration, and aggregate stability. However, the application of direct methods such as the Visual Evaluation of Soil Structure (VESS) to evaluate the solid phase and imaging techniques to evaluate the porous space is now considered an emerging and more promising approach (Rabot et al., 2018). The VESS method is a quick and simple semi-quantitative evaluation, conducted directly in the field, which evaluates soil properties related to aggregates (e.g., size, strength, and porosity) and biological soil attributes (Guimarães et al., 2011). The method has already been used with satisfactory results by authors assessing the quality of soil structure in sugarcane areas in Brazil. In the studies by Cherubin et al. (2017) and Castioni et al. (2018), the authors found significant correlations between VESS scores and important soil properties, such as density, moisture, average aggregate diameter, resistance to penetration, and abundance of earthworms. Therefore, VESS is a useful method to assess the physical functioning of the soil on a macro scale, directly in the field. Soil micromorphology is a direct method of evaluation using the characterization of soil structure using microscope images of undisturbed samples prepared in blocks or slides (Castro & Cooper, 2019). This methodology enables the evaluation of structural changes in the soil on a microscale, at the millimeter or micrometric level, by quantifying pores by their size and shape and thus detect alterations due to management to the porous space of the soil (Castro & Cooper, 2019).

Developing methods for quantitative analysis of the soil's capacity to provide ecosystem services is still a challenge that few studies have addressed (El Chami et al., 2020). A strategy for assessing the provision of soil-related ecosystem services is to use an approach with the same principles as those developed to assess soil quality. Cherubin et al. (2016) developed a quantitative method for assessment of soil physical quality for sugarcane expansion areas in center-southern Brazil, which was later successfully applied by Cavalcanti et al. (2020) in sugarcane fields also in northeastern Brazil. Through this methodology, the data collected from a minimum dataset of selected soil attributes are integrated into a single soil quality index that considers the main soil physical functions. The methodology is now being expanded to integrate soil functions into an index of ecosystem service provision, as recently published by Oliveira et al. (2019). The advantage of the methodology is to transcend the evaluation of specific attributes only, progressing from them to the quantification of the provision of ecosystem services by the soil, following the soil mechanisms involved in this provision, as shown in Figure 1.2.

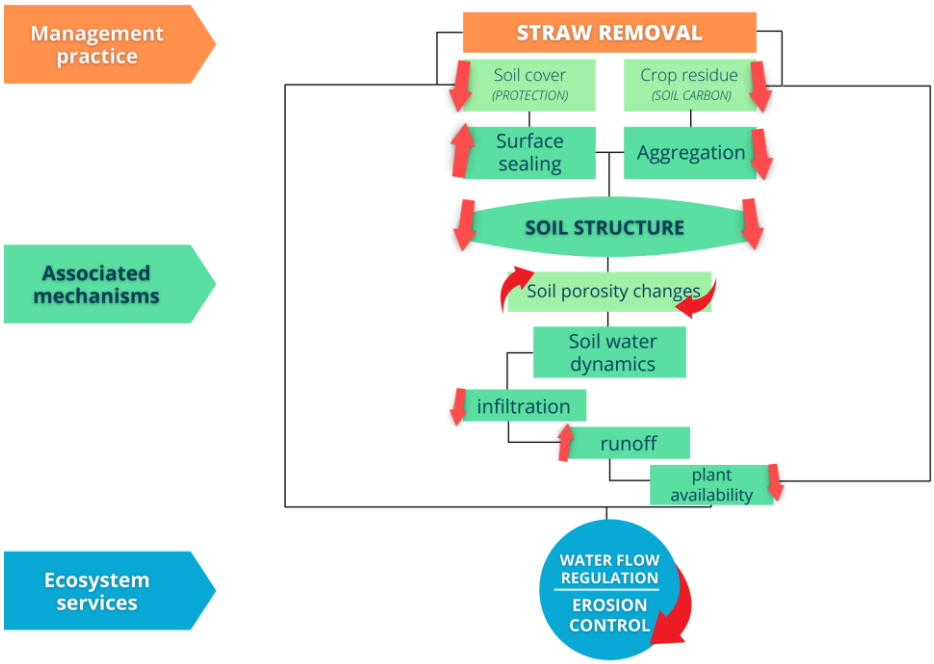

Figure 1.2. Soil mechanisms associated with ecosystem services provision affected by straw removal management.

The methodology was used in this dissertation to quantify the impact of sugarcane straw removal management on soil physical and hydraulic properties the soil functions that affect the provision of soil ecosystem services associated with erosion control and water flow regulation. The two hypotheses tested were that low straw removal rates from the soil surface would i) mitigate soil physical degradation caused by field traffic and maintain the soil's capability to provide the water flow regulation service; ii) mitigate the soil's susceptibility to erosion, consequently maintaining the provision of the erosion control service.

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2. ALTERATIONS IN SOIL PHYSICAL AND HYDRAULIC PROPERTIES UNDER SUGARCANE STRAW REMOVAL MANAGEMENT: BASIS FOR EVALUATION OF WATER FLOW REGULATION ECOSYSTEM SERVICE

ABSTRACT

The use of sugarcane straw (*Saccharum officinarum* L.) for bioenergy production is a growing management practice in Brazil's sugarcane industry. Straw is an opportunity to increase the industry's income, for it can be used as an industrial feedstock. However, soil compaction caused by field traffic is a serious problem in sugarcane areas, and the straw might mitigate the negative impacts on soil physical quality. Straw also contributes to the regulation of various soil processes and functions and consequently has a relevant role in supporting the provision of ecosystem services, such as water flow regulation. Thus, straw removal from the field may impact the soil's capability to provide this ecosystem service. In this context, we evaluated a six-year experiment with sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo state, to investigate the straw removal effects on soil physical and hydraulic properties, and then infer about the soil physical functionality, and soil capacity in providing the ecosystem service of water flow regulation. Four straw removal rates were tested: total (TR), high (HR), low (LR), and no removal (NR). Using disturbed and undisturbed samples from four soil layers (0 – 5, 5 – 10, 10 – 20, and 20 – 40 cm) and field evaluations, the following soil attributes were determined: water infiltration and runoff, hydraulic conductivity, soil bulk density and porosity, and available water-holding capacity. These attributes were used as selected indicators to study the mechanisms by which straw removal influences soil functions, and soil capacity to provide the water flow regulation ecosystem service. Soil bulk density values were high (~ 1.5 g cm^{-3}), and macroporosity results were below the limiting value (0.10 m^3 m^{-3}), indicating soil compaction. The water flow regulation indexes indicate low service provision for all treatments. Our data suggested that intense machinery traffic along the cycle led to soil physical degradation and the straw could not mitigate it. Thus, we concluded that by the end of the sugarcane cycle (5~6 ratoon), straw removal has no or little effect on soil physical and hydraulic indicators, and consequently had little impact on the soil functions and the water flow service provision. Nevertheless, straw management should be carefully planned to consider other key functions and soil-related ecosystem services (e.g., nutrient mineralization, C sequestration, soil biodiversity conservation) benefited by straw retention in the field.

Keywords: soil compaction, soil physical attributes, soil health, soil-related ecosystem service, bioenergy

2.1. Introduction

The current exceptional situation has caused severe shock in all sectors of economic activity. Trends that were certain to continue, such as the growth of renewable fuel participation in the global energy matrix (IEA, 2019), suffered a considerable turnaround (IEA, 2020). In Brazil, the world's second-largest ethanol producer and home to a fleet of twenty-nine million vehicles that use ethanol as a fuel (EPE, 2019), the demand for hydrated ethanol fell almost 17% in the first semester of 2020 (ANP, 2020) and the real price of the liter fell more than 14% between April and December of the same year (CEPEA, 2020). Specifically, in the Brazilian case, over 90% of the ethanol produced is from sugarcane, which can be used in the production and sale of other products such as sugar and, more recently, bioelectricity, to minimize the economic impact of the crisis on mills.

The cogeneration system, which enables sugarcane mills to be self-sustainable from an energy standpoint, by producing bioelectricity from sugarcane bagasse, is now a common feature of Brazilian sugarcane

mills. The practice of sending surplus electricity to the national grid is also a reality since 2013 when the electricity production became higher than the self-consumption of the mills (UNICA, 2020). An EPE report showed that 200 of the 369 sugarcane mills installed in Brazil exported electricity to the grid in 2018, with a total amount of 21.5 TWh. Reports have shown that the currently installed sugarcane industries have the potential to produce and offer for sale to the grid an additional 45.8 TWh, by using sugarcane straw as fuel (Cervi et al., 2019), in addition to the bagasse.

The high availability of sugarcane straw is a result of the transition from a manual burnt-cane system to a mechanized green-cane system, especially in the Center-South region of Brazil where around 90% of the country's sugarcane production is concentrated (CONAB, 2020). Mechanized harvesting, without burning, results in the addition of 10–20 Mg ha^{-1} of straw over the soil per year (Menandro et al., 2017; Cherubin et al., 2018), which corresponds to one-third of the total energy potential of the crop (Leal et al., 2013). Therefore, in addition to the benefits to human health and the environment, the transition to mechanized harvesting grants the possibility of using crop residues as feedstock for the production of cellulosic ethanol, or as fuel to increase cogeneration of electricity (Alves et al., 2015; Carvalho et al., 2017; Carvalho et al., 2019; Cervi et al., 2019), which can be economically positive for mills (Sampaio et al., 2019).

Although it is a market opportunity, the trade-offs associated with straw removal from the field cannot be neglected. Recent studies indicate that indiscriminate sugarcane straw removal for bioenergy production can cause a series of negative effects on soil functions (Carvalho et al., 2017; Cherubin et al., 2018; 2021a; Bordonal et al., 2018), mainly related to the reduction of physical quality (Castioni et al., 2018; Castioni et al., 2019; Lisboa et al., 2019, Cherubin et al., 2021b), that can reduce the capacity of the soil to adequately provide soil-related ecosystem services, such as water flow regulation.

The deterioration of the soil structure by compaction caused by field traffic in a high straw removal scenario, as related by Castioni et al. (2018), negatively alters the porous space of the soil, reducing the size, continuity, and functionality of the pores, and consequently negatively impacts the water flow in the soil. With the increase in surface sealing (Silva et al., 2012) and the reduction of porosity, water infiltration is restricted, surface runoff increases, and, consequently, water retention in the soil decreases (Gmach et al., 2019). Water availability to the crop is then restricted (Gmach et al., 2019), which can be a serious problem for sugarcane, a semi-perennial crop that is subject to periods of severe water deficiency during its cultivation cycle in the largest producing area in Brazil. Ultimately, sugarcane yield is affected, as water deficit is the main cause of the yield gap in sugarcane fields in Brazil (Dias and Sentelhas, 2018).

Reconciling industrial and agri-environmental applications of sugarcane straw, therefore, implies identifying the amount of straw that can be removed from the field for the production of bioenergy without compromising the capacity of the soil to regulate water flow. Some recent, short-term studies have indicated that the amount of straw required to fully cover the soil surface is 7 Mg ha^{-1} (Silva et al., 2019) and that keeping up to 10 Mg ha^{-1} of straw on the soil surface is sufficient to sustain productivity levels (de Aquino et al., 2018, Lisboa et al., 2018) and prevent soil structural degradation (Castioni et al., 2018; Castioni et al., 2019). Thus, in areas with high productive potential that result in a large amount of straw left on the soil surface, the removal of this surplus to generate bioenergy may be a viable alternative. However, the intensity of the changes catalyzed by the management of straw removal is specific to the situations evaluated (Bordonal et al., 2018; Carvalho et al., 2019).

Therefore, it is still necessary to understand how the mechanisms of water regulation are affected by the removal of straw to develop appropriate management recommendations.

In this context, the hypothesis tested was that low straw removal rates would mitigate the physical degradation caused by field traffic and maintain the soil's capacity to regulate water flow. To test this hypothesis, a field study was conducted in southeastern Brazil aiming to evaluate the effect of straw removal on soil physical and hydraulic properties, and then, in the capacity of the soil to provide water flow regulation services.

2.2. Material and Methods

2.2.1. Study area and original experimental design

A field experiment of sugarcane straw removal was installed in a sugarcane plantation in Iracemápolis (22°36'S – 47°34'W), in São Paulo state, the largest sugarcane producing region in Brazil. The selected area has been cultivated with sugarcane for over 30 years and has a history of frequent applications of organic residues such as vinasse and filter cake, and the harvesting has been mechanized for approximately 10 years. The area has an altitude of 613 m above sea level, a mean annual rainfall of 1420 mm, a mean annual temperature of 20.4°C, and the climate type, following Köppen's climate classification, is Cwa (humid subtropical with dry winter) (Alvares et al., 2013). The soil type, according to the USDA-Soil Taxonomy, is Rhodic Eutrudox. The chemical and physical characterization of the soil was done before the experiment was installed, in April 2013 (Table 2.1).

Table 2.1. Soil chemical and physical characterization for the installation of the original straw removal experiment in April 2013. Data represents the average of four replicates.

Soil depth	pH	P	K	Ca	Mg	H+Al	CEC	BS	Organic carbon	Clay	Silt	Sand
(m)		(mg dm^{-3})			($mmol_c$ dm^{-3})			(%)	(g kg^{-1})			
0.0-0.1	5.5	104	20	58	22	16	116	86	27.4	556	190	254
0.1-0.2	5.3	71	21	50	22	16	108	84	24.4	578	161	261
0.2-0.3	5.0	34	24	34	13	18	89	76	20.7	588	158	254
0.3-0.4	4.9	15	21	24	9	17	72	74	16.7	605	151	244

CEC - potential cation exchange capacity; BS - base saturation; Soil chemical analysis was performed following Raij et al. (2001) and soil texture according to Teixeira et al. (2017). *Source: adapted from Castioni et al. (2018).*

The original field experiment was installed in April 2013 in a randomized block design with four treatments and four replicates, 16 experimental plots in total. Each plot measured 10m x 12m, with 8 sugarcane rows at a 1.5m spacing. After each harvest, the straw left on the field was quantified with a 0.25 m^2 metallic frame randomly thrown ten times. Straw moisture measurements were taken in the field using a hay moisture meter with a coupled electrode. After quantifying the straw dry mass, the four straw removal rates (i.e., the treatments) were established: total removal (TR – 0 Mg ha^{-1}), high removal (HR–5 Mg ha^{-1}), low removal (LR – 10 Mg ha^{-1}), and no removal (NR – 15 Mg ha^{-1}). The correct amount of dry straw to be deposited within each plot was adjusted

manually, with rakes and forks. This procedure, firstly performed after the plant-cane harvest (2013), was repeated after each ratoon (Fig. 2.1).

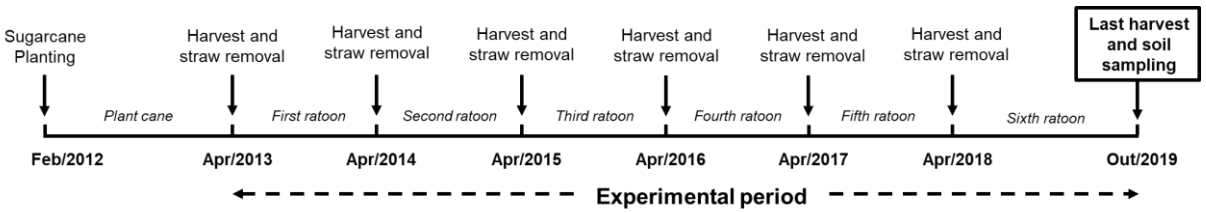


Figure 2.1. Timeline and activities during the experimental period (e.g., setting up of straw removal rates and soil sampling). *Adapted from Castioni et al. (2018)*

2.2.2. Soil sampling and analysis

Soil samples were collected in October 2019, immediately after the last harvest of the production cycle, during the end of a long period of the dry season. From the center of the 0 – 5, 5 – 10, 10 – 20, and 20 – 40 cm layers were extracted undisturbed soil cores in volumetric rings (~100 cm^3) for evaluation of quantitative soil physical quality indicators in the laboratory (e.g., soil porosity and bulk density). All samples were taken at the middle of the inter-row. Additionally, assessments of water infiltration and runoff were made directly in the field.

2.2.3. Soil hydraulic conductivity

Saturated soil hydraulic conductivity (Ks) was determined using a constant-head permeameter, with a Mariotte bottle supplying a constant water flow (40 mm in depth) to the rings containing the undisturbed soil samples. The water that passed through the cores was collected in recipients and the volume was measured in a graduated cylinder every two minutes. The soil saturated hydraulic conductivity (Ks, measured in cm min^{-1}) was calculated by Equation 2.1.

$$K_s = \frac{Q \times L}{A \times (L + h)} \quad (2.1)$$

where:

Q is the water flow rate, in $cm^3\ min^{-1}$; L is the sample's height, in cm; A is sample section area (cm^2); h is water depth above the sample.

