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Sugarcane cultivation effects on soil physical properties, functions, and related-ecosystem services

Felipe Bonini da Luz

Thesis presented to obtain the degree of Doctor in Science.
Area: Soil and Plant Nutrition

Piracicaba
2022

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ABOUT THE AUTHOR

Felipe Bonini da Luz was born on May second, 1991 in Panambi-RS, Southern Brazil. He grew up in a rural area named Linha Gramado where he studied at São João Batista School. He also studied to be an agriculture technician at IMEAB institute in the city of Ijuí-RS. Felipe is a Lab Technician at the Federal University of Santa Maria with a professional interest in soil quality scientific studies. Felipe graduated from the Federal University of Santa Maria campus Frederico Westphalen with a bachelor's degree in Agronomy and holds a master's degree in Agronomy, Agriculture, and Environment. In 2019, Felipe started his Ph.D. in Soils and Plant Nutrition at Luiz de Queiroz College of Agriculture/University of São Paulo (ESALQ/USP) with an internship at Wageningen University & Research in the Netherlands. Felipe is eternally grateful to his family, professors, teachers, and friends who inspirited him during his personal and professional career.

Felipe is passionate about soils and soil science. Soil is where nature's contributions to people such as food begin. His studies focus on soil functions and soil health in Brazilian agriculture. He hopes that his studies can contribute to tropical agriculture, soil and water conservation, and environmental conditions. More information about the author and his studies can be seen on the following websites: http://lattes.cnpq.br/4603069391625727 and https://www.sohmaesalq.com/.

*“**Tudo passa pela educação**” “It is all about education”*

Bronildo Jose Wenzel – Brazilian farmer who got a bachelor in Agronomy at 73 years old

CONTENTS

RESUMO

Efeitos do cultivo de cana-de-açúcar nas propriedades físicas, funções e serviços ecossitêmicos do solo

O Brasil é o maior produtor mundial de cana-de-açúcar e está empenhado em promover a produção de cana-de-açúcar nos próximos anos. Contudo, a expansão da cana-de-açúcar pode degradar a qualidade física do solo e suas funções relacionadas, devido a práticas de manejo como o preparo convencional e o tráfego agrícola aleatório. Inversamente, práticas conservacionaistas, tais como o plantio direto e a adoção de zonas livre de tráfego tem sido investigadas como práticas de manejo que podem melhorar a estrutura do solo e, consequentemente, a capacidade do solo em realizar suas funções. As hipóteses deste estudo são que i) a expansão da cana de açúcar manejada com preparo convencional sobre áreas de pastagem extensiva degrada a estrutura do solo reduzindo as suas funções e ii) a adoção do preparo reduzido e zonas livre de tráfego ao invés do preparo convencional melhora a estrutura do solo e, consequentemente, as suas funções. O objetivo geral desta tese foi avaliar os efeitos de uma típica sequência de mudança de uso da terra (vegetação nativa - pastagem - cana-de-açúcar) para a expansão da cana de açúcar nas funções do solo e a adoção de diferentes práticas de manejo no seu cultivo. Para atingir este objetivo, este estudo avaliou i) os efeitos de uma típica sequência de mudança de uso da terra para a expansão da cana-de-açúcar na qualidade física do solo e dinâmica da água em solos com texturas contrastantes, ii) indicadores de disponibilidade de água e fluxos de ar no solo em dois solos com texturas contrastantes sobre preparo convencional e preparo reduzido associado com e sem adoção de zonas livre de tráfego, iii) os efeitos do preparo convencional e preparo reduzido com e sem adoção de zonas livre de tráfego na estrutura do solo, e iv) os impactos do controle de tráfego agrícola nas propriedades físicas e funções do solo relacionadas sob contrastantes texturas do solo. Os resultados mostraram que a conversão da vegetação nativa para pastagem extensiva induziu severa degradação na qualidade física do solo. Por outro lado, a conversão da pastagem para cana-de-açúcar não causou degradação adicional na estrutura do solo e na dinâmica da água do solo. De modo geral, o preparo convencional e preparo reduzido sob tráfego aleatório mostraram similaridade na estrutura do solo, disponibilidade de água e fluxos de ar no solo. No entanto, a adoção do preparo reduzido associado a zonas livre de tráfego melhorou a estrutura do solo independentemente das escalas de avaliação (ou seja, micro e macro escalas), bem como preservou a disponibilidade de água e os fluxos de ar no solo. Além disso, o controle de tráfego agrícola manteve a funcionalidade física do solo e a qualidade física do solo na linha de cultivo e não reduziu a qualidade física do solo em relação ao tráefgo aleatório na entre-linha de cultivo da cana-de-açúcar. Por último, este estudo identificou que a adoção do preparo reduzido e zonas livre de tráfego são dois dos pilares mais importantes para reduzir a compactação do solo no cultivo de cana-de-açúcar e, consequentemente, contribuir positivamente para a provisão de serviços ecossistêmicos relacionados a qualidade física do solo.

Palavras-chave: Qualidade do solo, Estrutura do solo, Controle de tráfego ágricola, Sistema plantio direto, Conservação do solo, Bionergia

ABSTRACT

Sugarcane cultivation effects on soil physical properties, functions, and related-ecosystem services

Brazil is the world's largest sugarcane producer and is committed to promoting sugarcane production in the following years. However, sugarcane expansion can degrade soil physical quality and related soil functions due to management practices such as conventional tillage and random machinery traffic. Conversely, conservation tillage practices such as reduced tillage and the adoption of traffic-free seedbed zones have been investigated as management practices that can improve soil structure and, consequently, its functional capacity. The hypotheses of this study are that i) sugarcane expansion under conventional tillage on pasture areas degrades soil structure and reduces the related soil functions and ii) the adoption of reduced tillage and traffic-free seedbed zones instead of conventional tillage improves soil structure and consequently the related soil functions. The overall objective of this study was to evaluate the effects of a typical land-use change sequence (native vegetation – pasture – sugarcane) on soil functions for sugarcane expansion and the adoption of different tillage practices in its cultivation. To meet this objective, this study has assessed i) the effects of a typical land-use change sequence for sugarcane expansion on soil physical quality and water dynamics in contrasting soil textures, ii) soil water availability and air flux indicators in two soils with contrasting textures under conventional and reduced tillage practices associated with random and without machinery traffic, iii) the effects of conventional and reduced tillage practices with random and without machinery traffic on soil structure, and iv) the impacts of agricultural traffic control on soil physical properties and related functions under contrasting soil textures. The findings showed that conversion from native vegetation to extensive pasture induced severe degradation in soil physical quality. On the other hand, conversion from pasture to sugarcane did not cause additional degradation on soil structure and soil water dynamics. In general, conventional tillage and reduced tillage under random traffic showed similar soil structure and soil water availability and air fluxes. However, the adoption of reduced tillage and traffic-free seedbed zones improved soil structure regardless of assessment scales (i.e., micro and macro scales) and it also preserved soil water availability and air fluxes. In addition, agricultural traffic control supported soil physical functionality and soil physical quality at the seedbed position and it did not reduce soil physical functionality related to uncontrolled traffic at the sugarcane inter-row position. Lastly, this study identified that adopting reduced tillage and traffic-free seedbed zones are two of the most important pillars for reducing soil compaction in sugarcane fields and, consequently, can contribute positively to provide nature's contribution to people.