2.2.4. Water retention parameters

The parameters of water retention in the soil were measured as the water content in three matric potentials. Initially, the soil samples collected in volumetric cylinders were saturated by capillarity with distilled water for 24h and weighed. Samples that did not reach saturation in this period were oven-dried at 40°C and re-saturated for another 24h. Then they were subjected to water drainage in the following matric potentials: −6, −10,

and −1500 kPa, in pressure plate extractors (Richards chambers). After reaching equilibrium at each potential, the soil samples were weighed to quantify the volumetric water content in the soil ($m^3\ m^{-3}$). Then, all soil samples were oven-dried at 105 ° C for 72 hours to quantify the mass of the dry soil and determine soil bulk density (BD, $Mg\ m^{-3}$). Soil particle density (PD, $Mg\ m^{-3}$) was determined with a gas pycnometer. The parameters extracted from the measured data were total porosity (TP, $m^3\ m^{-3}$), calculated as shown in Equation 2.2, macroporosity (MaP, $m^3\ m^{-3}$) calculated as the difference between soil water content at saturation and soil water content at the −6 kPa potential, and microporosity (MiP, $m^3\ m^{-3}$), calculated as the soil water content at the −6 kPa potential. Field capacity (FC, water potential at −10kPa), and the permanent wilting point (PWP, water potential at −1500kPa) were used to calculate the available water-holding capacity (AWC, $m^3\ m^{-3}$), as the difference between the water content in FC and PWP (Eq. 2.3), and the soil water (SWSC) and air (SAC) storage capacity indexes, as proposed by Reynolds et al. (2002) as tools for assessing soil quality. The soil water storage capacity (SWSC) is the ratio between water content in FC and TP (Eq. 2.4), and the SAC index is the ratio between drained pores in the −10kPa (CAt) potential and TP (Eq. 2.5)

$$TP = 1 - \frac{BD}{PD} \tag{2.2}$$

$$AWC = FC - PWP \tag{2.3}$$

$$SWSC = \frac{FC}{TP} \tag{2.4}$$

$$SAC = \frac{CAt}{TP} \tag{2.5}$$

2.2.5. Field assessments

2.2.5.1. Water infiltration and runoff

Infiltration and runoff rates were measured using a Cornell Sprinkle Infiltrometer (Ogden et al., 1997). The straw was removed from the surface of the soil before the installation of the infiltrometer. The Cornell Infiltrometer is a portable rain simulator and consists of a transparent acrylic reservoir with an approximate capacity of 20 liters, and 69 microtubules measuring 0.063 cm in diameter and 19 cm in length at the bottom. A ruler glued to the inner wall of the reservoir allows reading the height of the water, which will be used for the infiltration calculations, according to the methodology proposed by Ogden et al. (1997). To operate it, the infiltrometer was mounted on a 24 cm diameter metal ring set in the ground and leveled. This ring contains an opening in which a hose was inserted to lead the water resulting from surface runoff to a beaker for measuring runoff volume. It is possible to regulate the equipment's rain intensity using an air intake regulation system, and it was calibrated in a preliminary test at an average rain intensity of 300 $mm\ h^{-1}$. The high rain intensity was chosen to induce runoff. The readings of water height and runoff volume were taken every two minutes, for 40 minutes for each repetition. The onset of runoff was determined from the outlet of a continuous stream of water from the collecting hose, and the volume collected in a beaker was measured in a graduated cylinder (Fig. 2.2).

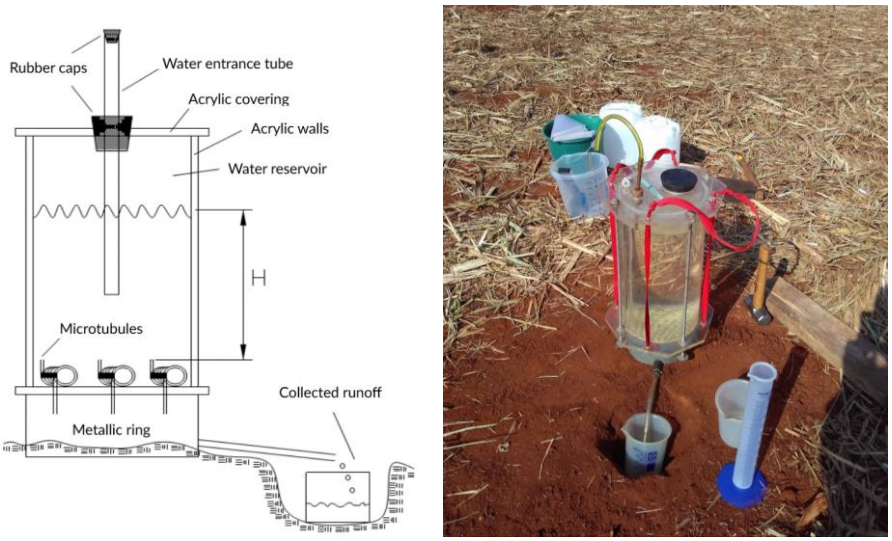


Figure 2.2. Diagram of the profile of a Cornell infiltrometer (left). H is the height of the water measured during the tests to calculate the intensity of rain. Source: Adapted from Ogden, Van Es and Schindelbeck (1997). Field measurements with the Cornell infiltrometer (right).

The rate of simulated rainfall (r, constant during the experiment) is determined by Equation 2.6.

$$r = \frac{[H_1 - H_2]}{T_f} \tag{2.6}$$

where:

H_1 is the water height read at the beginning of the measurement, in cm; H_2 is the water height reading at the end of the measurement, in cm; and T_f is the measurement time interval, in minutes.

The runoff rate (ro_t) is determined by Equation 2.7.

$$ro_t = \frac{V_t}{457{,}3 \times t} \tag{2.7}$$

2.2.6. Ecosystem Service Provision Index

For the integrated assessment of the impact of sugarcane straw removal on the physical functions of the soil and the provision of the water flow regulation ecosystem service, we used the methodology proposed by Cherubin et al. (2016) to evaluate soil physical quality and expanded by Oliveira et al. (2019) to include soil-related ecosystem services. The main mechanisms through which straw removal may affect water flow regulation are: loss of the protective covering increases surface sealing and runoff and the decrease in carbon input depletes resources for the soil food web and decreases soil resistance and resilience to physical degradation. The methodology consists of four steps to calculate an index for assessing the provision of soil-related ecosystem services (I_{SES}). The first step is to define the soil functions to be evaluated, and their corresponding weight in the final index. The soil functions selected must be related to the mechanisms that regulate the soil-related ecosystem service being studied. The second step was to select a minimum set of indicators (*minimum dataset*) that represents the soil functions related to the provision of the water flow regulation service (Table 2.2).

Table 2.2. Soil indicators and functions were selected to compose the index for the provision of water flow regulation ecosystem service for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil.

Soil-related ecosystem service	**Soil functions**	**Indicators (*proxies*)**
SES(i) – Water fluxes regulation	*f(i)* – Water entrance flow and water movement in the soil	*p(i)* – Infiltration rate; *p(ii)* – Runoff rate; *p(iii)* – Soil saturated hydraulic conductivity; *p(iv)* – Macroporosity
	f(ii) – Water retention	*p(i)* – Microporosity
	f(iii) – Water availability to plants and organisms	*p(i)* – Available water-holding capacity; *p(ii)* – SWSC

In the second step, the indicators were interpreted, and the measured values of each indicator were transformed into dimensionless values between 0 and 1. The transformations were performed using linear equations, where each indicator was ranked according to the type of specific scoring curve for each soil function. The specific scoring curves were: i) the more the better, where the higher the measured values the higher (better) is the score (e.g. water infiltration); ii) the less the better, where the higher the measured values, the lower (worse) the score; (e.g. runoff); iii) optimum point, at which there is an optimal measured value as a maximum score, and values lower or higher than this optimum point having lower scores (e.g. SWSC index). In the third step, the values obtained in the previous step were integrated and transformed into a single, dimensionless value, composing the ecosystem service provision index (I_{SES}).

The water flow indexes for each treatment were calculated using the weighted method where weights were assigned to indicators and soil functions according to the number of indicators that compose each function (Eq. 2.8), and the number of functions that compose the final index.

$$I_{SES} = \sum_{i=1}^{n} p_{(i)} \times weight_{(i)} \quad (2.8)$$

where:

p(i) refers to the scores for each indicator; n is the number of indicators included in the index; weight *(i)* is the weight attributed to each indicator.

2.2.7. Data Analysis

The data of the indicators evaluated were initially subjected to Shapiro-Wilk's test for normality analysis, then to Levene's test for homogeneity of variance analysis. When appropriate, the data was then subjected to Fisher's ANOVA or to Welch's ANOVA to test the effects of sugarcane straw removal as a management strategy. When found significant by the F test ($p < 0.05$), the means were compared using Tukey ($p < 0.10$), or Games-Howell ($p < 0.10$) posthoc tests. In the data integration for the evaluation of the soil-related ecosystem service, the analytical strategies outlined in Cherubin et al. (2016) and Oliveira et al. (2019) were used as described above.

2.3. Results

2.3.1. Water infiltration and runoff rates

The total infiltration for the time assessed (40 minutes each measurement) was similar between the straw removal levels (TR ~ 4100 mm, LR ~ 5100 mm, NR ~ 4800 mm), except for the HR treatment (~ 8400 mm). However, the basic infiltration rates increased with the amount of straw, the TR treatment with 46.3 mm h^{-1}, LR with 55 mm h^{-1}, and NR with 105 mm h^{-1} (Fig. 2.3).

The runoff interception time for the HR treatment (~ 23.9 min) was considerably higher than every other tested straw removal level (TR ~7.8 min, LR ~ 7.1 min, NR ~ 3.6 min), possibly because of the mentioned fauna activity. Total runoff volume for the time assessed varied more between treatments, which is to be expected since the drip rate is not fixed. The HR treatment showed the lowest runoff value between treatments, with ~ 5500 mm, followed by TR with a runoff volume of approximately 7400 mm. The treatments with more straw had higher drip rates, and consequently showed higher total runoff values, LR with ~ 9700 mm, and NR with ~ 10.130 mm.

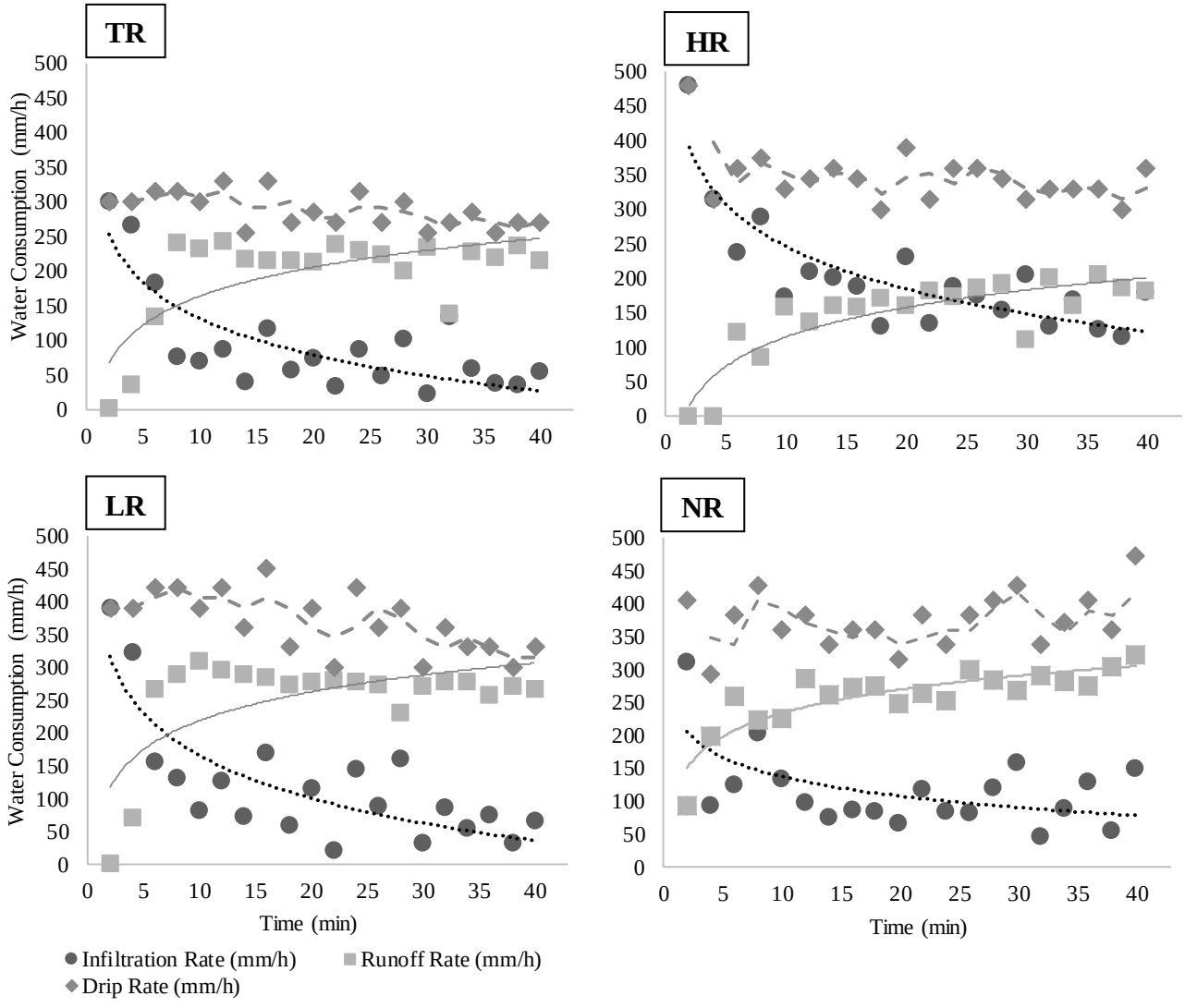


Figure 2.3. Soil water infiltration and runoff rates measured with a Cornell Sprinkle Infiltrometer for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. *TR = 0 Mg ha^{-1}; HR = 5 Mg ha^{-1}; LR = 10 Mg ha^{-1}; NR = 15 Mg ha^{-1}*

2.3.2. Soil saturated hydraulic conductivity (K_s)

Soil hydraulic conductivity was not significantly affected by straw removal rates, except for a specific change observed in the 5 – 10 cm layer (Fig. 2.4). For this specific layer (5 – 10 cm) average K_s values reached 3.4 cm min^{-1} in the NR treatment, with was 74, 88, and 98% higher than LR, HR, and NR treatments, respectively. In the other soil layers, however, straw management did not affect K_s ($p < 0.05$), likely due to the high variation of the measurements, typically observed for this attribute.

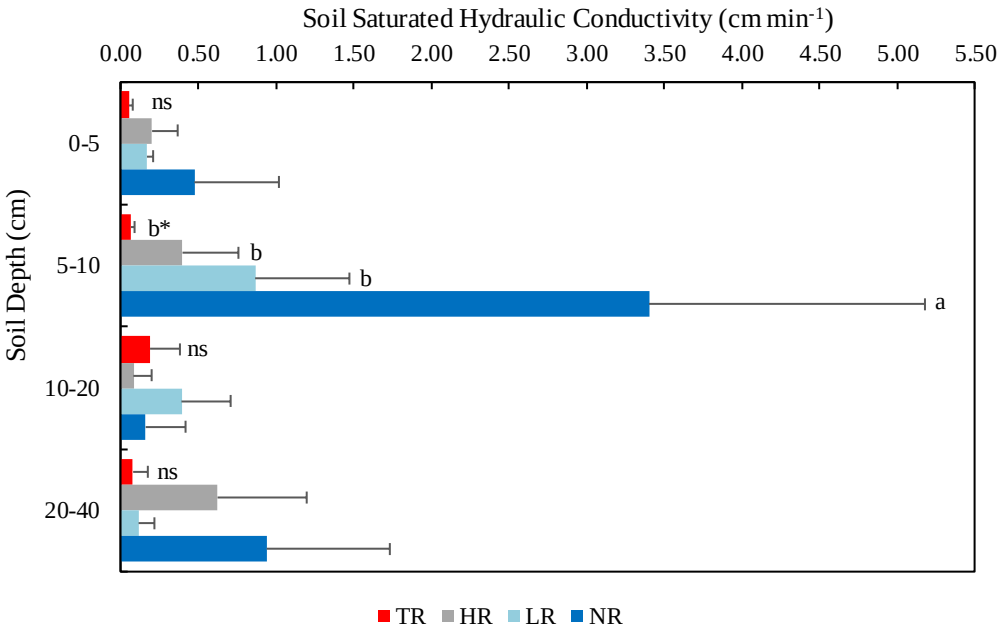


Figure 2.4. Soil saturated hydraulic conductivity measured with a constant-head permeameter in four soil depths for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. *TR = 0 Mg ha^{-1}; HR = 5 Mg ha^{-1}; LR = 10 Mg ha^{-1}; NR = 15 Mg ha^{-1}. * Means within each soil depth followed by the same letters did not differ significantly among themselves according to Tukey's test ($p < 0.1$).*

2.3.3. Soil pore size distribution

Differences in porosity between treatments were detected only in MiP at 10 – 20 cm layer. No amount of straw was effective in protecting MaP from degradation (Fig. 2.5). All treatments in all soil depths evaluated showed MaP levels around or below what is considered a limiting value for adequate soil aeration (0.10 $m^3 m^{-3}$), as indicated by the red dashed line. At the third soil layer, MiP of the TR and LR treatments differed from HR. Total porosity in the 5 – 10 cm layer was lower than in other layers (~12% lower than the mean of the 0 – 5 cm layer), for all straw removal levels, and MaP was especially lower for the TR, HR, and LR treatments, as compared to the other layers.

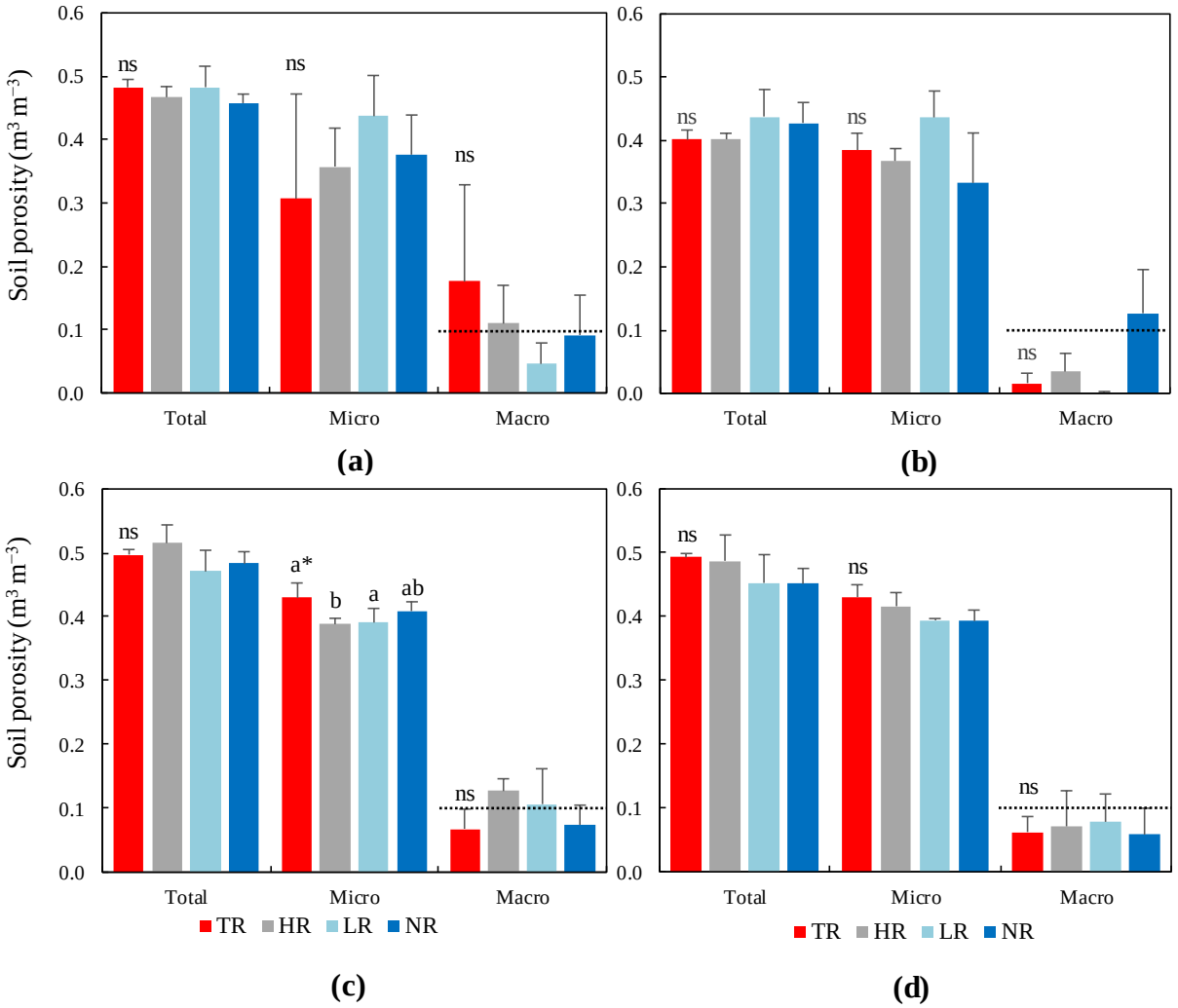


Figure 2.5. Total soil porosity, microporosity and macroporosity in four soil depths (a = 0-5 cm; b = 5-10 cm; c = 10-20 cm; d = 20-40 cm) for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. *TR = 0 Mg ha^{-1}; HR = 5 Mg ha^{-1}; LR = 10 Mg ha^{-1}; NR = 15 Mg ha^{-1}. *Bars from the same parameter with identical letters showed no statistical difference (Tukey; p > 0.10). The dashed line indicates limiting MaP values for plant growth (Erickson, 1982).*

2.3.4. Available water-holding capacity (AWC)

No changes to AWC induced by straw management were detected ($p < 0.05$) (Fig. 2.6). In the 0 – 5 cm layer, AWC varied from 0.06 m^3 m^{-3} in the NR treatment to 0.19 m^3 m^{-3} in the LR treatment. In the 5 – 10 cm, LR had again the highest value, with 0.27 m^3 m^{-3}, and the lowest AWC was 0.08 m^3 m^{-3}, from the HR treatment. In the 10 – 20 cm and 20 – 40 cm layers, all treatments showed AWC around 0.10 m^3 m^{-3}. In general, low values were measured, with LR showing more favorable conditions in the 0 – 10 cm layer. The AWC values showed high variation, with calculated coefficients of variance reaching from 11% up to 100%.

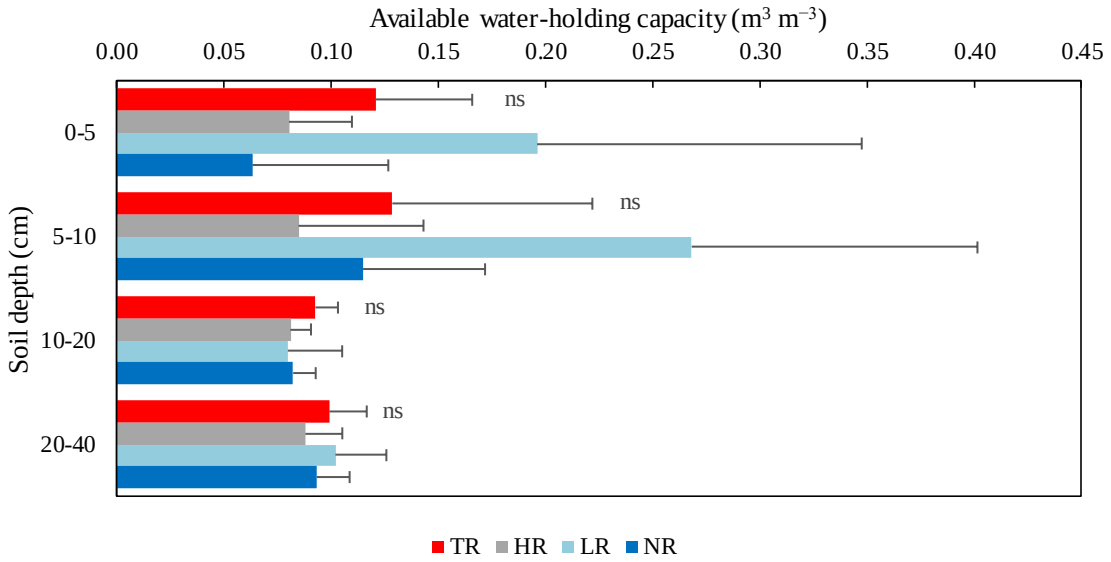


Figure 2.6. Available water-holding capacity in four soil depths for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. *TR = 0 Mg ha $^{-1}$; HR = 5 Mg ha $^{-1}$; LR = 10 Mg ha $^{-1}$; NR = 15 Mg ha $^{-1}$*

2.3.5. Soil Water Storage Capacity (SWSC) and Soil Air Content (SAC)

Overall, no changes to SWSC and SAC were induced by straw management ($p < 0.05$) (Fig. 2.7). In the 0 – 5 cm soil layer, only the HR treatment was close to the ideal ratio, with average SWSC values of 0.68. All other treatments showed SWSC values below (TR, with 0.62), or above (LR with 0.85, and NR with 0.78) the ideal ratio. In the 5 – 10 cm soil layer, NR values were below the ideal ratio (0.55), whereas LR had no SAC (SWSC of 1.0), and the SWSC values for the TR and HR treatments were above the ideal ratio (0.91 and 0.90, respectively), severely compromising aeration. The 10 – 20 cm and 20 – 40 cm layers exhibited a similar pattern, where all treatments had SWSC values above the ideal ratio.

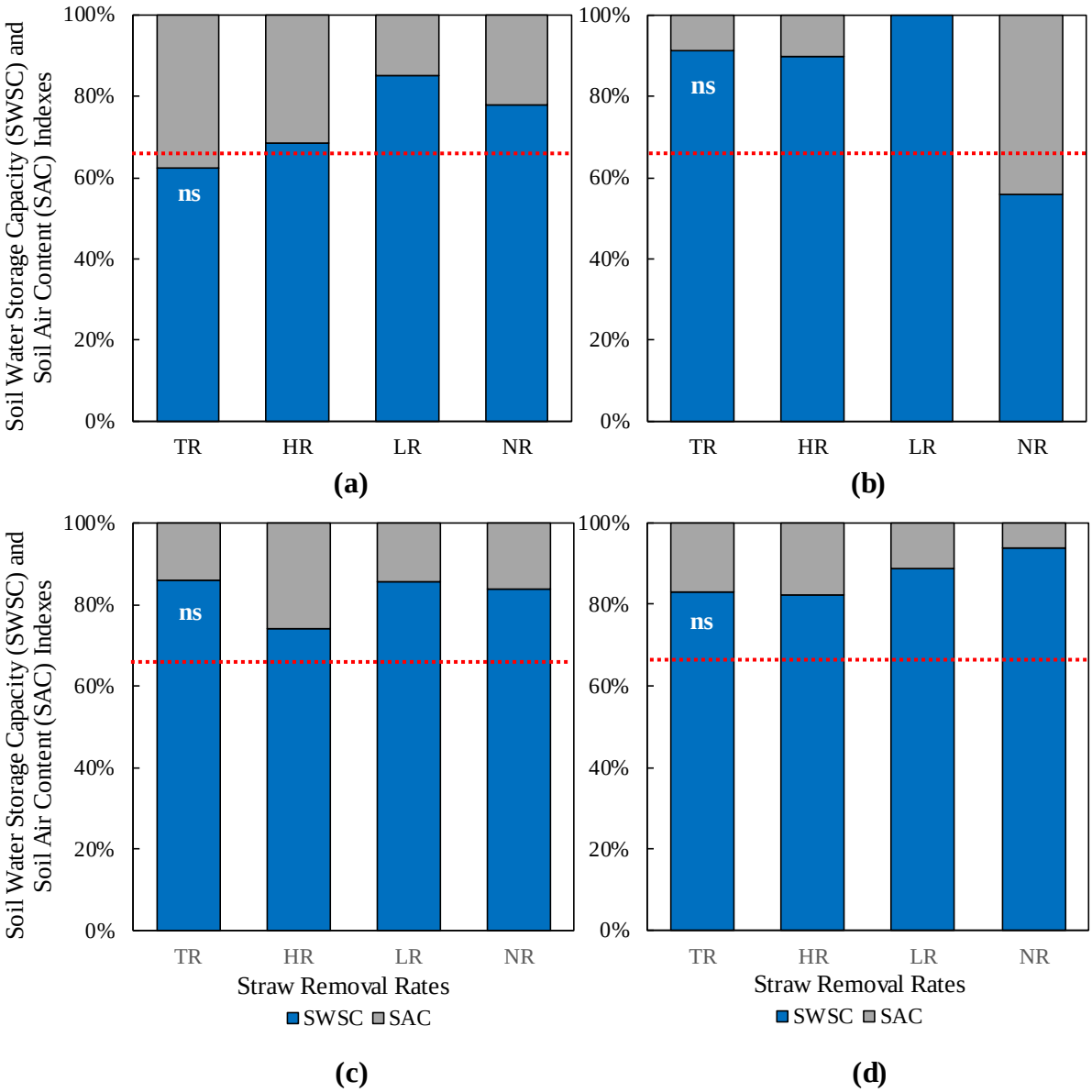
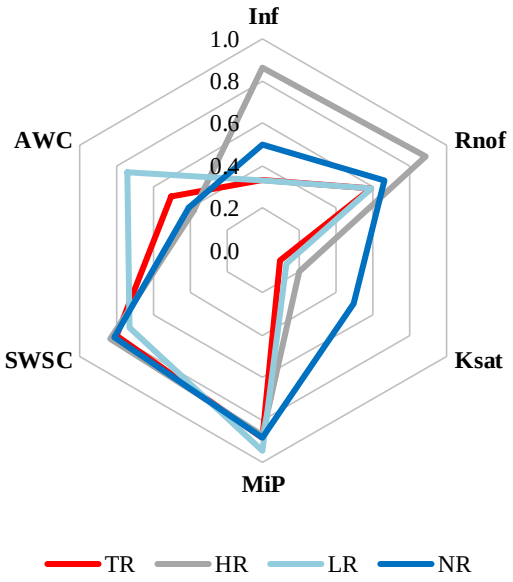


Figure 2.7. Soil Water Storage Capacity (SWSC) and Soil Air Content (SAC) in four soil depths (a = 0-5 cm; b = 5-10 cm; c = 10-20 cm; d = 20-40 cm) for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. *TR = 0 Mg ha $^{-1}$; HR = 5 ton ha $^{-1}$; LR = 10 Mg ha $^{-1}$; NR = 15 Mg ha $^{-1}$. The dashed red lines indicate the critical limit of water and air ratio to root growth, as proposed by Reynolds et al. (2002) (ideal ratio: SAC ~ 0.33, and SWSC ~ 0.66).*

2.3.6. Soil-related ecosystem service assessment

For the first soil function, concerning the infiltration and movement of water, HR was the treatment with the best score (0.217), whilst TR and LR had lower scores. The NR scores did not differ from the other two groups for the first function. For the second function, measuring water retention, no differences between treatments were found. For the soil third function evaluated, water availability to plants, LR had the best scores, followed by TR and finally, the treatments with the lowest scores were NR and HR. For the water flux provision index itself, we found no differences between the treatments ($p < 0.05$) (Fig 2.8). The index values varied from 0.56 for the TR

treatment (lowest score) to 0.64 for the LR treatment (highest score), indicating soil degradation across all treatments, with a low provision of the soil-related ecosystem service.



Straw removal rate	Soil physical functions			**ISES**
	f(i)	*f(ii)*	*f(iii)*	
TR	0.113^{b*}	0.281^{ns}	0.169^{ab}	**0.56**^{ns}
HR	0.217^{a}	0.284	0.126^{b}	**0.63**
LR	0.117^{b}	0.279	0.247^{a}	**0.64**
NR	0.184^{ab}	0.282	0.135^{b}	**0.60**

Figure 2.8. Calculated soil functions and water flow regulation indexes for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. *TR = 0 Mg ha $^{-1}$; HR = 5 Mg ha $^{-1}$; LR = 10 Mg ha $^{-1}$; NR = 15 Mg ha $^{-1}$. Inf* = water infiltration*; Rnof* = water runoff*; Ksat* = hydraulic conductivity*; MiP* = microporosity*; SWSC* = Soil Water Storage Capacity index (Reynolds, 2002)*; AWC* = available water-holding capacity. *f(i)* = Water infiltration flux and water movement in soil; *f(ii)* = Water retention; *f(iii)* = Water availability to plants. **Means within each soil physical function followed by the same letters did not differ significantly among themselves according to Tukey's test (p < 0.1).*

2.4. Discussion

2.4.1. Impact of straw removal on physical and hydraulic indicators

Soil physical degradation by compaction as a result of field traffic is a well-documented problem in mechanized sugarcane systems (Lozano et al., 2013; Júnnyor et al., 2019; Jumenez et al., 2021). High contact pressure and heavy axle loads of the tractors, harvesters, and wagons increase soil bulk density by reducing soil porosity. Consequently, water infiltration and soil available water-holding capacity are reduced. In this study, we found that the mean soil bulk density value was 1.55 g cm^{-3}, whereas the bulk density of the soil in 2013, measured during the establishment of the experiment was 1.40 g cm^{-3} (Castioni et al., 2019). The increase in bulk density is reflected in MaP reduction and low available water-holding capacity. As straw is linked to several processes that favor the strengthening of soil structure and porosity (e.g. soil cover, soil C inputs, and aggregation), our initial hypothesis was that heavy straw removal would catalyze further soil physical degradation by traffic, which was not confirmed. In a short-term analysis, at the end of one cultivation cycle, the amount of sugarcane straw left on

the soil was not sufficient to preserve the clayey soil's physical quality. Looking at recent studies, other management practices, such as controlled traffic and double row spacing (de Souza et al., 2014, Esteban et al., 2019), and reduced tillage (Barbosa et al., 2019) seem to have a higher impact on the mitigation of soil structural and physical degradation.

Our data showed that soil porosity degradation has occurred over the sugarcane cycles, regardless of straw removal. By comparing soil porosity data with the data reported by Castioni et al. (2018), collected from the fourth year of the same experiment, it is possible to see that porosity was altered as a consequence of further soil compaction caused by heavy machinery traffic during the two-year gap between the studies (Table 2.3) in all treatments. There was a decrease in average pore diameter, which can be seen by the reduction in MaP (27 to 88%) coupled with an increase in MiP (67 to 110%). The reduction in MaP was extreme, as we recorded MaP values close to and below the critical value of 0.10 $m^3 m^{-3}$ (Erickson, 1982) from the surface up to 40 cm deep (Fig. 2.5), which compromises soil aeration in the soil layer where a large portion of the sugarcane root system is located. Maintaining straw in the soil surface, regardless of the amount, was not able to mitigate this reduction in macroporosity, as Castioni et al. (2018) had already reported and is even more apparent in the present study. Other authors have reported similar macroporosity alteration in soils under sugarcane, especially at the end of the cultivation cycle, after five to six years of field traffic (Cherubin et al., 2016; de Oliveira et al., 2019). Recently, Cherubin et al. (2021c) concluded that the "damper" effect of sugarcane straw left on the soil surface is very subtle (i.e., increased 15 kPa in soil load-bearing capacity), and is thus presumably insufficient to diminish the risk of soil compaction caused by successive stresses promoted by heavy machinery traffic in sugarcane production fields.

Table 2.3. Alterations in porosity between the fourth and sixth years of an experiment with four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil.