Keywords: Soil health, Soil structural quality, Agricultural traffic control, no-tillage, Soil conservation, Bioenergy

1. INTRODUCTION

Brazil is the world leading sugarcane producer, and responsible for 39% of global production. Its cultivated area accounts for about 10 million hectares (Conab, 2022). In order to meet the future scenario of increment in the domestic and international demands of biofuels, an expansion of about 5 million hectares is estimated by 2030 (Andrade Junior et al., 2019). The sugarcane expansion has occurred in areas previously covered with pasture, extensive and poorly managed pastures, marginal lands (e.g., sandy soils) as well as non-marginal lands (e.g., clayey soils) located in the central-south region (Spera et al., 2017). In addition, 20 million hectares occupied by pasture lands are currently available for sugarcane expansion in that region (Hernandes et al., 2021). In the last decade, some studies have revealed the impacts of sugarcane expansion on soil quality in areas previously covered with pasture (e.g., Cherubin et al., 2016a; Bordonal et al., 2018; Oliveira et al., 2019). Compared to pasture, sugarcane cultivation has impaired soil physical quality (Cherubin et al., 2016b). This is due to soil mobilization caused by planting and replanting/renewal procedures followed by soil compaction through heavy machinery traffic during de sugarcane cultivation cycle (Guimarães Júnnyor et al., 2022).

To find solutions to prevent and mitigate negative impacts on soil physical quality by soil mobilization and compaction are still challenging for sugarcane farmers, scientists, and stakeholders. Those processes cause degradation of soil structure which is a key element to an improved understanding of soil functions (Vogel et al., 2021). Therefore, sugarcane expansion can degrade soil physical quality and hinder soil functional capacity by reducing of soil functions such as primary productivity, soil physical stability and support, soil water retention, soil aeration, soil carbon storage, and habitat for biodiversity. In the same way, the degradation of soil structure in sugarcane fields not only impacts the farmers but also society as a whole through the reduction of nature's contributions such as fresh water, energy security and climate regulation.

The degradation of soil structure and related soil functions can be maximized by management practices such as conventional tillage with subsoiling, plowing, and disking as well as by random machinery traffic in the field. Currently, both conventional tillage and heavy machines (e.g., harvesters and transloaders) are widely used by sugarcane farmers in planting/renewal and harvesting events. Conventional tillage has been used to alleviate soil compaction preceding the sugarcane planting; however, the positive effects of mechanical disturbance have short persistence and soil returns to the same degree of compaction after one or two harvesting events (Barbosa et al., 2021, Oliveira et al., 2022). On the other hand, conservation tillage practices such as no-tillage or reduced tillage and the adoption of traffic-free seedbed zones by controlled traffic in the mechanical operations have been investigated as management practices that can improve soil structure and, consequently, its functional capacity.

Soils differ in their relative capacity to perform each soil function, as determined by its inherent properties, land and environmental conditions, and adopted management practices (Schulte et al., 2014). Therefore, understanding the soil response to sugarcane expansion and adoption of different management practices in sugarcane fields under contrasting soil conditions is imperative to promote more sustainable bioenergy production in the country (Cherubin et al., 2021; Rossetto et al., 2022). In addition, studies evaluating the adoption of reduced tillage in sugarcane fields under controlled traffic conditions are scanty and should be a research priority in Brazil (Bordonal et al., 2018). Thus, the hypotheses of this study are that i) sugarcane expansion under conventional tillage on pasture areas degrades soil structure and reduces its related functions and ii) the adoption of reduced tillage and traffic-free seedbed zones instead of conventional tillage improves soil structure and consequently the related soil functions and services (Figure 1).

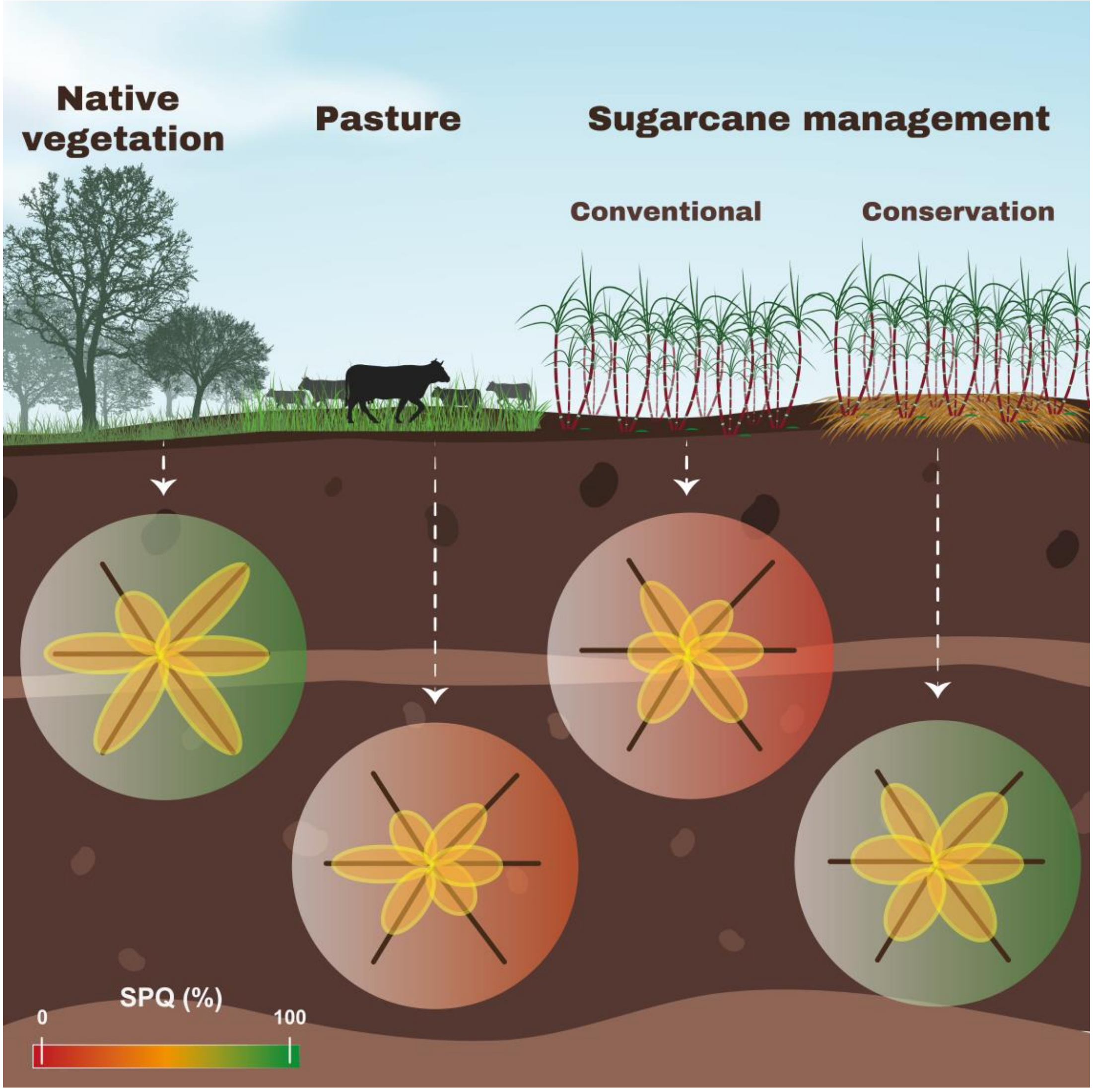

Figure 1. Soil physical quality (SPQ) responses to land-use change and different management practices in sugarcane cultivation. The size of each petal and circle color represents the magnitude of soil functions and SPQ respectively. According to the hypotheses, conversion from pasture to sugarcane degrades soil structure. However, the adoption of conservation management practices in sugarcane cultivation improves soil structure and related soil functions. Native vegetation represents a natural condition and the best SPQ. Red and green colors represent poor and good SPQ respectively.