Straw removal rate	Fourth year *Castioni et al. (2019)*		Sixth year *Present study*		Δ	
	MaP	MiP	MaP	MiP	MaP	MiP
0-10 cm	($m m^{-3}$)		($m m^{-3}$)		(%)	
TR	0.15	0.20	0.10	0.35	-33	75
HR	0.14	0.21	0.07	0.36	-50	71
LR	0.16	0.21	0.02	0.44	-88	110
NR	0.15	0.21	0.11	0.35	-27	67
10-20 cm						
TR	0.18	0.22	0.07	0.43	-61	95
HR	0.18	0.21	0.13	0.39	-28	86
LR	0.19	0.23	0.11	0.39	-42	70
NR	0.19	0.23	0.07	0.41	-63	78

TR = 0 Mg ha $^{-1}$; HR = 5 Mg ha $^{-1}$; LR = 10 Mg ha $^{-1}$; NR = 15 Mg ha $^{-1}$
MaP = macroporosity; MiP = microporosity; Δ is the difference in percentage between the first and the second recorded values.

The relatively high water infiltration and hydraulic conductivity in the Oxisol tested in this study are strongly correlated to the soil's granular microstructure, and the high amount of microaggregates with high inter-aggregate porosity (Pessoa, 2020), rather than management practices (Silva et al., 2009). In natural conditions, these soils have a bimodal pore distribution, with a high total pore volume composed of up to 2/3 by drainable pores (diameter > 5 μm), responsible for the soil's high permeability, and 1/3 by small pores (diameter < 0.2 μm), that can retain water with very high energy (Klein & Libardi, 2002). However, although some of the results for

infiltration and runoff were affected by fauna activity, it is still possible to see differences in the basic infiltration rate for the straw removal levels (Fig. 2.3). The treatment without removal had an infiltration rate more similar to the expected from this soil type, while the other treatments not skewed by fauna activity had basic infiltration rates 56% (for TR) and 47% (for LR) lower than NR. This could not be related to the higher hydraulic conductivity seen for the NR treatment in the 5-10 cm layer. In general, however, the total amount of infiltrated water and runoff was not modified by the straw removal management. On the other hand, the results for water conductivity are lower than the values found in other studies with soils from the same class (da Silva et al., 2009). It can be explained by the high variability typically observed in Ks data, and especially in highly disturbed soils (Zimmermann & Helmut, 2008), and they were uneven between soil layers (Fig. 2.4). Uneven hydraulic conductivity can lead to water accumulation on top of the layer with lower conductivity, which can lead, in seasons of high rainfall, to accelerated root decomposition (Lovera et al., 2021), and also increase the risk of soil erosion.

The decrease of total porosity and MaP affected soil water holding capacity twofold – the soil can contain a smaller volume of water in its pores, and a great portion of this water is not available for plants. The total available water holding capacity for each treatment was below the value considered limiting to plant development (0.15 m m^{-1}) in most soil layers. Gmach et al. (2019) also observed values of water retention capacity below the limiting range, though, for the sandy clay loam Oxisol that was evaluated in that study, low straw removal rates were capable of mitigating this effect. The SWSC/SAC ratios exhibit this imbalance of water availability and aeration due to porosity changes. Though the majority of the SWSC ratios found were higher than the ideal ratio (Fig. 2.7), indicating more water-occupied pore space, in this situation, most of the water is retained with very high energy in micropores and inaccessible to plant roots. Besides the lack of available water, the lack of adequate aeration shown by low SAC also constitutes an obstacle for root growth and plant development and can have an impact on sugarcane yield, as reported by Castioni et al. (2019) and Cherubin et al. (2021 a). The authors of both studies observed a direct correlation between soil structural degradation and losses in sugarcane yield.

2.4.2. Soil water flow regulation under straw removal management

Based on our assessment, the soil was providing the water flow regulation ecosystem service at 56 to 64% of the soil's full capacity under sugarcane cultivation (Fig. 2.8), indicating loss of soil functions and the soil-related ecosystem service provision, as a result of physical degradation. Nevertheless, we did not detect the direct influence of straw removal with loss of function and service provision. The main driver for degradation appears to be compaction caused by field traffic throughout the years of cultivation (Cherubin et al., 2016). When compared to sandy soils, clayey soils are more susceptible to compaction due to their particles holding a higher water content and remaining in a plastic state for longer periods, compressing when a load is applied to the soil. Therefore, as recent studies show, straw removal seems to have less impact on soil functions in clayey soils, when compared to sandy soils. Cherubin et al. (2021a) conducted an assessment in 12 field experiments using SMAF to investigate the broad impact of straw removal on soil health and found that sandy soils were more prone to degradation under high straw removal levels, especially because of soil organic carbon decline. Therefore, to preserve soil functions straw management decisions have to consider the inherent characteristics of each specific soil.

Loss of soil physical functions by degradation under sugarcane cultivation is not exclusive to the heavily mechanized systems. Cavalcanti et al. (2020), evaluating a sandy loam Ultisol in Northeastern Brazil, in an area

where sugarcane is burned, manually harvested, and mechanically collected with conventional loaders, found soil functions reduced from 88% of its full capacity in the native forest to 67% in the sugarcane ratoon. In this case, total straw removal by burning reduced soil organic carbon stocks and aggregate stability, degrading soil structure, which can partially explain the loss of soil physical functions. In addition, compaction is also high in this system, since traffic is not oriented in lines, and the entire area is trampled (Cavalcanti et al., 2019). Soil organic carbon stock losses caused by straw removal can to a degree be mitigated by tillage practices. Tenelli et al. (2019) observed that moderate straw removal when combined with reduced tillage, can preserve soil carbon stocks and sustain sugarcane yields during the cycle. Straw removal management in sandy soils requires more caution, however, as Tenelli et al. (2021) reported depletion of soil organic carbon stocks in sandy soils, regardless of the removal rate.

Loss of soil functions is not only an ecological problem but also an agronomic and economic one. Several studies investigated the effect of soil quality over sugarcane yield from different perspectives (e.g., Souza et al., 2014, de Aquino et al., 2018, Bordonal et al., 2018, Lisboa et al., 2018, Cherubin et al., 2021a), with the conclusion that soil degradation leads to losses in yield and, consequently, in food and bioenergy production, finally reducing profitability. Therefore, it is important to include the state of soil health and soil functions in yield predictions and economic decision-making processes.

2.5. Conclusions

Mechanized sugarcane cultivation causes degradation of soil physical quality, mainly through compaction caused by heavy machinery traffic, and reduces the soil's capacity to regulate water flow. Straw has little to no capacity to mitigate compaction and its effects on the provision of this soil-related ecosystem service, hence straw removal does not catalyze further degradation. Therefore, it is possible to remove the straw from the soil for the production of bioenergy and increase profitability at the end of the cultivation cycle without causing further damage, at least in clayey soils. However, it is important to note that other soil factors such as soil organic carbon may be negatively affected by continuous straw removal and that short-term observations such as the one conducted in this study may not reveal the full picture. A straw removal rotation approach, in addition to the adoption of traffic and tillage practices more adequate to soil conservation, might be the path to attain the goal of balancing the economic, agronomic, and environmental benefits of sugarcane straw.

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3. SOIL STRUCTURAL CHANGES UNDER SUGARCANE STRAW REMOVAL MANAGEMENT: BASIS FOR EVALUATION OF EROSION CONTROL ECOSYSTEM SERVICE

ABSTRACT

Soil erosion intensified by human activities is one of the biggest challenges for soil conservation. Soil erosion effects are not only felt in agricultural land but the entire ecosystem. Most soil erosion occurs in territory under agriculture, especially areas where the soil is left bare or disturbed by tillage. Reducing tillage and maintaining the soil covered are, therefore, effective management practices to reduce soil erosion. The current system used in the main sugarcane-producing area of Brazil, with no burning and mechanized harvesting, allows for the formation of a straw blanket that covers the soil during the 5-6 years of the culture's cycle. The straw has economic benefits for sugarcane mills, in addition to the benefit of reducing soil erosion susceptibility, as it can be used to produce cellulosic ethanol, or burned to produce bioelectricity. However, straw removal management has to be done rationally as to not harm soil functions and the ability of the soil to provide ecosystem services, namely erosion control. In the present study, our objective was to determine whether straw removal would reduce the capacity of soil to provide erosion control service. We evaluated a straw removal experiment [i.e., total (TR, 0 Mg ha^{-1}), high (HR, 5 Mg ha^{-1}), low (LR, 10 Mg ha^{-1}), and no removal (NR, 15 Mg ha^{-1})] installed in clayey soil in central-southern Brazil, after the last harvest of the sugarcane cycle. Using several key soil indicators such as penetration resistance, aggregate stability, and organic carbon content, as well as visual analysis in the macro scale using Visual Evaluation of Soil Structure (VESS) and the micro-scale through micromorphological analysis, we calculated an ecosystem service provision index (ISES) to four straw removal rates. Our results revealed that total straw removal promoted the reduction of total soil organic carbon in the 0 – 5 cm layer. Bulk density, soil resistance to penetration, VESS scores, and the total area of pores all indicate sharp degradation of soil structure by compaction, which straw could not mitigate. Straw removal led to I_{SES} decline, regardless of the removal rate (TR, HR, and LR). All I_{SES} were higher than 70%, which suggests that straw removal has a low impact on the erosion control service for this clayey soil. Therefore, moderate straw removal from soils with high structural stability can be a strategy to increase bioenergy output without increasing soil erosion susceptibility.

Keywords: soil physical quality, erodibility, water infiltration, soil structure

3.1. Introduction

Soils are a critical resource to human survival and flourishing. The ecosystem services provided by soils, such as filtering and storing water, carbon sequestration, and the provision of food, fibers, and fuel are the basis for all human societies (Adhikari & Hartemink, 2016). With a growing population, the pressure to increase food production has put a strain on soils, threatening their conservation and sustainability. Soil erosion aggravated by anthropogenic action is one of the major degradation factors and a threat to soil functions (Montanarella et al., 2016), especially in agricultural lands. Recent global estimates of soil loss by erosion range from 17 Pg y^{-1} (Borrelli et al., 2017) to 20 Pg y^{-1} (Doetterl et al., 2012), and the primary land use associated with erosion was found to be agriculture. In the study conducted by Borrelli et al. (2017), although only about 11% of the examined territory was used for agriculture, it was responsible for around 50% of the total predicted soil erosion.

In humid tropical regions such as parts of South America, with high rainfall erosivity (R-factor) and ongoing deforestation, erosive events can cause extensive damage to soil and water resources (Restrepo et al.,

2015, Anache et al., 2017). In Brazil, land-use change from native vegetation to agriculture has increased soil erosion exponentially (Oliveira et al., 2015). For sugarcane cultivation, a crop of which Brazil is the world's largest producer (FAOSTAT, 2019), the expansion has occurred overwhelmingly over degraded pastures, with no direct contribution to deforestation (Bordonal et al., 2018a; Cherubin et al., 2021). However, even though the crop has a reputation for sustainability, soil erosion remains an issue in the sugarcane production system (Sparovek & Schnug, 2001; Gomes et al., 2019) due mainly to management practices not suitable for soil and water conservation (Politano & Pissarra, 2005).

Currently, two distinct production systems predominate in sugarcane cultivation. The traditional system, or burnt cane, with pre-harvest detrashing by fire; and the green cane system, without pre-harvest burning. In the burnt cane system, still widely used in various producing regions worldwide such as in India (Sahu et al., 2021), and northeastern Brazil (Rangel et al., 2018), sugarcane fields are burnt before harvesting. The burning reduces the incidence of pests and diseases, as well as the volume of leaf matter, which facilitates the process of cutting and loading the sugarcane stalks. This is particularly important because, usually, in this system sugarcane stalks are manually harvested. In the green cane system, currently the predominant system in Brazil's largest sugarcane producing region, the sugarcane stalks are harvested without burning and the detrashing is done mechanically, by cutting the pointers and removing the attached leaves (Bordonal et al., 2018b). The green leaves, pointers, and dried leaves are left in the field, covering the soil with a thick layer of straw. In the majority of regions that adopt this system, the sugarcane stalks are mechanically harvested, as it is operationally difficult and possibly harmful to worker's health to manually harvest the green cane (Yang, 2018; Mgode et al., 2019). Adoption of the green cane system has grown partially because the practice of burning sugarcane fields before harvesting causes severe hazards to human health, negative environmental impacts e.g. high greenhouse gases emission and depletion of soil carbon and nitrogen stocks (Cerri et al., 2011; Capaz et al., 2013; Cherubin et al., 2018), negative agronomic impacts i.e., soil degradation, nutrient loss, and increased fertilizer demand, and accelerates the deterioration of the harvested stalks (Solomon, 2009). An additional negative result of using fire to detrash sugarcane, reported in several studies, is the loss of the straw blanket, which increases erosion (Silva et al., 2012) undermines soil conservation and the capacity of the soil to provide ecosystem services and decreases the overall sustainability of the crop.

Soil erosion is a concern in sugarcane production systems, varying from 16 Mg ha^{-1} yr^{-1} to approximately 150 Mg ha^{-1} yr^{-1} depending on several factors (Hartemink, 2008), though different drivers are responsible for soil degradation in each system. The main driver for the decrease in soil conservation, present in both systems, is tillage. In major production areas, the sugarcane is replanted after the fifth or sixth ratoon (~5-6 years), and the conventional replanting process requires tillage operations. The mechanical soil disturbance reduces soil compaction and increases soil physical conditions for root growth in the short term (Barbosa et al., 2019), however, soil tillage also breaks soil aggregates, reduces soil structural stability, and diminishes soil resistance to erosion (Cherubin et al., 2016; Cavalcanti et al., 2020). In the burnt cane system, the removal of the straw layer by fire results in exposure of the soil surface to the impact of raindrops, and reduction of the organic matter input (Graham et al., 2002). Without the straw covering dissipating the kinetic energy of raindrop impact, and a decrease in the carbon stock (Galdos et al., 2009), the degree of aggregation and the resistance and structural resilience of the soil decreases (Blair, 2000), leaving the exposed soil more susceptible to surface sealing and erosion. In the green cane system, another important driver causing soil degradation is heavy machinery traffic

(Hamza & Anderson, 2005). Although the straw layer dissipates a small portion of the pressure caused by machinery passes (Cherubin et al., 2021) and increases soil structural resilience through a higher organic carbon content (Cerri et al., 2011), soil compaction is still a major problem in this system (Cherubin et al., 2016). In addition to reducing crop yield, compaction also increases soil erosion through lower water infiltration rates and higher runoff volume (Valim et al., 2016).

In addition to the agronomic and environmental benefits, sugarcane straw can also provide producers with additional economic benefits (Sampaio et al., 2019), as it can be used as industrial feedstock by mills. Sugarcane bagasse is already widely used in Brazil by mills in the cogeneration system, which provides them with self-sustaining energy capabilities (UNICA, 2020). A high percentage of mills is sending the surplus electricity produced from bagasse to the national grid, and the interest in using the straw to increase the output of bioelectricity is growing. Straw can also be used by the industry in the production of cellulosic ethanol, increasing the output of renewable fuel. For the use of straw as industrial feedstock to be a viable strategy, it is imperative to know how the removal affects the provision of soil ecosystem services, namely erosion control, as the straw plays a key role in this service (Martins Filho et al., 2009; Carvalho et al., 2017).

In this context, the hypothesis tested in this study was that the removal of sugarcane straw from the soil surface would degrade soil structure and, consequently increase the soil's susceptibility to erosion, reducing the provision of the erosion control service. To test this hypothesis, a field study was conducted in a mechanized sugarcane system in southeastern Brazil aiming to evaluate the effect of straw removal on soil structural properties, and then, in the capacity of the soil to provide the erosion control service.

3.2. Material and Methods

3.2.1. Study area and original experimental design

The description of the study area, the original experimental design, the timeline of activities, and the treatments are explained in detail in item 2.2.1 of this dissertation.

3.2.2. Soil Resistance to Penetration and Bulk Density

Soil resistance to penetration (SRP) was determined using a bench penetrometer (MA 933 Marconi) in the soil cores collected with volumetric rings. Each core's water content was stabilized at –6kPa inside Richard's chambers before the determination, to prevent results differing due to water content variations. The bench penetrometer used has a cone with a base diameter of 4 mm and a 60° angle, and the insertion velocity used was 20 mm min^{-1}. The samples were then oven-dried at 105°C for 48 hours to determine soil moisture and soil bulk density. Soil bulk density (BD) was calculated as the sample dry mass divided by the ring volume.

3.2.3. Soil Aggregation

Aggregate stability was determined by two methodologies – a method adapted from Elliott (1986), and the method proposed by Le Bissonnais (1996). For Elliott's methodology (1986), semi-deformed samples were manually separated by breaking the aggregates in their natural weakness planes, to pass through an 8 mm sieve. After air drying, 50 g of aggregates were weighted and saturated by capillarity with water for 24h, and then placed in contact with water over a set of sieves stacked in a column that oscillated vertically at 30 cycles per minute for 10 minutes, on a Yoder-type shaker. The procedure allowed for the separation of the following fractions: (i) large macroaggregates (> 2000 µm), (ii) small macroaggregates (250-2000 µm), (iii) micro aggregates (53-250 µm), and (iv) silt + clay particles (≤ 53 µm). The content of aggregates retained in each sieve was taken to a drying oven (50ºC) and then weighed. Aggregate stability was also expressed from the mean weighted diameter of the aggregates, calculated by Equation 3.1.

$$MWD = \sum_{i=1}^{n} \bar{xi} \times Pi \tag{3.1}$$

where:

$\bar{xi}$ is the mean aperture diameter (mm) of adjacent sieves, Pi is the dry mass of the aggregates retained in each sieve (g).

The Le Bissonnais (1996) aggregate stability methodology consists of submitting 5g samples of aggregates calibrated by diameter using 5 mm and 3 mm sieves to three laboratory pretreatments, sieving the resulting fractions, and then calculating the mean weight diameter (MWD) of stable aggregates. The pretreatments are fast wetting or slacking (FW), slow wetting (SW), and mechanical breakdown (MB). For these three pre-treatments described in the methodology, three sets of 5 g each of the same sample were weighted, taken from the aggregates retained in the 3 mm sieve. These sets of samples were then dried at 40°C for 24h. For the FW pretreatment, one set of dry samples were immersed for 10 minutes in a beaker containing 50 mL of deionized water, and the water was then suctioned from the beaker using a pipette. For the SW pretreatment, one set of dry samples were wetted by capillarity for 30 minutes over wet filtering paper spread in a foam saturated with deionized water. For the MB pretreatment, one set of dry samples were immersed for 10 minutes in a beaker containing 50 mL of ethanol, and the ethanol was then suctioned from the beaker. The samples were transferred to 250 mL Erlenmeyer flasks containing 50 mL of deionized water, and the water volume was adjusted to 250 mL.

The flasks were then sealed and manually agitated 20 times in pendular movements (Fig. 3.1), and set to rest for 30 minutes for coarse particles sedimentation. After 30 minutes, the deionized water was suctioned from the flasks with a pipette.

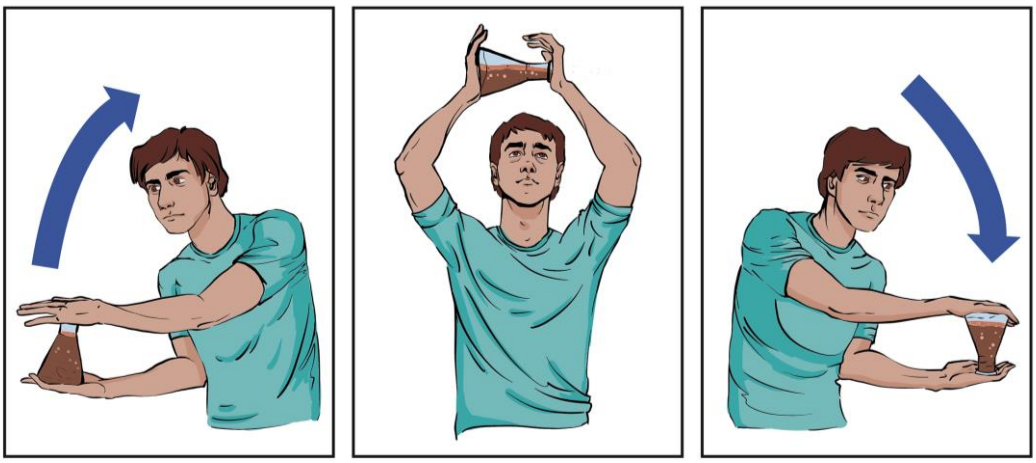


Figure 3.1. Pendular movements to obtain the mechanical breakdown (MB) of aggregates pre-treatment as per the Le Bissonnais (1996) methodology.

After each pretreatment, the aggregates were placed in a 53 µm sieve previously immersed in ethanol and manually moved in a circular motion 20 times, and then oven-dried at 40°C. When dry, the >53 µm fraction resulting from each pretreatment was sieved manually in sieves stacked in a column to obtain the distribution of the aggregates for openings of 2000, 1000, 500, 250, 106, and 53 µm. The mean weight diameter of stable aggregates for each pretreatment was calculated as previously indicated in Equation 3.1. With the mean weight diameter of the FW and SW pre-treatments, a soil structure index (SSI) was calculated to express aggregates' resistance to slaking (Eq 3.2).

$$SSI = \frac{MWD_{SW} - MWD_{FW}}{MWD_{FW}} \quad (3.2)$$

where:

MWD_{SW} is the mean weight diameter of the aggregates submitted to the SW pre-treatment and MWD_{FW} is the mean weight diameter of the aggregates submitted to the FW pre-treatment.

3.2.4. Soil Organic Carbon

Soil organic matter fractions were obtained by a methodology based on Cambardella & Elliott (1993). Firstly, the soil samples were air-dried and sieved in a 2.00 mm mesh. Then, approximately 5g of soil were weighted, mixed with 30mL of a sodium hexametaphosphate solution (5g L^{-1}), and were stirred for 15 hours on a horizontal shaker. Then, the suspension was passed through a 53-µm sieve with deionized water. The particulate organic matter fraction (POM) was retained in the sieve, and the mineral-associated organic matter fraction (MAOM) passed through the sieve. Both fractions were oven-dried at 50°C, weighted, ground to pass through a 0.150-mm sieve, and analyzed by dry combustion in an elemental analyzer. Soil organic carbon was calculated for both fractions, and the total organic carbon (TOC) was calculated as the sum of both fractions.

3.2.5. VESS (Visual Evaluation of Soil Structure)

The visual assessment of the soil structure was carried out following the VESS methodology described by Guimarães et al. (2011). Small trenches (30 x 30 x 30 cm) were opened between the sugarcane planted lines, and a block of undeformed soil (20 x 25 x 10 cm) was removed from one of the walls of the trench using a shovel. The samples were transferred to plastic trays, and the aggregates were manually exposed, being broken in their natural fractures. The contrasting structural layers were identified and measured, and scores (Sq - structural quality) were assigned according to the criteria, descriptions, and photos contained in the VESS chart (Guimarães et al., 2011). The general score of the sample was calculated using the weighted average based on the Sq assigned to each layer and its depth (Eq 3.3).

$$VESS\ Sq = \sum_{i=1}^{n} \frac{Sqi\ Pi}{PT} \tag{3.3}$$

where:

VESS Sq is the general Sq of the sample, *Sqi* is the Sq of the layer; *Pi* is the depth of the identified layer, and *PT* is the total depth of the sample.

3.2.6. Soil Micromorphology

To collect undeformed samples, a one-meter-deep trench was opened to each treatment, between the sugarcane planting lines. The samples were collected in two depths (0 - 12 cm, and 12 – 24 cm) using specific boxes (measuring 7 x 12 x 5 cm) by carving the exact shape with a spatula. The undeformed samples were dried and impregnated by capillarity with a polyester resin, a styrene monomer, a catalyst for hardening the solution, and a fluorescent pigment that allows for distinguishing the porous space of the soil matrix under ultraviolet light. The samples were then cut into vertical blocks, sanded, and polished to achieve surface smoothness. The blocks were used to obtain a qualitative and quantitative analysis of the soil porous configuration. The procedure for analyzing the polished blocks, as described in detail by Castro and Cooper (2019), involves marking them for obtaining photomicrographs using a stereoscopic microscope, and evaluating them using specialized software (Fig. y). In each block, 15 to 20 microphotographs (1.12 cm^2) were scanned at 1024 x 768 pixels with a digital camera coupled to a stereoscopic microscope with a 10x magnification. The microphotographs were then processed using the Noesis Visilog and SPIA (Soil Pore Image Analysis) software to obtain the area occupied by pores, the pore size (small, medium, and large), and the types of pores (rounded, elongated or complex).

3.2.7. Soil-related Ecosystem Service Index

The erosion control ecosystem service was assessed through the same methodology used to assess the water flow regulation service, described in item 2.2.6 of this dissertation. The soil indicator used as proxies, as well as the soil functions evaluated to compose the erosion control I_{SES} are described in Table 3.1.

Table 3.1. Soil indicators and functions were selected to compose the index for the provision of erosion control ecosystem service for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil.

Soil-related Ecosystem Service	Soil Functions	Indicators (*proxies*)
I_{SES} – Erosion control	*f(i)* – Resistance and resilience of soil structure to degradation	*p(i)* – MWD; *p(ii)* – Organic carbon content (TOC); *p(iii)* – Soil stability index (SSI)
	f(ii) – Support for plant development	*p(i)* – Bulk density (BD); *p(ii)* – Resistance to penetration (SRP); *p(iii)* – Visual Evaluation of Soil Structure (VESS) *p(iv)* – Total Pore Area (TPA)

3.2.8. Data analysis

The data of the different parameters evaluated were initially subjected to Shapiro-Wilk's test for normality analysis, then to Levene's test for homogeneity of variance analysis. When appropriate, the data was then subjected to Fisher's ANOVA or to Welch's ANOVA to test the effects of sugarcane straw removal as a management strategy. When found significant by the F test ($p < 0.05$), the means were compared using Tukey ($p < 0.10$), or Games-Howell ($p < 0.10$) posthoc tests. In the data integration for the evaluation of the erosion control ecosystem service, the analytical strategies outlined in Cherubin et al. (2016) and expanded in Oliveira et al. (2019) were used. For the micromorphometric analysis, the mean area occupied by pores was calculated from the microphotographs, which served as pseudo-replicates to compare straw removal levels. Dataset was subjected to the same tests as the others indicators.

3.3. Results

3.3.1. Soil Bulk Density

No differences between treatments were found for bulk density (Fig. 3.2). Mean soil bulk density for all treatments reached around 1.55 g cm^3, in all soil layers sampled.

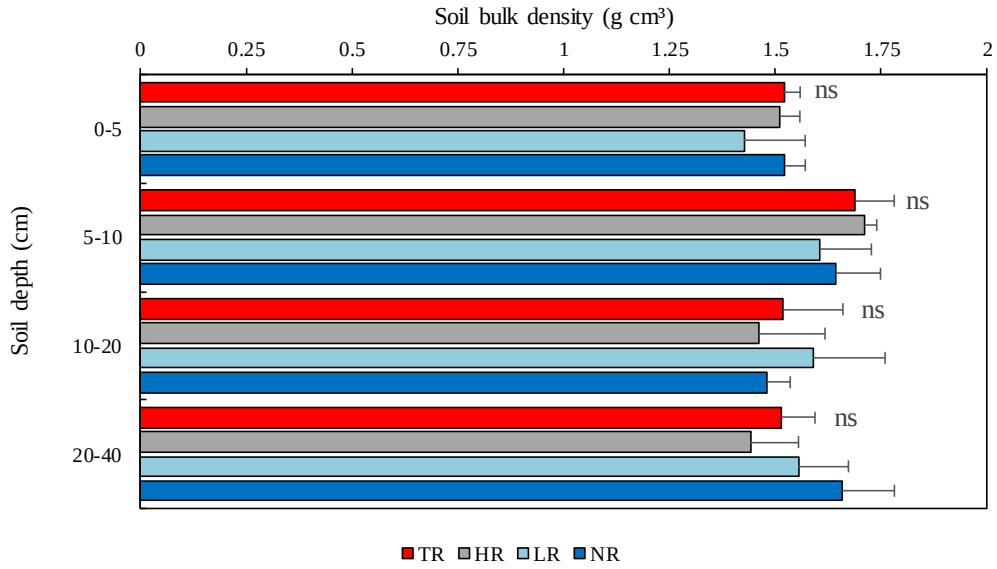


Figure 3.2. Soil bulk density in four soil layers for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. *TR = 0 Mg ha^{-1}; HR = 5 Mg ha^{-1}; LR = 10 Mg ha^{-1}; NR = 15 Mg ha^{-1}*

3.3.2. Soil Resistance to Penetration

In the same soil layer, no differences were detected between treatments (Fig. 3.3). However, penetration resistance results were higher in the surface (0 – 10 cm), when compared to deeper layers (20 – 40 cm). There was a 48%, 39%, 47%, and 27% increase in SRP for the TR, HR, LR, and NR treatments, respectively.

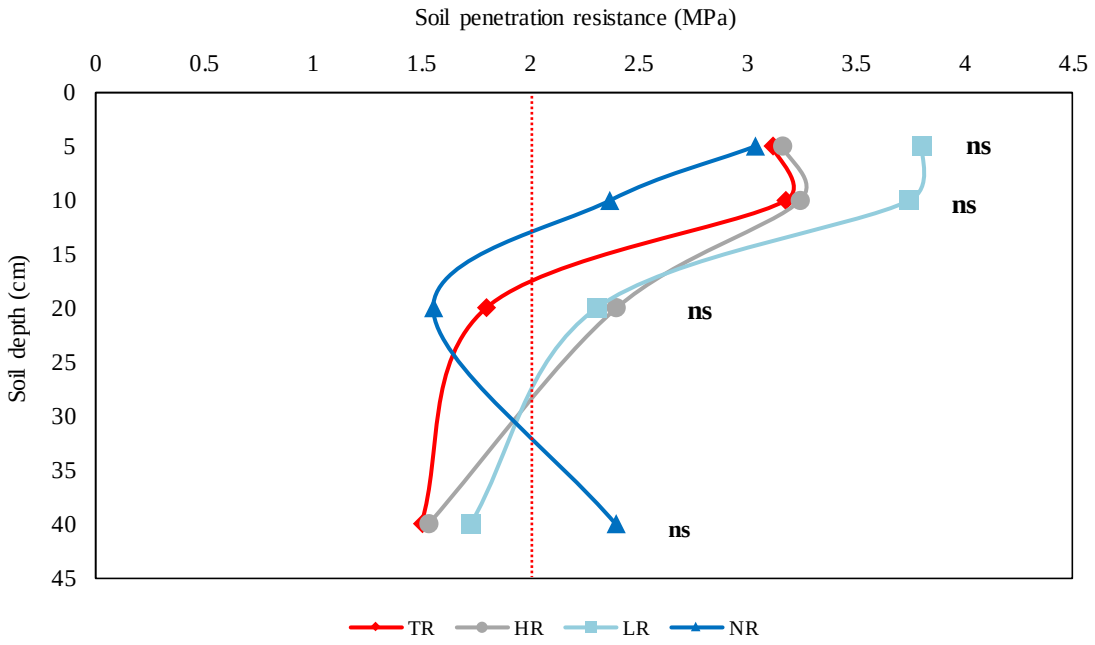


Figure 3.3. Soil resistance to penetration for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. TR = 0 Mg ha $^{-1}$; HR = 5 ton ha $^{-1}$; LR = 10 Mg ha $^{-1}$; NR = 15 Mg ha $^{-1}$. *The soil resistance values above the red dotted line are limiting to sugarcane roots growth (Otto et al., 2011). ns, not significant.*

3.3.3. Soil Aggregation

In the 0 – 5 cm layer for the Elliott methodology, the proportion of macroaggregates in the treatments with straw cover was higher as compared to the TR treatment, without any differences between the HR, LR, and NR treatments (Fig. 3.4a). This result was not observed in the other three soil layers, which showed no differences between the four treatments (Fig. 3.4b-d). No differences were observed in the proportion of microaggregates. The silt + clay fraction results did not differ between treatments in the 0 – 5 cm, 5 – 10 cm, and 20 – 40 cm soil layers, in the 10 – 20 cm layer the HR treatment differed from the TR treatment.

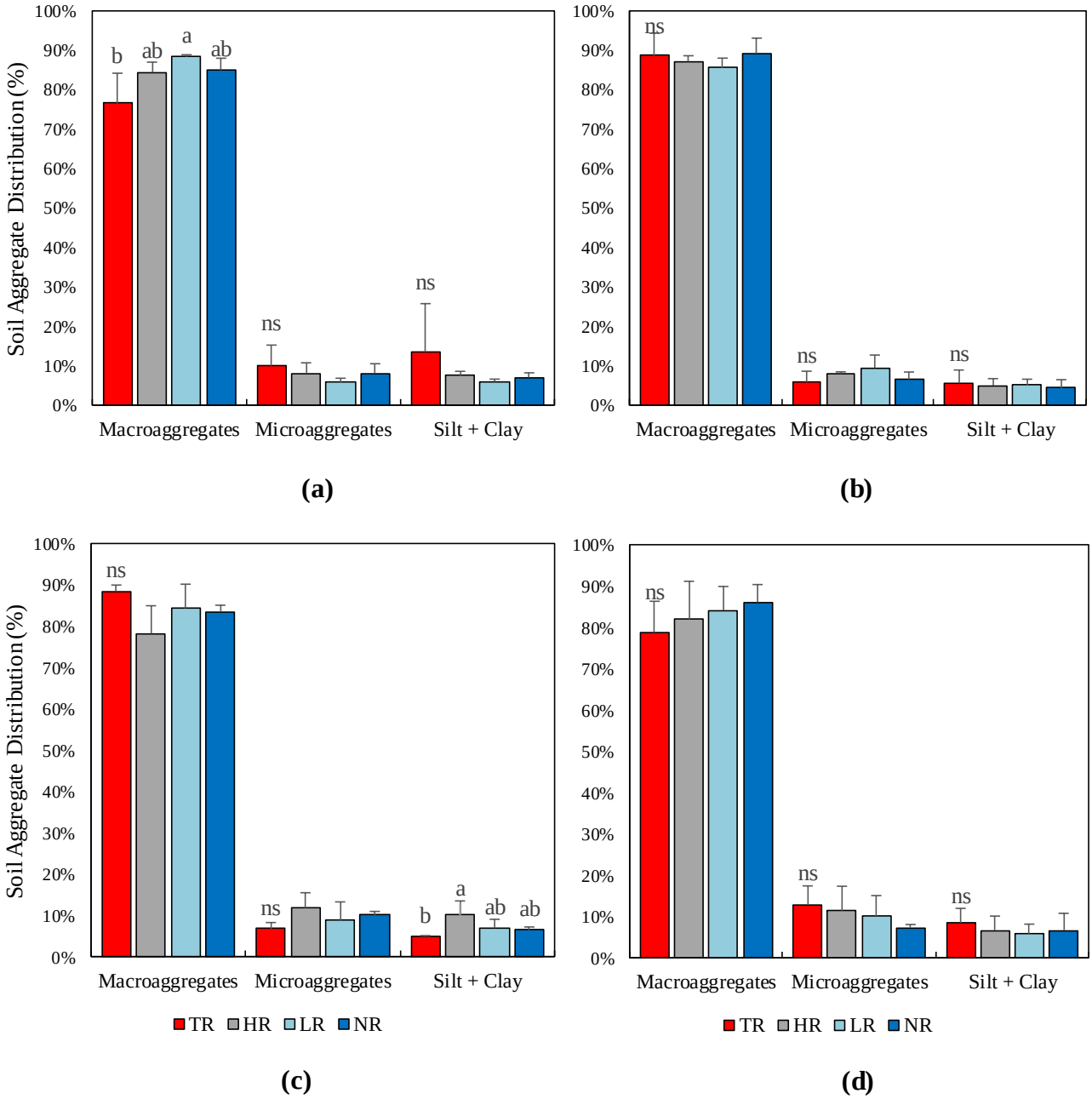


Figure 3.4. Soil aggregate distribution obtained by the Elliott methodology for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil, in the (a) 0 – 5; (b) 5 – 10; (c) 10 – 20 and (d) 20 – 40 cm soil layers. *TR = 0 Mg ha^{-1}; HR = 5 Mg ha^{-1}; LR = 10 Mg ha^{-1}; NR = 15 Mg ha^{-1}. *Means within each aggregates fraction followed by the same letters did not differ significantly among themselves according to Tukey's test ($p < 0.1$). ns, not significant.*

Straw removal did not induce changes in MWD in the aggregates subjected to the Elliott methodology, in all treatments and soil layers (Fig. 3.5).