The overall objective of this study was to evaluate the effects of land transition from pasture to sugarcane, and the adoption of different tillage and traffic control practices along sugarcane cultivation on soil physical properties, functions and related-ecosystem services. To meet this objective, this thesis is arranged into six chapters. In the **first** one, a general introduction about the thesis subject is presented. The **second** one analyzes soil hydro-physical changes induced by a typical land-use change sequence for sugarcane expansion in Brazil (native vegetation – pasture – sugarcane). In the **third** chapter, the impacts of tillage practices on soil water availability and air fluxes were quantified in two soils with contrasting textures. The **fourth** one measures the soil structure changes and related functions induced by tillage and reduction of machinery traffic using a diversity of assessment scales (from macro-scale to micro-scale). In the **fifth** one, the impacts of agricultural traffic control on soil physical properties and related functions are described. Lastly, final remarks of this study are presented in the **sixth** chapter.

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2. LINKING SOIL WATER CHANGES TO SOIL PHYSICAL QUALITY IN SUGARCANE EXPANSION AREAS IN BRAZIL [1]

Abstract

Brazil is the world's largest sugarcane producer with projections for expanding the current area by 30% in the coming years mainly in areas previously occupied by pastures. We assess soil water changes induced by land-use change (LUC) for sugarcane expansion in the central-south region of Brazil. For that purpose, soil samples were collected in a typical LUC sequence (native vegetation-pasture-sugarcane) in two contrasting soil textures (i.e., sandy and clayey). Soil hydro-physical properties such as pores size distribution, bulk density, soil water content, water tension, and drainage time at field capacity, plant available water, and S-index were analyzed. Our data showed that long-term LUC from native vegetation to extensive pasture induced severe degradation in soil physical quality and soil water dynamics. However, conventional tillage used during conversion from pasture to sugarcane did not cause additional degradation on soil structure and soil water dynamics. Over time, sugarcane cultivation slightly impaired soil water and physical conditions, but only in the 10-20 cm layer in both soils. Therefore, we highlight that sustainable management practices to enhance soil physical quality and water dynamics in sugarcane fields are needed to prevent limiting conditions to plant growth and contribute to delivering other ecosystem services.

Keywords: Land-use change; Soil water retention curve; Soil quality; Soil compaction; Bioenergy production

2.1. Introduction

Brazil is the world's largest sugarcane producer, accounting for 40% of global production. Currently, the sugarcane area covers 10 million hectares, predominantly concentrated (92%) in the central-south region of Brazil (CONAB, 2020). Growing global bioenergy demand has driven a substantial increment of the sugarcane cultivated area since the early 2000s. In the last decade only, the Brazilian sugarcane area increased by 50% (CONAB, 2020). Despite the economic challenges that many countries face nowadays, Brazil is committed to promoting sugarcane production in the next years, having projections for expanding the current sugarcane area by 30% (Goldemberg et al., 2014; Andrade Junior et al., 2019). This expansion has occurred in the central-southern region (CONAB, 2020) mainly in areas previously covered with pasture (Adami et al., 2012; Strassburg et al., 2014). The Brazilian large-scale sugarcane production system is predominantly based on conventional tillage and intensive machinery traffic during the cultivation cycle (Lima et al., 2020). Therefore, soil physical degradation as soil compaction induced by field traffic has become one of the major concern among sugarcane farmer, consultants, and researchers (Martíni et al., 2020). Recent studies have shown that land-use change (LUC) for sugarcane cultivation can negatively affect several soil physical properties such as pore size (Cavalcanti et al., 2020) and shape (Canisares et al., 2019), bulk density and penetration resistance (Cherubin et al., 2016a), and soil structural stability (Franco et al., 2020). Those changes in soil physical properties inevitably can alter hydraulic

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conductivity (Cherubin et al., 2016a) and retention in the soil. Moreover, physically degraded soils may reduce the water-availability to plants and soil biota, compromising not only provisioning ecosystem services expressed by crop yield, but also other related ecosystem services, such as C sequestration, erosion control, and water purification.

Nevertheless, there is a paucity of studies that focused on soil water changes induced by LUC to sugarcane expansion. For example, Cherubin et al., (2016a) conducted a comprehensive evaluation of LUC effects on soil physical quality, but they only measured soil hydraulic conductivity to infer about potential changes in soil water dynamics. In addition, the authors highlighted that these modifications could depend on the elapsed time since the LUC, tillage, and other management practices adopted on sugarcane cultivation. Conventional tillage increases soil hydraulic conductivity (Cherubin et al., 2016a), besides this soil physical benefit conventional tillage causes negative effects on soil (e.g., inversion of soil horizons, breakdown of macro-aggregates, aggregate slaking, clay dispersion, accelerated oxidation of soil organic carbon, and accelerated decomposition of plant root and shoot), as well as are no longer noticeable after successive cycles including heavy mechanization (Cavalcanti et al., 2020; Barbosa et al., 2019). Therefore, the initial impact of conversion from pasture to sugarcane (i.e., first time impact) over water dynamics in soil remains poorly explored, representing an important research gap for broader sustainability assessment of sugarcane expansion and production in Brazil (Oliveira et al., 2019) and elsewhere.

Soil water management is an environmental and socio-technical challenge to sugarcane expansion in tropical regions (Hess et al., 2016). Monitoring the water resources is essential to ensure that sugarcane expansion will not compromise them (Scarpare et al., 2016), not only in soils more resistant to degradation (i.e., clayey soils, as a consequence of higher aggregate stability and lower susceptibility to erosion) but also in soils more susceptible to degradation (i.e., sandy soils, as a consequence of poor soil structure, lower aggregate stability, and higher susceptibility to erosion) (Luz et al., 2019; Huang & Hartemink 2020), which are prevalent in most regions of sugarcane expansion in Brazil. Besides that, it is estimated that 70-80% of the yield gap in sugarcane fields is caused by water deficit throughout the crop cycle in different regions of Brazil (Dias and Sentelhas, 2018), which can be associated with degraded soil structure, poor soil aeration and reduced water storage (Meurer et al., 2020).

Soil hydraulic properties, which are useful for describing the patterns of water in the soil, can be extracted from the soil water retention curve. The soil water retention curve is described as the relationship between soil water content and matric potential (Reynolds et al., 2009). From this relationship, some physical indicators associated to pore-size distribution (Ghiberto et al., 2015), water and air capacity, drainage time (Twarakavi et al., 2009), field capacity, permanent wilting point, and hydraulic conductivity (Reynolds et al., 2002), can be obtained. Additionally, soil physical quality can be linked to water dynamics and pore-size distribution through the S-index derived from the soil water retention curve (Reynolds et al., 2002; Dexter, 2004). The use of those indicators may provide better comprehension about the impacts of LUC on soil water and air fluxes, as well as its impact on soil functions and ecosystem services related to water dynamics regulation and soil erosion control (Dominati et al., 2014).