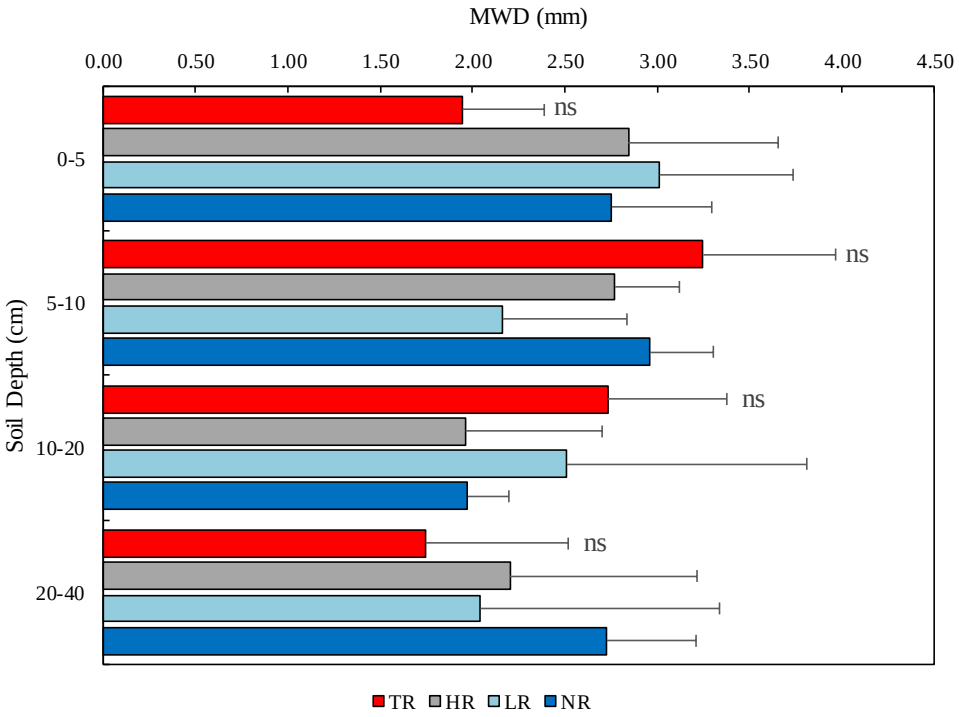


Figure 3.5. Mean weight diameter (MWD) of aggregates from a clayey soil in Iracemápolis, São Paulo, Brazil treated following an adapted Elliott (1986) methodology for four sugarcane straw removal rates. *TR = 0 Mg ha^{-1}; HR = 5 Mg ha^{-1}; LR = 10 Mg ha^{-1}; NR = 15 Mg ha^{-1}. ns, not significant.*

For the aggregates submitted to the methodology proposed by Le Bissonnais (1996), no differences in MWD between treatments were detected for the same soil layers and pre-treatments evaluated (Fig. 3.6). However, while SW and MB had similar results across soil layers, above 2.5 mm, the mean MWD results for the FW pre-treatment were higher in the surface, as compared to the deeper layers. Also, mean MWD values for this pre-treatment were lower as compared to the other pre-treatments tested, below 2.5 mm. The MWD results obtained for the SW and MB pre-treatments were closer to those obtained by the Elliott (1986) methodology.

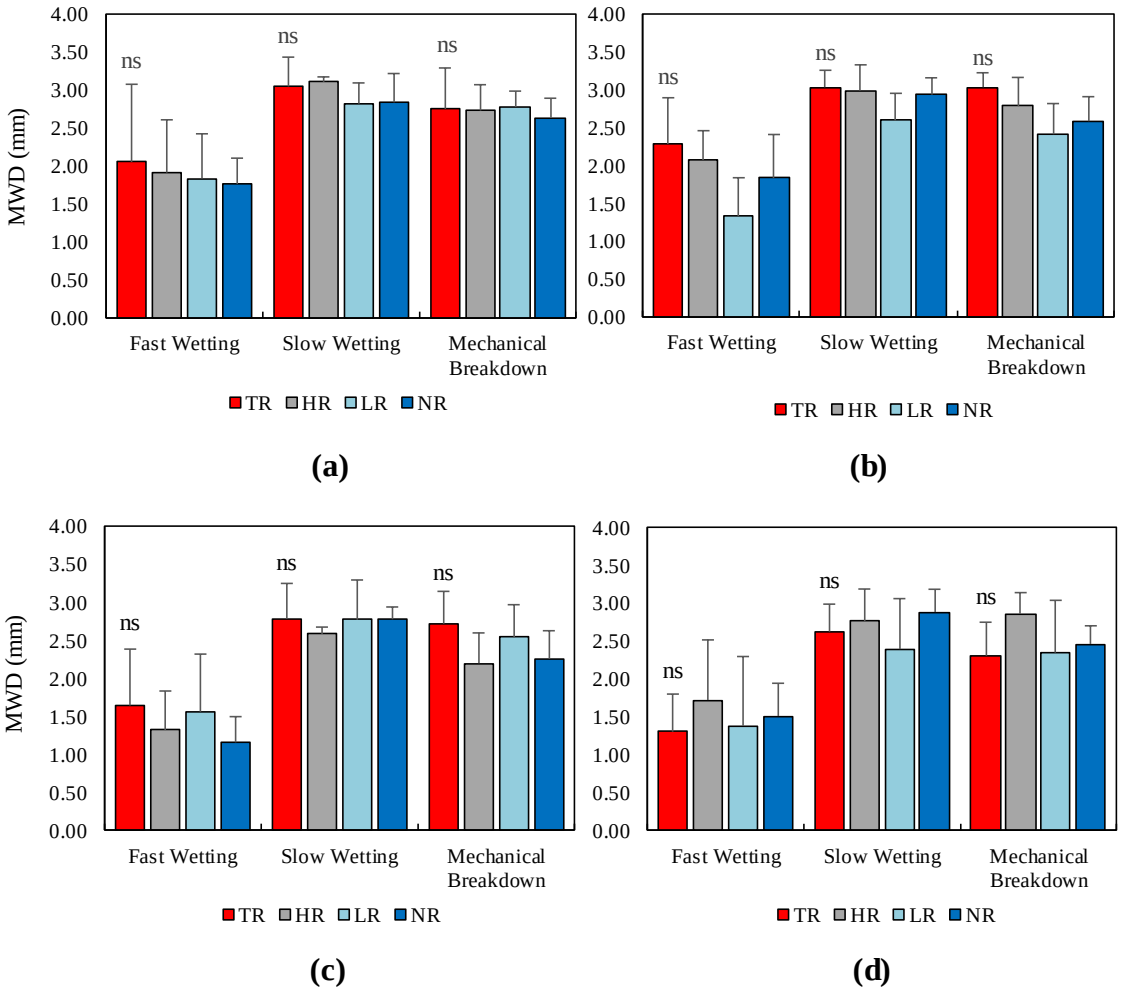


Figure 3.6. Mean weight diameter (MWD) of aggregates from a clayey soil in Iracemápolis, São Paulo, Brazil treated following the Le Bissonnais (1996) methodology for the (a) 0 – 5; (b) 5 – 10; (c) 10 – 20 and (d) 20 – 40 cm soil layers. *TR = 0 Mg ha^{-1}; HR = 5 Mg ha^{-1}; LR = 10 Mg ha^{-1}; NR = 15 Mg ha^{-1}.*

3.3.4. Soil organic carbon

Total removal of straw depleted soil TOC in the surface layer (0 – 5 cm), as compared to the LR treatment (Fig. 3.7c). The TOC content in this layer for the LR treatment was 23, 14, and 8% higher than the TOC content of the TR, HR, and NR treatments, respectively. There were no detected differences in TOC between treatments in the other soil layers evaluated, and the TOC content in the last layer (20 – 40 cm) was 21% lower than in the surface for the TR, HR, and NR treatments, and 31% lower for LR.

As the content from the MAOM fraction was not different for the four treatments (Fig. 3.7b), the difference detected in TOC is driven mainly by the POM fraction. In the 0 – 5 cm layer, the highest POM content was found for LR, followed by NR, and then by HR and TR. In the 5 – 10 cm layer, NR had the highest POM content, and no differences were found between the other treatments (Fig. 3.7a). In the 20 – 40 cm layer, NR and LR had similar results, as well as HR and TR.

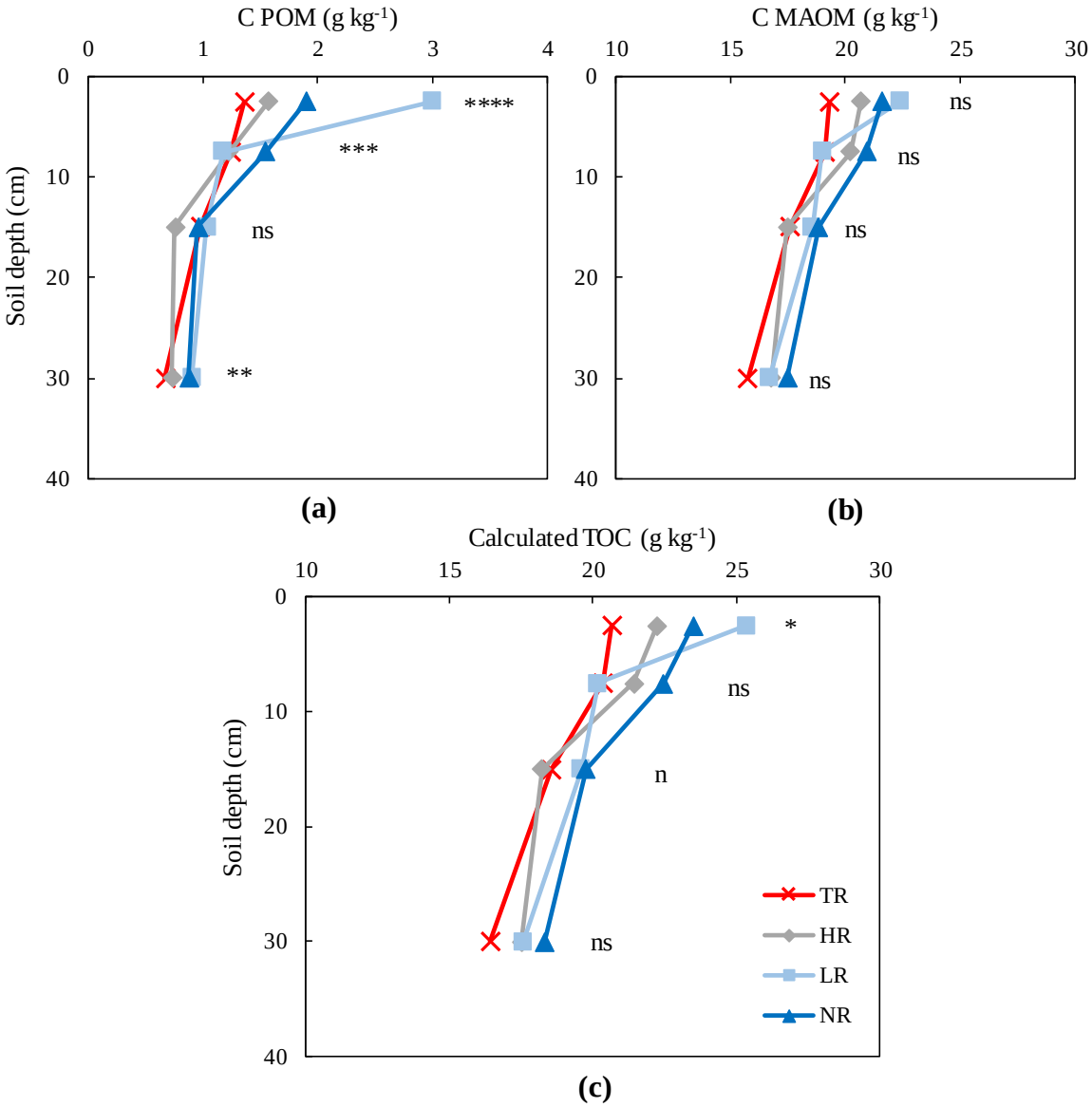


Figure 3.7. The carbon content for particulate organic matter (POM) and mineral-associated organic matter (MAOM), and calculated total carbon content (TOC) for a clayey soil in Iracemápolis, São Paulo, Brazil, under 0 Mg ha^{-1} (TR); 5 Mg ha^{-1} (HR); 10 Mg ha^{-1} (LR); and 15 Mg ha^{-1} (NR) sugarcane straw removal rates. **means that straw removal treatments differ among themselves according to Tukey's test ($p < 0.1$). ns, not significant.*

3.3.5. Visual Evaluation of Soil Structure (VESS)

The VESS scores for each layer and the whole soil layer evaluated (0 – 25 cm) did not differ between straw removal treatments (Fig. 3.8). In addition, as by Ball et al. (2007), soil plots with scores above the Sq=3 threshold are considered in need of short-term improvements in soil management (Fig. 3.9). Except for the HR and LR treatments for the first soil layer, all treatments passed this threshold.

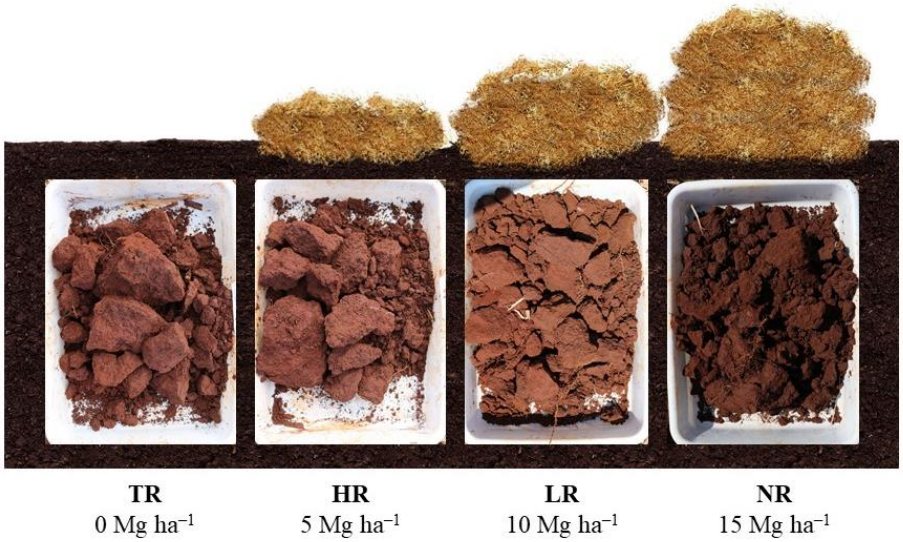


Figure 3.8. Soil samples collected for the Visual Evaluation of Soil Structure (VESS) four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil.