Comprehensive in-field studies are fundamental to design more sustainable management practices that increase water retention, plant available water content, and soil porosity, optimizing the landscape management in the current climate change age (Dlapa et al., 2020). For that purpose, the study objective was to evaluate the effects of a typical LUC sequence (native vegetation-pasture-sugarcane) for sugarcane expansion on soil water dynamics in contrasting soil textures in central-southern Brazil. Our hypothesis is that soil hydro-physical properties are negatively affected as a consequence of this LUC sequence, and successive sugarcane cultivation, regardless of soil texture, affecting negatively soil water processes and associated functions.

2.2. Materials and Methods

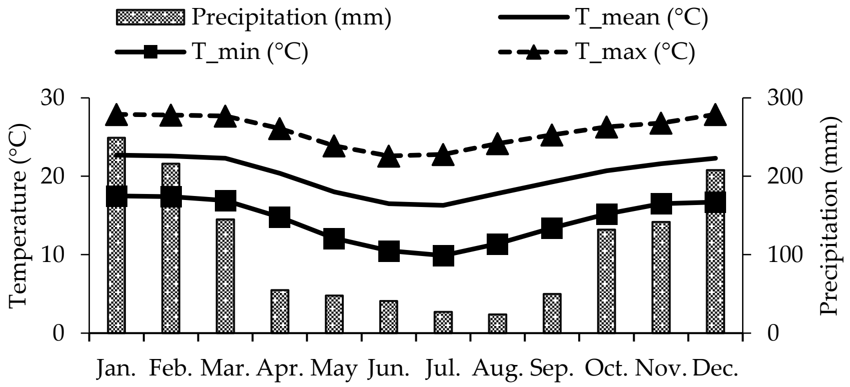
2.2.1. Experimental site and LUC sequence

The study was conducted in two sites with contrasting soils textures located in Brotas (22°17' S and 48°07' W) and Manduri (23°00' S and 49°19' W), São Paulo (SP) state, central-south region of Brazil, the main site of sugarcane expansion of the country. The soil classification and texture, and climate information for each site can be found in Table 1 and Figure 1, respectively. To facilitate the presentation and interpretation of results, we named the sites as Sandy soil (site 1) and Clayey soil (site 2) and used it throughout the manuscript. The LUC soil sampled sequence in both sites represents the most ordinary LUC's convention in central-southern Brazil (i.e., native vegetation (NV) – pasture (PA) – sugarcane (SC)). Sugarcane fields were further analyzed shortly after the conversion, during plant cane cycle (SCplant) and for a longer period after the conversion, during ratoon cycles (SCratoon). The sugarcane cycle is about five years with annual harvestings. The first year after planting is considered the plant cane cycle. After the first harvesting (i.e., 12 - 18 months after the planting) start the ratoon cycles which represent the interval between following annual harvesting from the second to the fifth year. After the fifth year, the sugarcane is replanting using soil tillage practices. In our study, SCratoon was in the first ratoon cycle in the Sandy soil and second ratoon cycle in the Clayey soil, therefore soil conditions were similar between the two sites, even the age of LUC was different. The land-use history and the management practices for both places are shown in Table 2. The mineralogical composition of Sandy soil and Clayey soil is presented in Figure S1 and Figure S2 respectively.

Table 1. Location and soil particle-size distribution at the Sandy and Clayey soil in State of São Paulo, Brazil.

Site identification	Sandy soil				
Geographical location	Brotas-SP (22°17' S and 48°07' W)				
Soil classification	Arenosol (WRB, 2015), Quartzipsamments (Soil Survey Staff, 2014)				
	Soil particle-size distribution (%)				
depth (cm)		NV*	PA	SCplant	SCratoon
0-20	clay	05	05	07	08
	silt	01	02	01	00
	sand	94	93	92	92
20-40	clay	07	10	12	15
	silt	02	02	02	00
	sand	91	88	86	85
Site identification	Clayey soil				
Geographical location	Manduri-SP (23°00' S and 49°19' W)				
Soil classification	Ferralsol (WRB, 2015), Oxisol (Soil Survey Staff, 2014)				
	Soil particle size-distribution (%)				
depth (cm)		NV	PA	SCplant	SCratoon
0-20	clay	59	47	62	58
	silt	31	27	29	32
	sand	10	26	09	10
20-40	clay	61	50	65	58
	silt	30	25	29	31
	sand	09	25	06	11

Sandy soil



Clayey soil

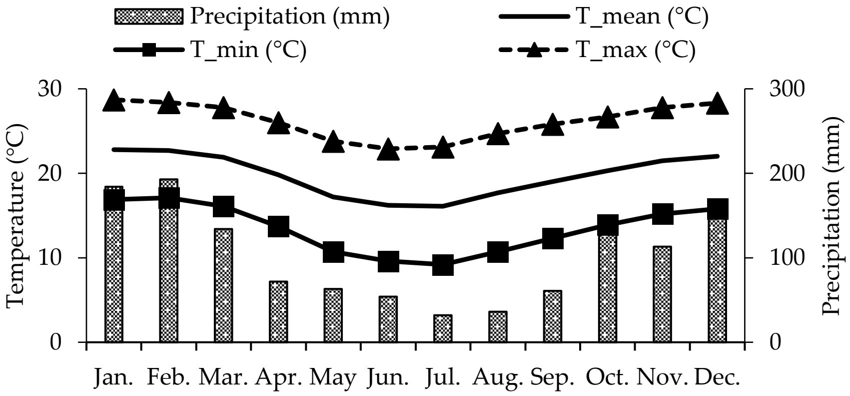


Figure 1. Mean monthly temperature (maximum, mean and minimum) (°C) and mean annual precipitation (mm) for Sandy soil (near the city of Brotas-SP) and Clayey soil (near the city of Manduri-SP). Source: climate-date.org (https://pt.climate-data.org/).

2.2.2. Soil sampling

Undisturbed soil cores were sampled in both sites during the summer in February 2019. The samplings consisted of four sample points spaced 50 m apart in each land-use to represent LUC. Samples were taken from the center of soil layers 0-10, 10-20, and 20-30 cm using cylindrical rings of ~100 cm^3 (5 cm in diameter by 5 cm in height). In sugarcane fields, the samples were taken from the crop inter-row position five months after conversion and planting in SCplant in both places, in the first ratoon in the Sandy soil and second ratoon cycle in the Clayey soil in SCratoon. A total of 96 samples were taken and then forwarded to the laboratory for analysis.

Table 2. History of land-use and description of management practices conducted in each study area.

Site	Use*	Description
Sandy soil	NV	Secondary vegetation and seasonal semi-deciduous forest composed of Trichillia clausenii, Euterpe edulis, and Aspidosperma polyneuron as dominant species.
	PA	The LUC from NV to PA occurred in 1975. The PA was cultivated with brachiaria grass (Brachiaria decumbens) cv. Basilik, without mineral fertilizer inputs, and with an average stocking rate of ~7 animal units (AU) (7 AU ha^{-1}) until 2018. The B. decumbens was replaced by Brachiaria brizanta cv. Marandu in 2018. During this process, 2 Mg ha^{-1} of lime, fertilizer inputs of 200, 135, and 115 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were applied on the soil surface. The stocking rate was kept the same as in the previous period. Cattle grazing is continuous, without a resting period for the pasture.
	SCplant	The LUC from PA to SCplant occurred in 2018. The conversion occurred with conventional tillage by plowing and disking. In this area, 2 Mg ha^{-1} of lime was applied on the soil surface. Fertilizer inputs of 60, 150, and 120 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were applied in planting furrows. The sugarcane cultivar planted was IAC SP 97-4039.
	SCratoon	The LUC from pasture to SCratoon occurred in 2002. In the following years, harvesting was done mechanically without burning or straw removal. The sugarcane renewal (replanting) was done every five years when the soil was tilled by plowing and disking. The last sugarcane planting was in 2017 with cultivar IAC SP 97-4039. After the last harvesting in 2018, 155, 41, and 86 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were applied, as mineral fertilizers.
Clayey soil	NV	Similar description as for Sandy soil.
	PA	The LUC from NV to PA occurred in 1970. This PA was composed of Brachiaria decumbens and poorly managed without mineral fertilizer. Cattle grazing is continuous, with an average stocking rate of 1.2 AU ha^{-1}.

	SCplant	The LUC from PA to SCplant occurred in 2018. This conversion occurred with conventional tillage, by plowing and disking. In this area, 2 Mg ha^{-1} of lime was applied on the soil surface, and 50, 150, and 50 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were applied in planting furrows.
	SCratoon	The LUC from pasture to SCratoon occurred in 2016. Mechanical harvesting without burning or straw removal was performed in 2017 and 2018. Every year, 90 and 80 kg ha^{-1} of nitrogen and potassium, respectively, were applied.

2.2.3. Soil water retention curve determination

To avoid any confusion in signals and for the mathematical formulation, the matric potential (Ψ) will be described in terms of water tension (*h*), which can be given as $h = |\Psi|$. The undisturbed soil cores were saturated with distilled water by capillarity for 48 h and subjected to the *h* of 10, 30, 60, 100, 330 and 1000 hPa, whereas disturbed soil samples previously sieved through a 2 mm sieve, saturated in small rings of known volume and subjected to the *h* of 5000, 10000 and 15000 hPa. Both undisturbed and disturbed soil sampled were equilibrated using a pressure plate apparatus. After reaching the hydraulic equilibrium, the samples were weighed and oven-dried at 105 °C for 24 h to determine the water content and bulk density. Bulk density was calculated as the ratio between oven-dried soil mass and the total volume of the soil, whereas the gravimetric water content was calculated as the difference between the mass of the samples at each water tension and that at oven-dried conditions.

Soil water retention data were fitted to the van Genuchten model (Van Genuchten, 1980), Eq. 1:

$$\theta(h) = \theta_r + \left[\frac{(\theta_s - \theta_r)}{[1 + (\alpha h)^n]^{(1-1/\mathrm{n})}}\right] \tag{1}$$

where θ and *h* are the volumetric water content (m^3 m^{-3}) and soil water tension (hPa), respectively, θ_s and θ_r are the fitted saturated and residual water contents (m^3 m^{-3}), and *a* and *n* are fitting parameters (Table S1).

The van Genuchten-based approach given by Assouline and Or (2014) was used for calculation of the *h* at field capacity (*h*FC) (Eq. 2), which was used to calculation of the volumetric water content at field capacity (*θ*FC) (using Eq. 1):

$$h_{FC} = \frac{1}{\alpha}\left(\frac{n-1}{n}\right)^{(1-2n)/n} \tag{2}$$

The saturated hydraulic conductivity was estimated using the θ_s and *a* van Genuchten parameters, as described by Guarracino (2007). From the saturated and unsaturated soil hydraulic conductivities, we calculated the time to reach the field capacity (*t*FC) using the procedure given by Assouline and Or (2014) and Meskini-Vishkaee et al. (2018) (Eq. 3):

$$t_{\mathrm{FC}} = -\frac{[z(\theta_s - \theta_r)]}{K_s} \ln\left[\frac{K(\theta_{\mathrm{FC}})}{K_s}\right] \tag{3}$$

where z is the soil depth (cm), K_s is saturated hydraulic conductivity (cm d^{-1}), $K(\theta FC)$ is the unsaturated hydraulic conductivity at the volumetric water content at the field capacity (cm d^{-1}), which was calculated by the van Genuchten (1980) procedure.

Plant-available water (PAW) was then calculated using the water content available between the θ_{FC} and that measured at -15000 hPa. Pore-size distribution was determined using the soil pore volume fractions for the *h* values < 30 hPa, 30-100 hPa, and > 100 hPa, which were used as thresholds for calculation of the macro-, meso- and micropores, following Cavalcanti et al. (2020). The soil pore volume correspondent to the macro-, meso- and microporosity were extracted from the fitted water retention curve (applying Eq. 1) for each one of the land-uses. Finally, S-index was calculated using the van Genuchten parameters by applying the expression given by Dexter (2004) (Eq. 4):

$$S = -n\left(\frac{\theta_s-\theta_r}{\mathrm{BD}}\right)\left[\frac{2\mathrm{n}-1}{n-1}\right]^{\left[\frac{1}{n}-2\right]} \tag{4}$$

where S is the S-index, *n*, θ_s and θ_s (volumetric water contents) are van Genuchten parameters, and BD is soil bulk density.

The S -index has been used as a sensitive indicator of soil physical quality. According to Dexter and Czyz (Dexter and Czyz, 2007), based on S-index values, the soil physical quality can be classified as very poor (S-index < 0.020), poor (0.020 > S-index < 0.035), good (0.035 > S-index < 0.050), and very good (S-index > 0.05).

2.2.4. Data analysis

The analysis of variance (ANOVA) was calculated through the PROC GLM routine to test LUC effects on soil pores size distribution, bulk density, and parameters from SWRC within each site. When the values of the ANOVA results were significant ($p < 0.05$), the means were separated using Tukey HSD test ($p < 0.05$). All statistical procedures were performed using Statistical Analysis System - SAS 9.3 software (SAS Inc., Cary, USA). Moreover, a canonical discriminant analysis was used to examine variables relationships and treatment differences in a multivariate approach. Biplot graphs were used to examine the dispersion of the canonical scores associated with original variables, as well as the impact of these variables on the discrimination of the treatments. The mean values of the canonical variables for each treatment were compared by 95% confidence spheres. The graphs and statistical procedures were performed using the R Software (Core Team, 2019).

2.3. Results

2.3.1. Soil pores size distribution and bulk denstiy

The pore-size distribution was altered due to conversion from NV to PA in both soils, although the magnitude of changes varied between soils (Figure 2a and Figure 2c). While microporosity increased in PA of the Sandy soil, no changes were observed in the Clayey soil. The mesoporosity was reduced in both soils (Figure 2), but macroporosity was reduced only in the surface layer of the Sandy soil, reaching a value lower than 0.10 $m^3\ m^{-3}$ (Figure 2a). Furthermore, this land transition from NV to PA reduced total porosity in the surface layer of the Sandy soil, and in the subsurface layers (10-20 and 20-30 cm) of the Clayey soil. The reduction of mesopores increased micropores in the Sandy soil but did not increase it in the Clayey soil (Figure 2c). Also, the reduction of mesopores was responsible for the reduction of total porosity in the Clayey soil (e.g., 10-20 and 20-30 cm layers).

Short-term conversion from PA to SCplant did not change the microporosity of both soils. On the other hand, conversion from PA to SCratoon altered microporosity in the 10-20 cm layer of both soils. Microporosity was reduced in the Sandy soil and increased in the Clayey soil. Consequently, this conversion increased mesoporosity in this same layer in the Sandy soil. Microporosity and macroporosity were also reduced in SCratoon in comparison to SCplant in the 10-20 cm layer in the Sandy soil. However, in both soils total porosity was not altered due to conversion from PA to sugarcane.