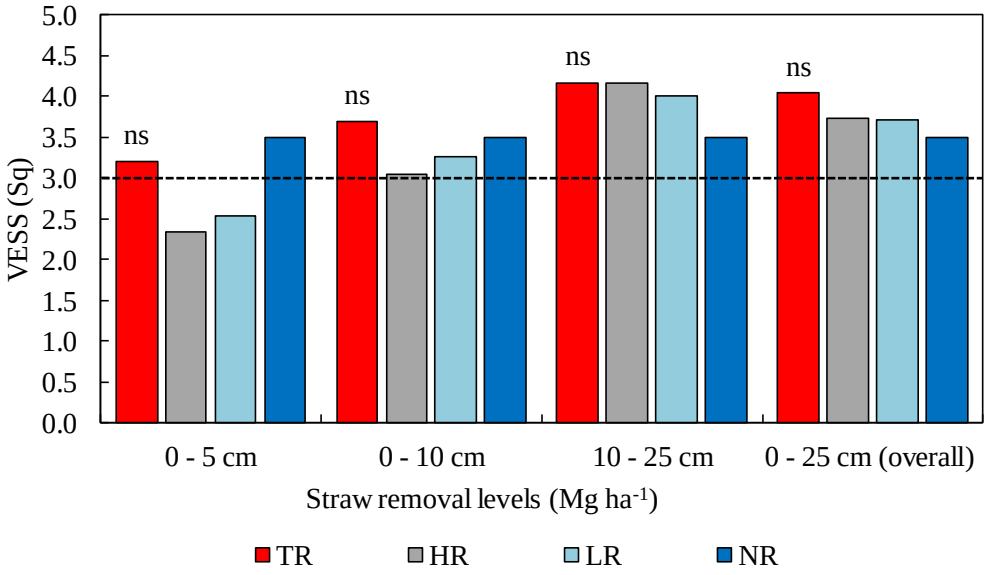


Figure 3.9. Visual Evaluation of Soil Structure (VESS) scores for the 0 Mg ha^{-1} (TR); 5 Mg ha^{-1} (HR); 10 Mg ha^{-1} (LR), and 15 Mg ha^{-1} (NR) sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. *The dashed line indicates the threshold above which short-term management changes are required to restore soil structure quality (Ball et al., 2007).*

3.3.6. Soil micromorphometric analysis

In the surface layer (0 – 12 cm), the total area of pores (TAP) of the NR treatment was 34%, 39%, and 66% higher than the TR, HR, and LR treatments, respectively (Fig. 3.10). In the subsurface layer (12 – 24 cm), however, straw removal did not catalyze significant changes in TAP (Fig. 3.10).

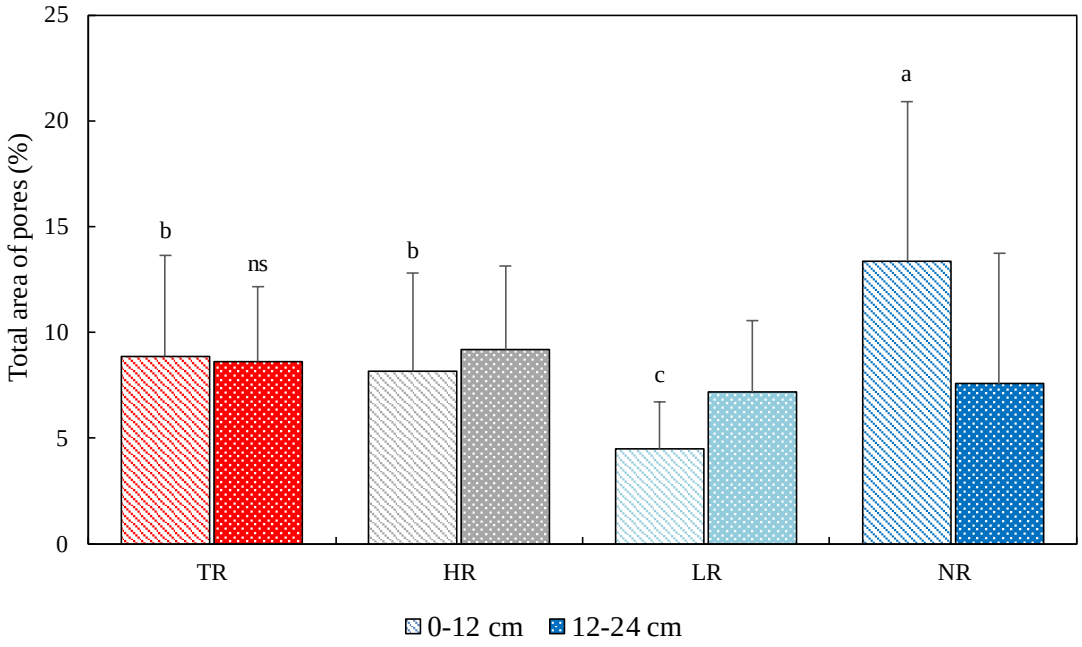


Figure 3.10. Total area of pores in the 0-12 cm and 12-24 cm layers for the 0 Mg ha^{-1} (TR); 5 Mg ha^{-1} (HR); 10 Mg ha^{-1} (LR) and 15 Mg ha^{-1} (NR) sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil. **Means within each soil depth followed by the same letters did not differ significantly among themselves according to Tukey's test ($p < 0.1$). ns, not significant.*

For the surface soil layer (0 – 12 cm), TR and NR show a predominance of large complex pores and a similar area of small and medium rounded pores. The NR treatment shows the greatest area of large and medium elongated pores and large rounded pores, as compared to the other treatments. The two intermediate treatments (HR and LR) showed a comparatively lower area of complex pores, with a predominance of small and medium rounded pores (Fig. 3.11).

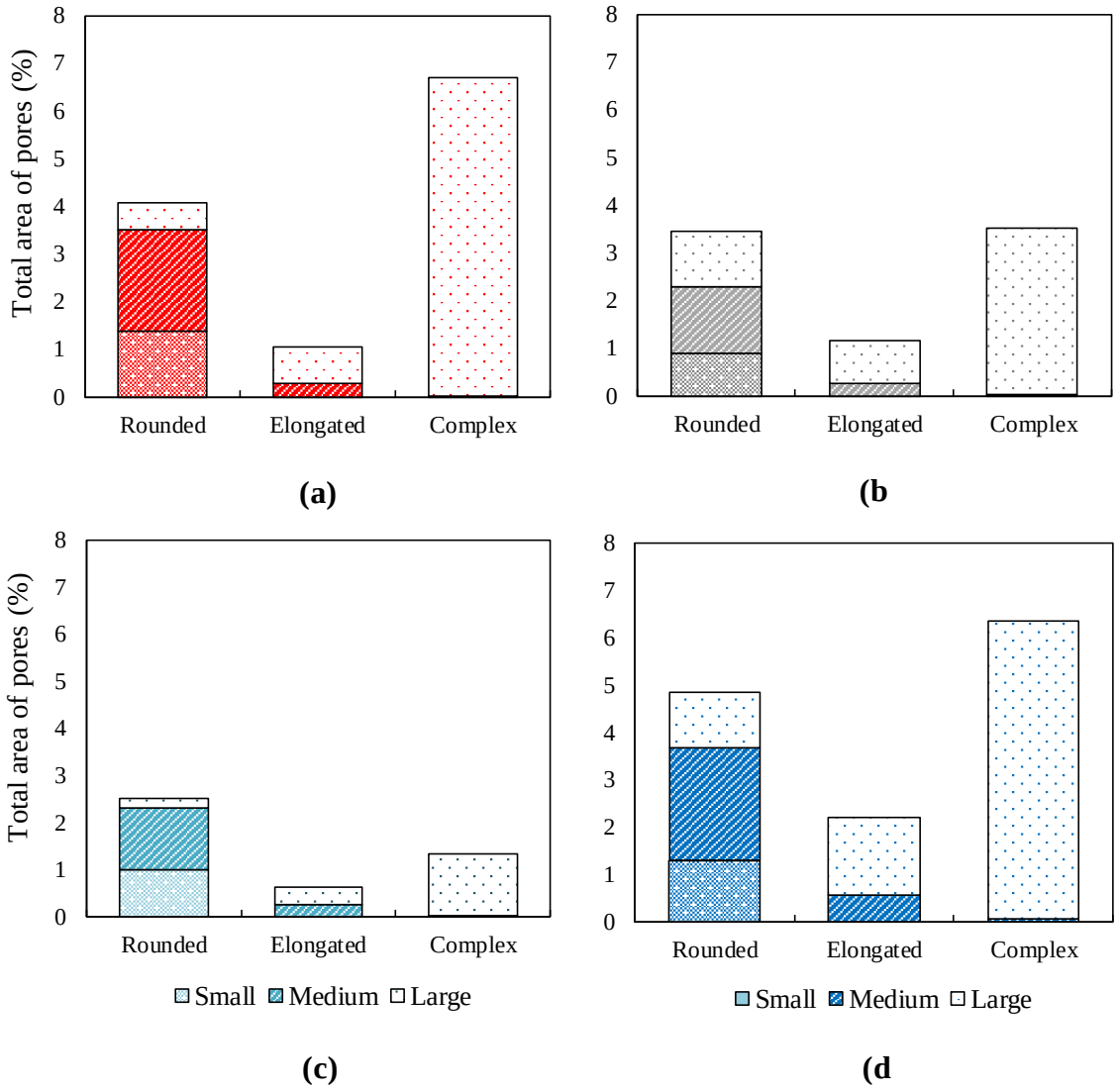


Figure 3.11. Pore size and shape distribution for the 0-12 cm layer for the (a) 0 Mg ha^{-1} (TR); (b) 5 Mg ha^{-1} (HR); (c) 10 Mg ha^{-1} (LR); (d) 15 Mg ha^{-1} (NR) sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil.

As compared to the 0 – 12 cm soil layer, there is a reduction of the large complex pore area for TR and NR in the 12 – 24 cm layer. This is accompanied, for TR and NR, by an increase and a decrease in the area of rounded pores, respectively. For HR, there was an increase in the area of small and medium rounded pores and large complex pores. The area of elongated pores was around 1% for all treatments in the 12 – 24 cm layer (Fig. 3.12).

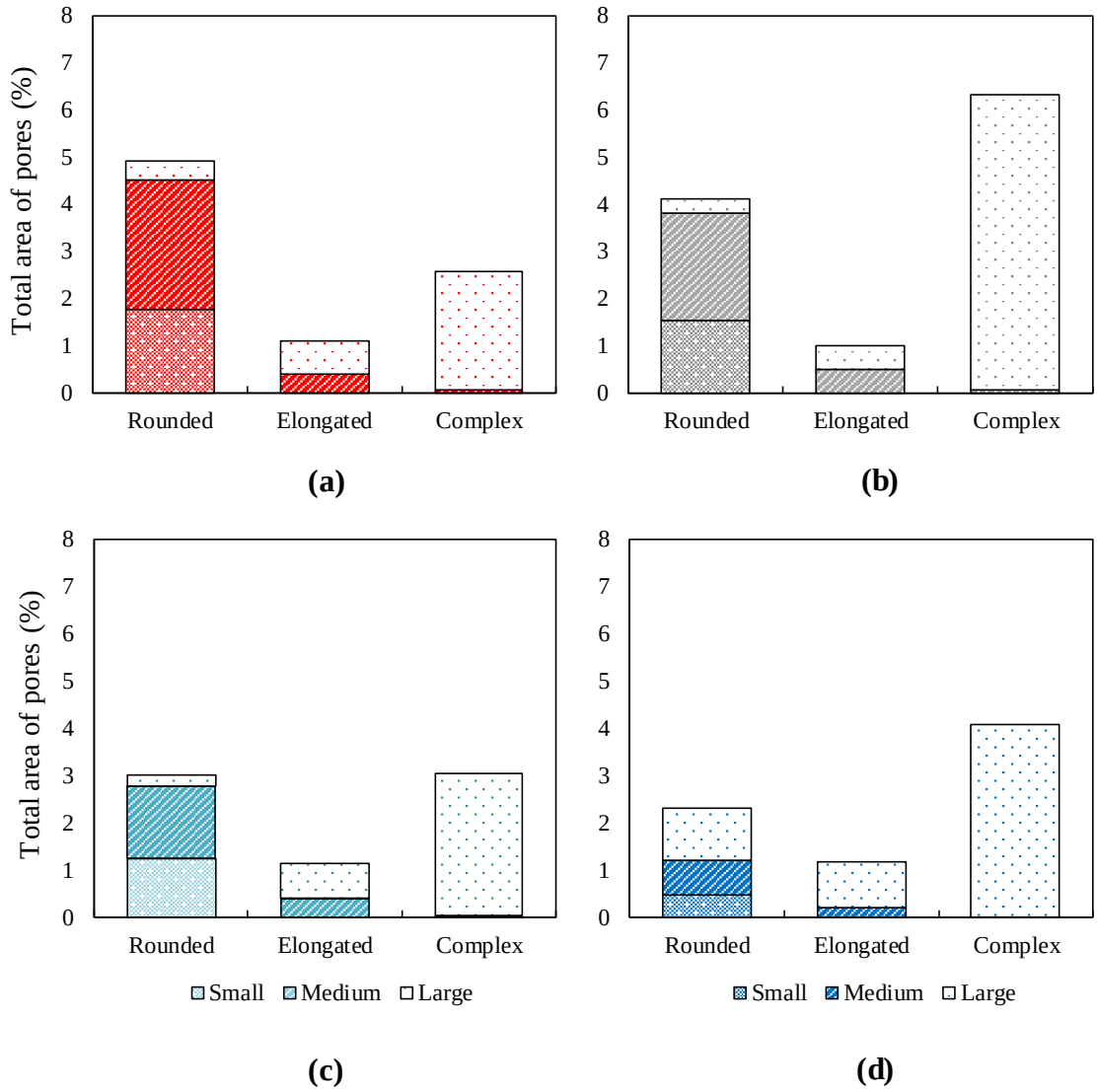


Figure 3.12. Pore size and shape distribution for the 12 – 24 cm layer for the (a) 0 Mg ha^{-1} (TR); (b) 5 Mg ha^{-1} (HR); (c) 10 Mg ha^{-1} (LR); (d) 15 Mg ha^{-1} (NR) sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil.

The binary microphotographs (Fig. 3.13) suggest that the presence of a greater area of large complex pores, especially in the TR and NR treatments in the 0 – 12 cm layer, is mainly due to the action of sugarcane roots.

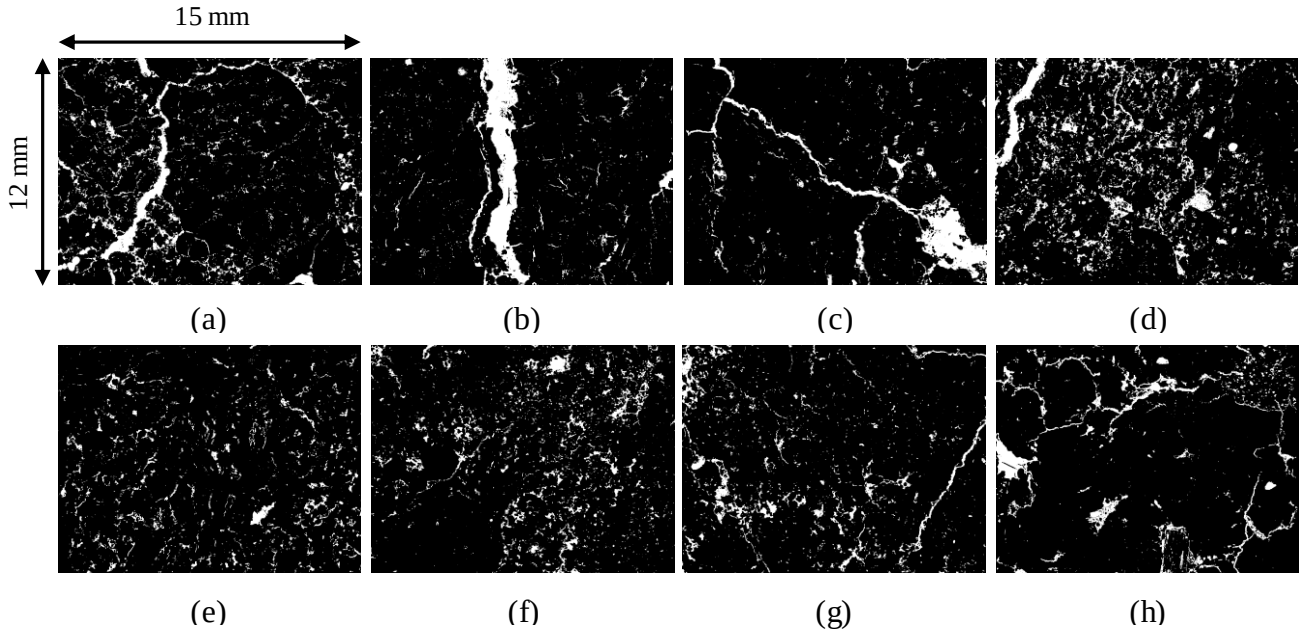
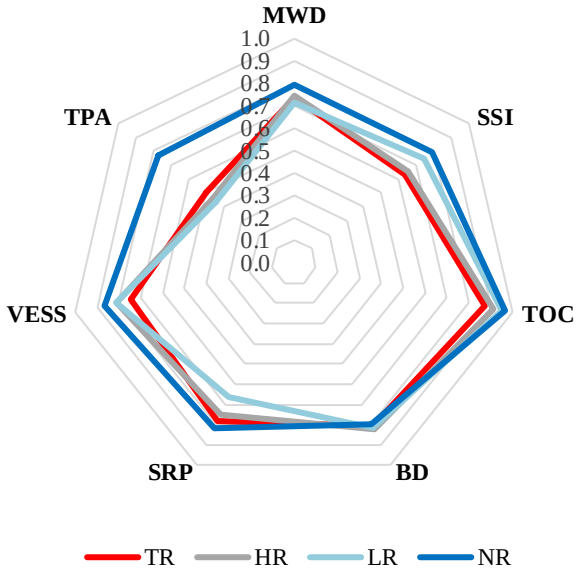


Figure 3.13. Binary microphotographs of the 0-12 cm soil layer for the (a) 0 Mg ha^{-1} (TR) (b) 5 Mg ha^{-1} (HR); (c) 10 Mg ha^{-1} (LR) and (d)15 Mg ha^{-1} (NR) straw removal levels; and of the 12-24 cm soil layer for the (e) 0 Mg ha^{-1} (TR) (f) 5 Mg ha^{-1} (HR); (g) 10 Mg ha^{-1} (LR) and (h)15 Mg ha^{-1} (NR) straw removal levels. The soil matrix is represented in black, and the pore space is white.