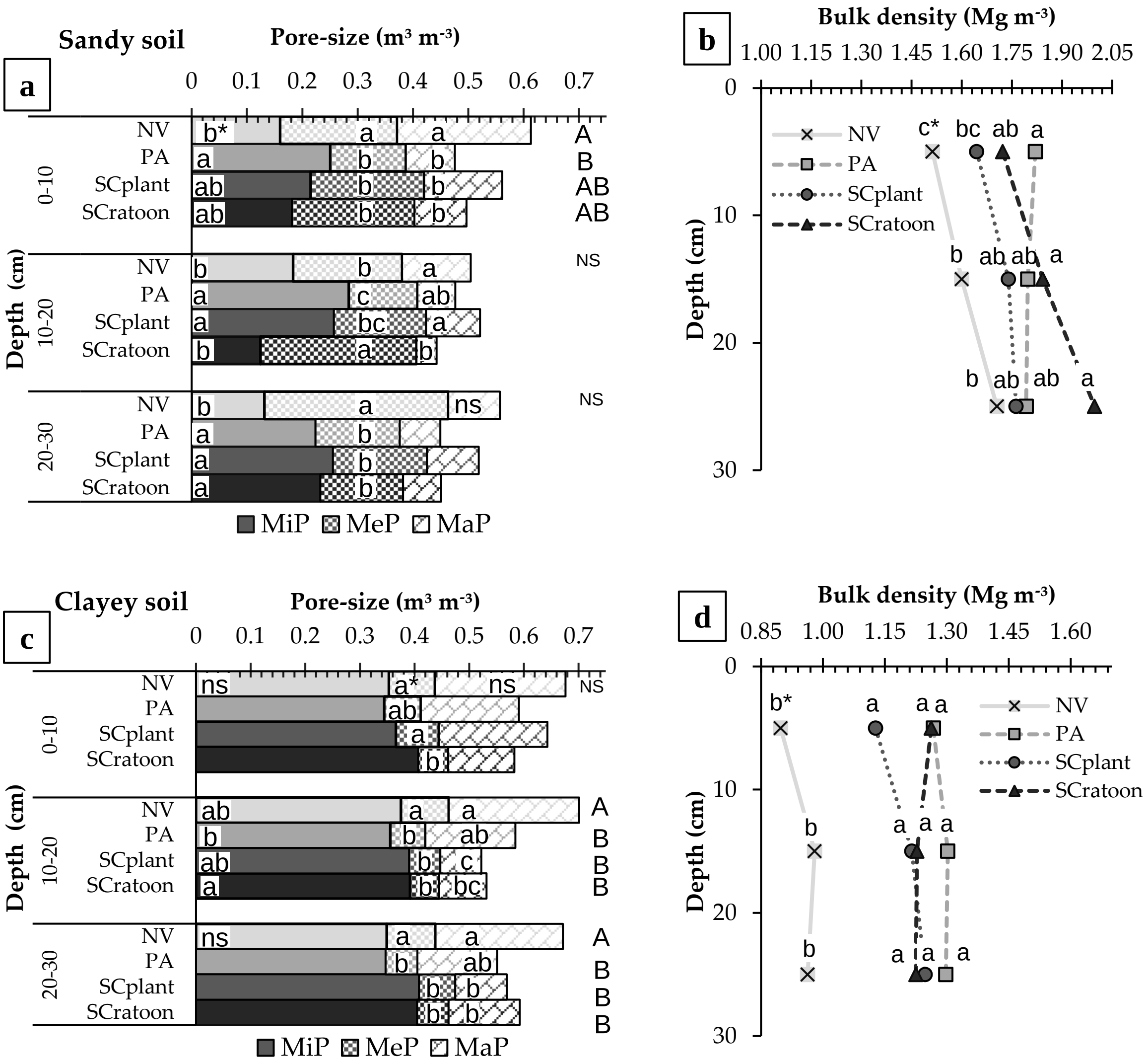


Figure 2. Soil pore-size distribution (Microporosity (MiP)= <15 μm, Mesoporosity (MeP)= 15–50 μm, Macroporosity (MaP)= >50 μm), total porosity (a, c), and bulk density (b, d) from 0-10, 10-20, and 20-30 cm layers under native vegetation (NV), pasture (PA), sugarcane plant (SCplant), and sugarcane ratoon (SCratoon) at Sandy soil (a, b) and Clayey soil (c, d). *Mean values within each site and each pore-size distribution in the same depth followed by the same letter do not differ among themselves according to Tukey's test (p < 0.05) ^{ns} Not significant.

The alterations in pores size distribution, e.g., total porosity and mesoporosity reflected in an increment of bulk density when NV was converted to PA. Bulk density increased by 17% in the surface layer of the Sandy soil (Figure 2b) and about 27% in all layers of the Clayey soil (Figure 2d). Conversion from PA to SCplant reduced bulk density by 10%, but only in the surface layer in the Sandy soil. Moreover, sugarcane cultivation (SCratoon) did not induce changes in bulk density in comparison to PA. In SCratoon bulk density values were lower than 1.30 Mg m^{-3} (Figure 2d) in the Clayey soil and varied between 1.74 Mg m^{-3} and 2.0 Mg m^{-3} in the Sandy soil (Figure 2b).

2.3.2. Field capacity (*ϑFC, hFC, tFC*) and soil water retention curve (SWRC)

The conversion from NV to PA did not alter *θ*FC in the Sandy soil, where it varied from 0.17 to 0.23 $m^3 m^{-3}$ (Figure 3a). Besides that, this conversion reduced soil water content at field capacity in the 10-20 cm layer from 0.47 to 0.43 $m^3 m^{-3}$ in the Clayey soil (Figure 3b). The conversion from PA to SCplant did not alter the *θ*FC in both soils at all layers. However, the SCratoon reduced by 50% the *θ*FC when compared to PA and SCplant in the 10-20 cm soil depth, but it was not altered in other layers in the Sandy soil (Figure 3a). Therefore, the higher limit of plant available water was altered in 10-20 cm layer in both soils.

The hFC was increased by 50% after the conversion from NV to PA in the Sandy soil. In the Clayey soil, whose *h*FC varied from 30 to 100 hPa (Figure 2d), no change was observed after conversion. However, the conversion from PA to SCplant and SCratoon reduced *h*FC from 169 to 120 and 90 hPa, respectively, in the 10-20 cm layer of the Sandy soil (Figure 2c). Furthermore, conversion from NV to PA increased *t*FC in the soil surface, but the conversion from PA to SCplant and SCratoon did not alter *t*FC in this soil when compared to PA. In the Clayey soil, *t*FC varied from 1 to 22 h, and was not altered in the LUC sequence (Figure 3f). Therefore, neither *h*FC nor *t*FC were sensitive indicators to detect alterations due to LUC in the Clayey soil. It shows then that *h*FC and *t*FC are sensitive to alterations in soil structure mainly in the Sandy soil.

The SCratoon reduced *θ*FC in the 10-20 cm layer in the Sandy soil but did not alter other layers nor differed as to SCplant in the Clayey soil. Furthermore, the *t*FC and *h*FC did not differ between SCratoon and SCplant in both soils (Figure 3).

The SWRCs for both soils are shown in Figure 4. The total porosity was responsible for higher water retention in the NV at lower h in the Clayey soil as well as in the NV and SCplant in the Sandy soil. Therefore, the alterations on θFC can be seen in the SWRC. The higher θFC in NV related to PA, SCplant, and SCratoon in the 10-20 cm layer in the Clayey soil reflected on the difference observed in the SWRC close to tFC (i.e., 30 - 90 hPa) (Figure 4d). However, a higher proportion of mesopores corresponds to lower water retention, as shown in the Sandy soil when compared to the Clayey soil. The higher mesoporosity in the Sandy soil also affected tFC in function of depth (Figure 3e). This higher mesoporosity effected the SWRC due to higher decline of the curve in SCratoon (Figure 4c) and in NV (Figure 4e).

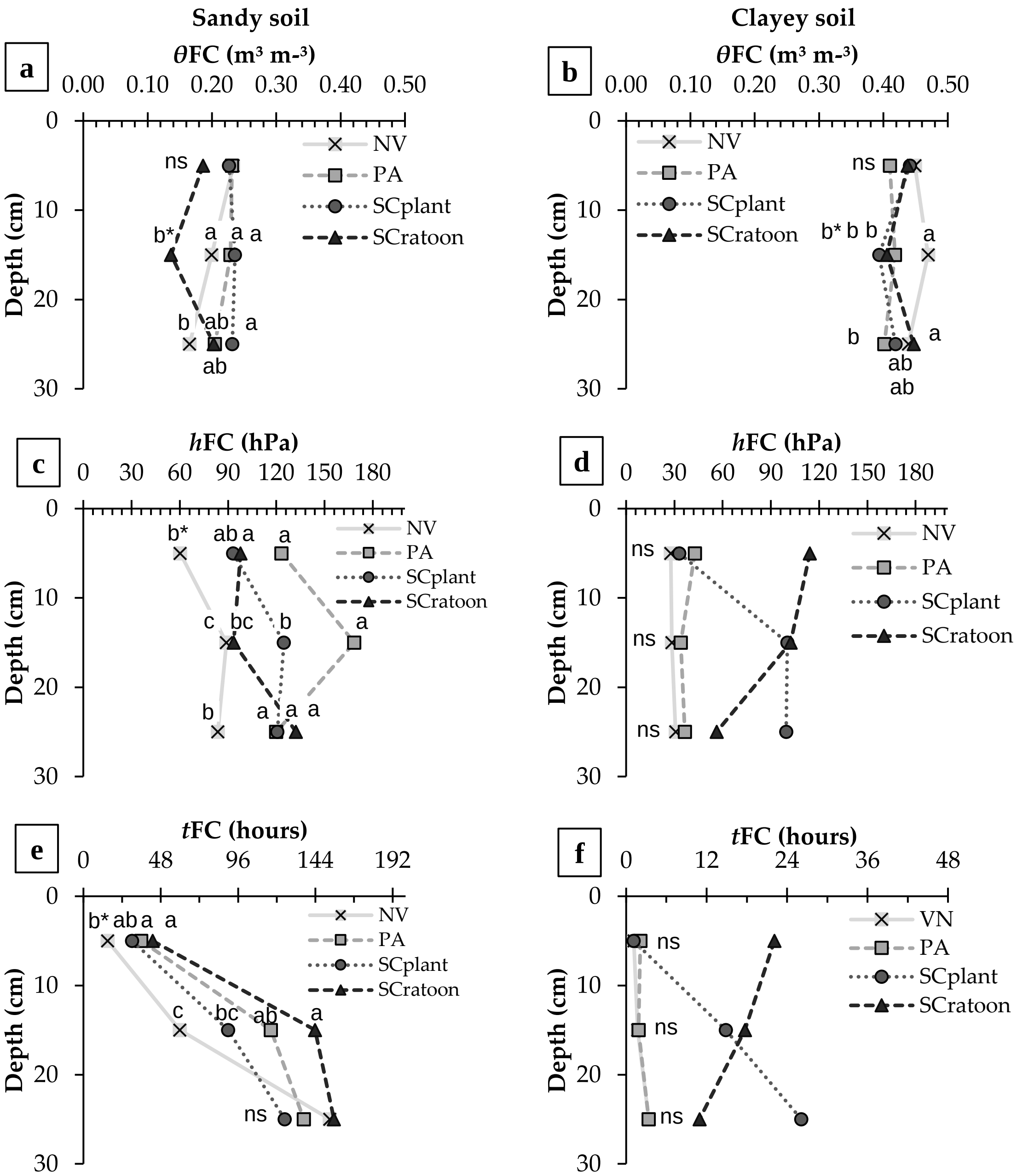


Figure 3. Water content at field capacity (*θ*FC) (a, b), water tension at field capacity (*h*FC) (c, d), drainage time to reach the field capacity (*t*FC) (e, f) from 0-10, 10-20, and 20-30 cm layers under native vegetation (NV), pasture (PA), sugarcane plant (SCplant), and sugarcane ratoon (SCratoon) at Sandy and Clayey soil. *Mean values within each site in the same depth followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$). ^{ns} Not significant.