3.3.7. Soil-related Ecosystem Service Index (I_{SES})

The first soil function, representing the resistance of soil structure to degradation, showed no differences between straw removal levels. For the second function, providing support for plant development, NR had the best score (0.407) and differed from the TR (0.355), HR (0.356), and LR (0.342) treatments. For the erosion control service, NR differed from the other treatments and showed the highest score (0.83), while the other treatments had very similar scores, 0.74 for HR and LR, and 0.73 for TR (Fig. 3.14). All scores were higher than 73%, which indicates an adequate provision of the erosion control service.



Straw removal rates	Soil physical functions		ISES
	f(i)_ Resistance of soil structure to degradation	*f(ii)_ Support for plant development*	
TR	0.374^{ns}	0.355^{b*}	**0.73^{b}**
HR	0.385	0.356^{b}	**0.74^{b}**
LR	0.401	0.342^{b}	**0.74^{b}**
NR	0.425	0.407^{a}	**0.83^{a}**

Figure 3.14. Calculated soil functions and soil erosion control indexes for four sugarcane straw removal rates in a clayey soil in Iracemápolis, São Paulo, Brazil.
TR = 0 Mg ha $^{-1}$; HR = 5 Mg ha $^{-1}$; LR = 10 Mg ha $^{-1}$; NR = 15 Mg ha $^{-1}$
MWD = mean weight diameter; SSI = soil structure index; TOC = total organic carbon; BD = bulk density; SRP = soil resistance to penetration; VESS = visual evaluation of soil structure; TPA = total pore area.
**Means within the same column followed by identical letters showed no statistical difference (Tukey; p > 0.10). ns, not significant.*

3.4. Discussion

3.4.1. Soil structural alterations influenced by straw removal

Soil bulk density is one of the most well-known and widely used indicators of soil structure changes, due to the ease of sample collection and analysis, and the correlation to the soil compaction process. We determined BD values at the end of the sugarcane cycle and observed no differences in BD between treatments, and an ~11% increase from the 1.35 – 1.40 g cm^{-3} measured at the beginning of the experiment and reported by Castioni et al. (2019). The higher BD values are a result of further soil compaction by heavy machinery traffic in the two years after the authors evaluated the experiment, in the fourth year, and could indicate limiting conditions to plant growth, as they correspond to low soil porosity. However, since optimal BD values vary considerably between

soils (Håkansson & Lipiec, 2000), it is best to add other indicators when evaluating the effects of compaction on soil quality and plant growth.

The VESS methodology is increasingly being used to assess the quality of soil structure in sugarcane systems in Brazil, due to the low-cost nature and the relatively short time necessary to perform the assessment, and to the high correlation between widely used soil physical quality indicators reported in the literature (Cherubin et al., 2017, Castioni et al., 2018; Franco et al., 2019). In this study, the VESS scores were adequate indicators, since they correlated with BD and SRP results, as both indicators showed values restrictive to plant development, with no significant differences between straw removal rates, and the VESS scores indicate the need for short-term intervention in the management strategy to prevent further degradation of soil structure (Sq > 3) (Guimarães et al., 2011). The scores obtained indicate the degradation of soil structure caused by compaction regardless of the straw amount (Fig. 3.9). Although Castioni et al. (2018), in a study that evaluated a similar experiment located close to our experiment in the fourth year of the cycle, reported VESS scores for the NR treatment below the critical threshold (Sq >= 3), the effect of straw is not visible at the end of the cycle. The high VESS scores, indicating degradation of soil structure, seem to be a common feature of the two most used sugarcane cultivation systems in Brazil. In a burnt sugarcane system in Northeastern Brazil, where straw is removed by fire, Cavalcanti et al. (2020) reported VESS scores above the limiting threshold (Sq = 3) and found that sugarcane cultivation decreased the soil's capacity to perform its physical functions. Cherubin et al. (2017) observed increasing VESS scores in a land-use change sequence from native vegetation to pasture, and then to sugarcane systems with mechanical harvesting and no traffic control. Sugarcane cultivation rapidly degraded soil structure, as per the VESS scores and physical quality indicators.

The soil micromorphology analysis confirmed that sugarcane straw removal management has a moderate effect on soil porosity modifications caused by sugarcane cultivation. Canisares et al. (2020) examined a land-use change sequence from native vegetation to pasture and then to sugarcane, and observed that sugarcane cultivation reduced TAP, as compared to pasture and native vegetation. The authors found that in clayey soil, while the TAP from the native vegetation was around 37% for the surface layer, TAP for the sugarcane areas was around 10%, close to the values obtained in our study (Fig. 3.10). Although for the surface layer the NR treatment had a higher TAP than the other treatments, straw was not able to significantly prevent the loss of porosity across the other examined layer, especially of elongated pores. Low TAP and the prevalence of rounded pores over elongated pores constitute an obstacle for water movement in the soil profile, as well as for gaseous exchanges. A visual analysis of the large complex pores present in the microphotographs elucidates that they are a result of the actions of sugarcane roots, and they predominate in the surface layer, as compared to the 12-24 cm layer (Fig. 3.13). New roots may use this pore space left by dead roots as channels to penetrate the heavily compacted soil, as the penetration resistance of the soil becomes limiting to root growth along the cycle, and as successive sugarcane ratoons are cultivated before replanting (Lovera et al., 2021). Considering the SRP results we found in this study, this mechanism would be of utmost importance in the soil surface layers (Fig. 3.5), which were all above the threshold of SRP > 2.0 MPa, which Otto et al. (2011) observed to severely restrict sugarcane root growth. An important remark about our SRP results is that they were obtained in laboratory conditions, with normalized water tension, which does not consider the inherent effect that straw has in maintaining soil moisture in field conditions (Gmach et al., 2019), as Satiro et al. (2017) observed in a short-term assessment of the impact of straw removal

over soil physical quality. Satiro et al. (2017) highlighted that higher SRP values were observed for higher straw removal rates in the surface layers.

The micromorphological analysis was an important tool to confirm the impact of sugarcane cultivation and straw removal in soil functions, as the aggregate stability tests were not as sensitive to measure the soil physical degradation caused by compaction (Fig. 3.4 – 3.6). The methodology proposed by Le Bissonnais (1996), although not originally intended to evaluate the effect of soil management practices, delivered more sensitive results when the fast wetting and slow wetting pre-treatments were combined in a single index, probably because it explores two mechanisms of water-soil interaction, as opposed to the methodology adapted from Elliott (1986). Our results accede to Rabot et al. (2018), who argued that the aggregate perspective was not the most adequate approach to assess soil functions from soil structure data, and favored the pore perspective instead, image analysis especially. By selecting indicators from both the aggregate perspective and the soil perspective, we strived to establish a more balanced approach to the assessment of soil functions, to obtain a more solid body of data to infer about the provision of a soil-related ecosystem service.

Soil organic carbon is an important agent in building and maintaining soil structure, as it regulates the activity of the organisms that make up the soil food web, and which have a key role in the construction of soil aggregation (Tisdale & Oades, 1982). Straw is an important source of organic carbon to the soil in sugarcane production systems and keeping the straw in the system by not burning fields promoted incremental carbon accrual (Cerri et al., 2011). Thus, several studies have been conducted to assess whether straw removal management would deplete soil organic carbon stocks and revert the benefits gained by the "green cane" system. Bordonal et al., (2018), in a short-term evaluation, concluded that complete straw removal depletes soil organic carbon stocks, while moderate or no straw removal maintained the stocks. More recently, a more comprehensive study conducted by Tenelli et al., (2021), in a medium-term evaluation, revealed that high straw removal rates depleted soil organic carbon, especially in the surface layers, where straw has a higher influence on carbon stocks. Both studies concluded that results tend to be site-specific and that sandy soils are more prone to lose soil organic carbon as a result of straw removal than clayey soils. In clayey soil, at the end of one sugarcane cycle, complete straw removal reduced soil C especially in the surface layer (Fig. 3.7). However, the low straw removal treatment presented the best results in terms of maintaining soil C content. This advises that planned and conscientious straw management can be a viable strategy to increase bioenergy production without depleting soil organic carbon stocks, and demand further studies to examine long-term consequences to carbon stocks, soil structure, and soil functions.

3.4.2. Implications of soil structural changes in the provision of the erosion control service

Through the soil-related ecosystem service index, we verified that sugarcane straw is moderately associated with the soil functions that uphold the erosion control service (Fig. 3.14) for the clayey soil studied, mainly, with support for plant growth.

Soil erosion is a recurring problem in sugarcane cultivation, posing a threat to soil conservation and the overall sustainability of the crop (Hartemink, 2008; Filoso et al., 2015; Youlton et al., 2016). Although the mechanized harvest system leaves sugarcane straw to protect the soil surface, instead of burning the straw, it can aggravate soil erosion by the indiscriminate opening of dirt access roads to the machinery used during the harvest to transport the stalks to mills (Bezerra et al., 2020). The critical period for soil erosion in sugarcane cultivation is

after the end of the culture's cycle when sugarcane areas are replanted (Martinelli & Filoso, 2008), as the replanting process currently includes deep tillage operations, which are greatly responsible for the subsequent loss of soil physical quality and increased susceptibility to erosion (Cherubin et al., 2016). However, soil erosion during the sugarcane cycle is not negligible. Alterations on soil porosity, as the decrease in TPA shown in the micromorphometric analysis (Fig. 3.10), happen as the result of soil compaction during the sugarcane cycle (Barbosa et al., 2019) and contribute to increasing soil susceptibility to erosion. Therefore, failure to adopt conservationist practices to prevent soil loss during the sugarcane cycle can lead to negative agronomic and environmental consequences.

Soil erosion in sugarcane cultivation areas can occur even under complete soil cover, as observed by Martins Filho et al. (2009). Thus, arises the concern that intensive straw removal management would leave soils more susceptible to erosive processes. Silva et al., (2012) measured soil loss by interrill erosion in plots with five straw rates and observed that with bare soil, soil loss was around 100 kg ha^{-1}, but decreased as the straw cover increased up until the treatment with 5.2 Mg ha^{-1} of straw, after which soil loss remained unchanged. The amount is close to the 7 Mg ha^{-1} of straw necessary to cover the soil, as proposed by Silva et al., (2019), and to the 10 Mg ha^{-1} of straw Sousa et al., (2012) found to reduce organic matter and nutrient losses.

Straw is related to several of the soil's physical functions that regulate the erosion control service. (Ranaivoson et al., 2017). Straw reduces the kinetic energy and the direct impact of raindrops on the soil surface, which reduces the release of particles by splashing and the surface sealing (Fernández-Raga et al., 2017). Straw also regulates the carbon stock (Fig. 3.6) (Tenelli et al., 2021), and the abundance and activity of soil organisms (Morais et al, 2019; Menandro et al., 2019), which in turn regulate the aggregation and strength of the soil structure (Six et al., 2002). The physical stability of the soil structure diminishes soil loss by preventing the breakdown of aggregates, followed by the detachment and transport of soil particles, and the clogging of surface pores which can severely compromise infiltration and increases water runoff. Valim et al., (2016) observed that sugarcane straw cover reduced soil and water loss, and water infiltration rates were 100% higher in the treatment without straw removal, as compared to the plots where straw was completely removed. However, the treatment with 4 Mg ha^{-1} of straw was already efficient in reducing water and soil loss, and increasing water infiltration.

Our data indicate that in soils with higher structural stability (i.e., oxidic clayey soils), although the treatment with no straw removal had higher scores (Fig. 3.14), the erosion control service can be adequately provided with reduced amounts of straw (Fig. 3.14), opening the possibility of moderate straw removal in areas with high productivity. The preoccupation with the service provision should lie especially in soils more susceptible to erosion, such as soils located in slope areas, and sandy soils. In sandy soils, which have lower stability and resilience as compared to clayey soils (Gregory et al., 2007), the depletion of carbon stocks by straw removal (Tenelli et al., 2021) and the degradation of soil structure by field traffic (Castioni et al., 2019) may compromise the provision of the erosion control service.

3.5. Conclusions

According to our approach, straw removal has a limited effect on the provision of the erosion control ecosystem service for soils with high structural stability at the end of the sugarcane cultivation cycle. Straw removal intensified the structural degradation and resulted in a reduction of the SES index by about 10%.

Nonetheless, based on our approach, we observed that even with straw removal the soil was able to reasonably provide the service (I_{SES} > 73%) demonstrating that intrinsic factors (e.g. mineralogy and texture) were the determinant components to sustain high stability of the soil structure. Based on that, our data suggest that moderate straw removal can be implemented in these soils as a strategy to amplify bioenergy production without diminishing the soil's capacity to provide the service. In soils inherently more susceptible to erosion, it is advisable to conduct site-specific studies to evaluate the soil's capacity to function correctly and provide erosion control service under straw removal management. In addition, it is important to note that other practices common in sugarcane cultivation, and that have a high impact on soil erosion, such as tillage during high precipitation periods and the inadequate construction of roads, should be reconsidered and readjusted to achieve the goal of reducing soil erosion for soil conservation.

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4. FINAL CONSIDERATIONS

The positive ramifications of the large-scale adoption of "green cane" mechanized systems in central-southern Brazil are well documented in the literature. Benefits to human health, both to sugarcane workers and the population that lives around areas where sugarcane fields were in the past burned, and environmental positive trade-offs such as the protection of the fauna and the reduction in greenhouse gas emissions are the most-known and commented achievements of the transition. There are also well-known economic and agronomic gains from the intensification, such as the high productivity of mechanical harvesters, and the formation of a protective straw blanket over the soil.

Many of the earlier studies consulted in the literature used the term "trash" to designate the mixture of dry sugarcane leaves, green leaves, and pointers left on the field by mechanized harvesting. The term, although then used with no negative connotations by the authors, has changed to the more positive term "crop residue" or "straw" in recent studies, demonstrating an upgrade in the status of the material in the collective eyes of researchers and sugarcane farmers. Straw is now viewed mostly as an asset within the sugarcane production system, that can act as a protective shield against splash erosion, a source of nutrients and organic matter to the crop and soil organisms, and as a potentially advantageous industrial feedstock.

As many previous studies have found, it is possible to remove a portion of the straw from the soil for the production of cellulosic ethanol or the generation of bioelectricity without catalyzing soil degradation, which can be a viable strategy to increase the financial sustainability of sugarcane mills, especially in uncertain scenarios. As this study reveals, at the end of the sugarcane cycle, and specifically in soils with high structural stability, straw has little to no impact on the water flow regulation service, and a moderate impact on soil erosion control service. However, straw is also connected to other soil-related ecosystem services that might be affected by the removal, such as nutrient cycling. In addition, there is data that shows that for sandy soils, straw removal might have a greater impact on soil functions, compared to clayey soils such as the one evaluated in this study. Therefore, to avoid long-term negative consequences to soil functions and ecosystem services provision, the best approach seems to be planning a straw removal rotation system privileging removal from areas with higher structural stability, removing straw only at the last harvest before replanting, and alternating between areas. Indubitably, other considerations, such as a cost-benefit analysis of the operation, circumscribe the possibilities when outlining such a management strategy. Nonetheless, soil conservation must be seriously considered in the planning, as the soil is an invaluable asset for agriculture.

The intensification of sugarcane production systems also contributed to soil conservation problems, as the use of heavy harvesters and loaders causes soil compaction and requires the construction of roads which increase soil erosion. The results for the selected soil indicators in this study showcase the loss of the soil's physical functions, especially the functions linked to water movements, at the end of the sugarcane cycle. Bulk density, soil resistance to penetration, macroporosity, and available water capacity results reached the critical values for each indicator, revealing the degradation caused by machinery traffic. The results obtained for the indirect indicators were corroborated by the visual evaluation of soil structure and the image analysis. The loss of physical functions led to a loss of water flow regulation service provision, as shown by the index. This can lead to yield losses due to water deficits, which is recognized as the main cause of the yield gap in sugarcane production in Brazil. To change this scenario of soil degradation and mitigate the effect of field traffic, farmers can adopt soil management practices

that reduce the area of machinery influx, such as controlled traffic, and that prevent the destruction of soil structure, such as reduced or no-tillage. In addition, data suggests that the implementation of more conservationist soil management practices reduces the impact of straw removal in soils more prone to degradation, thence coupling these practices may be the best strategy to allow for the removal of sugarcane straw from these soils without compromising their functioning.

The approach to quantify the provision of soil-related ecosystem services taken in this study aims to aid in the efforts to increase the tangibility of the idea. Thinking in terms of ecosystem services, instead of in terms of isolated soil attributes can open the comprehension to the nature of soils as a diverse and heterogeneous ecosystem within the larger agroecosystem. This way of thinking can prompt researchers and farmers to more carefully examine the broader effects of management practices in the sugarcane cultivation system on the soil, and consider the loss of these services as truly a financial loss. Therefore, with a reliable approach to quantify the provision of ecosystem services, researchers and farmers would be able to compare the effects and externalities of different soil management practices on the services and have a tool to monitor their progress when switching to more conservationist practices.

Presently, there are limitations to this approach of quantifying soil-related ecosystem service provision. The limitations are more apparent, in this study, for the erosion control service since no direct method to evaluate soil loss was used. The parameter measured, represented indirectly the soil susceptibility to erosion. To strengthen the accuracy of the index would require a study with erosion plots under sugarcane straw removal to measure soil loss, matched with the already-used approach of data collection from indicators, to then calculate the index and validate it with empirical soil loss data. Similar validation studies would be necessary to all other soil-related ecosystem services to adjust and consolidate the methodology. Further studies into the quantification of soil-related ecosystem services should take advantage of technological advances in data science tools, such as machine learning algorithms, to work with bigger datasets and allow artificial intelligence to infer the patterns of behavior in soil systems, thus diminishing the risks of oversimplification of such a complex system as soils.