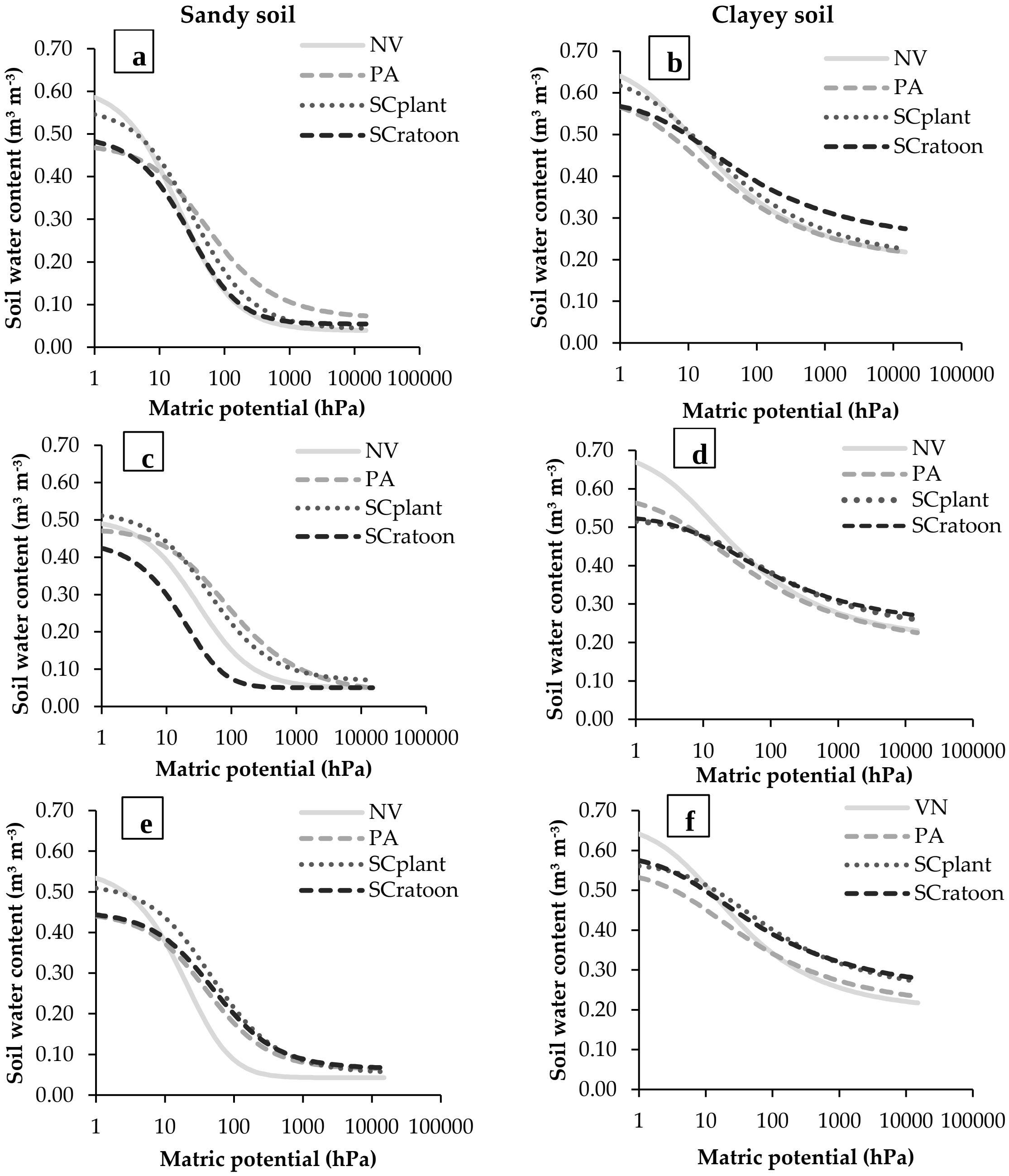


Figure 4. Average soil water retention curve (SWRC) from 0-10 (a, b), 10-20 (c, d), and 20-30 cm (e, f) layers under native vegetation (NV), pasture (PA), sugarcane plant (SCplant), and sugarcane ratoon (SCratoon) at Sandy soil (a, c, e) and Clayey soil (b, d, f).

2.3.3. Plant available water content (PAW) and S-index

PAW varied from 0.09 $m^3\ m^{-3}$ to 0.20 $m^3\ m^{-3}$ in the Sandy soil (Figure 5a) and from 0.17 $m^3\ m^{-3}$ to 0.27 $m^3\ m^{-3}$ in the Clayey soil (Figure 5b). For both soils, the conversion from NV to PA did not alter PAW. The main alteration in this parameter was a reduction observed in SCratoon compared to PA in the 10-20 cm layer in both soils. The pattern of PAW was different in SCratoon and SCplant in the 10-20 cm layer in each soil. While PAW was lower in the SCratoon in comparison to SCplant (Figure 5a) in the Sandy soil, SCratoon and SCplant presented similar PAW in that layer of the Clayey soil (Figure 5b).

The S-index derived from the SWRC was sensitive to detect alterations in soil structure due to LUC. Conversion from NV to PA reduced S-index from 0.13 to 0.06 in the Sandy soil (Figure 5c) and from 0.10 to 0.05 in the Clayey soil (Figure 5d). In contrast, the conversion from PA to SCplant did not have a negative impact on S-index, and even, promoted improvement in the surface layer of Sandy soil. Similarly, SCratoon also presented close or higher S-index values as compared to PA, reaching similar values to NV in the Sandy soil (Figure 5c). Lastly, based on S-index values, soil physical quality was classified as very good in all land-uses in the Sandy soil, very good in NV, and good in PA, SCplant, and SCratoon in the Clayey soil.

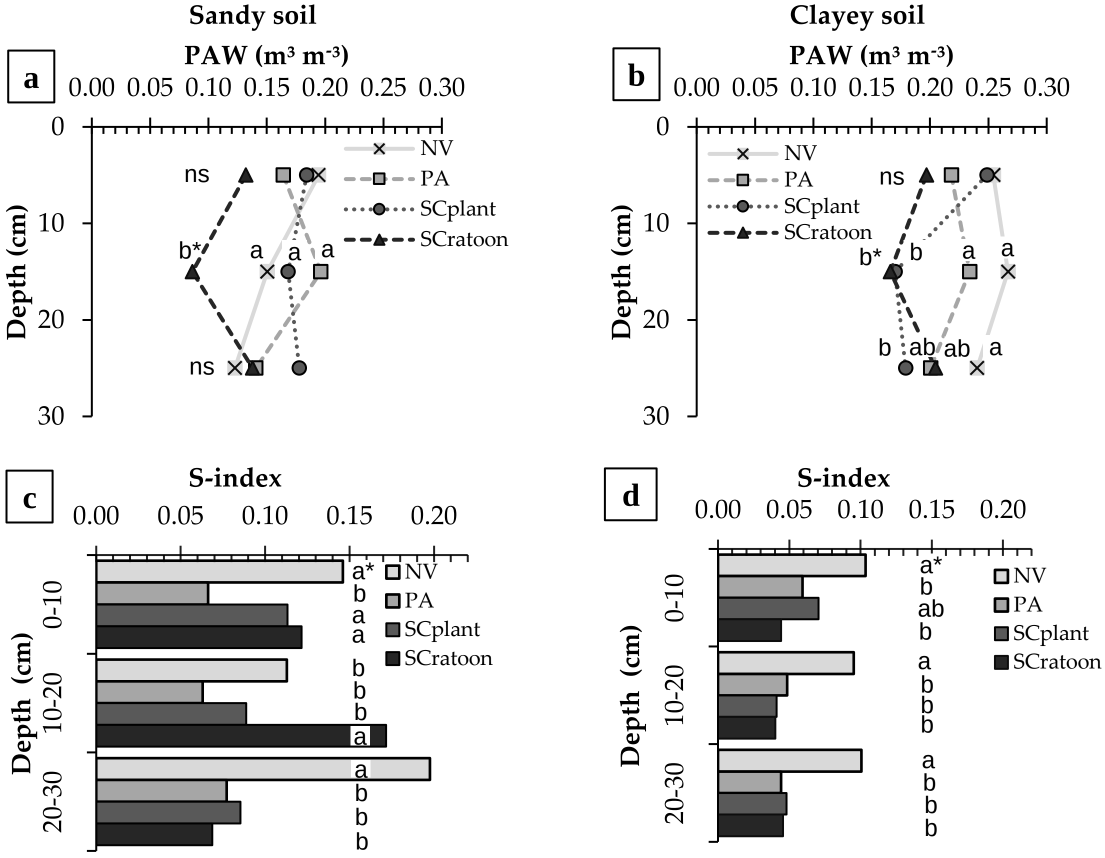


Figure 5. Plant available water (PAW) content (a, b), and S-index (c, d) from 0-10, 10-20, and 20-30 cm layers under native vegetation (NV), pasture (PA), sugarcane plant (SCplant), and sugarcane ratoon (SCratoon) at Sandy soil (a, c) and Clayey soil (b, d). *Mean values within each site in the same depth followed by the same letter do not differ among themselves according to Tukey's test (p < 0.05). ^{ns} Not significant.

2.3.4. Relationships among hydro-physical indicators and land-use

Figure 6 shows the distribution of land-use with soil water indicators as explanatory variables in the dispersion of the canonical scores in each soil. The two axes together explained 85% and 93% of the variance for the Sandy and Clayey soil, respectively. In both soils, S-index, mesoporosity, and macroporosity were associated with NV, whereas bulk density, microporosity, *h*FC, and *t*FC were not associated with NV.

Therefore, the CAN1 (Figure 6) which explained most of the total data variance showed better soil physical quality in NV when compared to PA, SCplant, and SCratoon in both soils.

In addition, PAW had a positive correlation with *θ*FC and microporosity in the Sandy soil and with macroporosity, mesoporosity, and S-index in the Clayey soil. On the other hand, the higher *h*FC and *t*FC were associated with higher bulk density and microporosity.

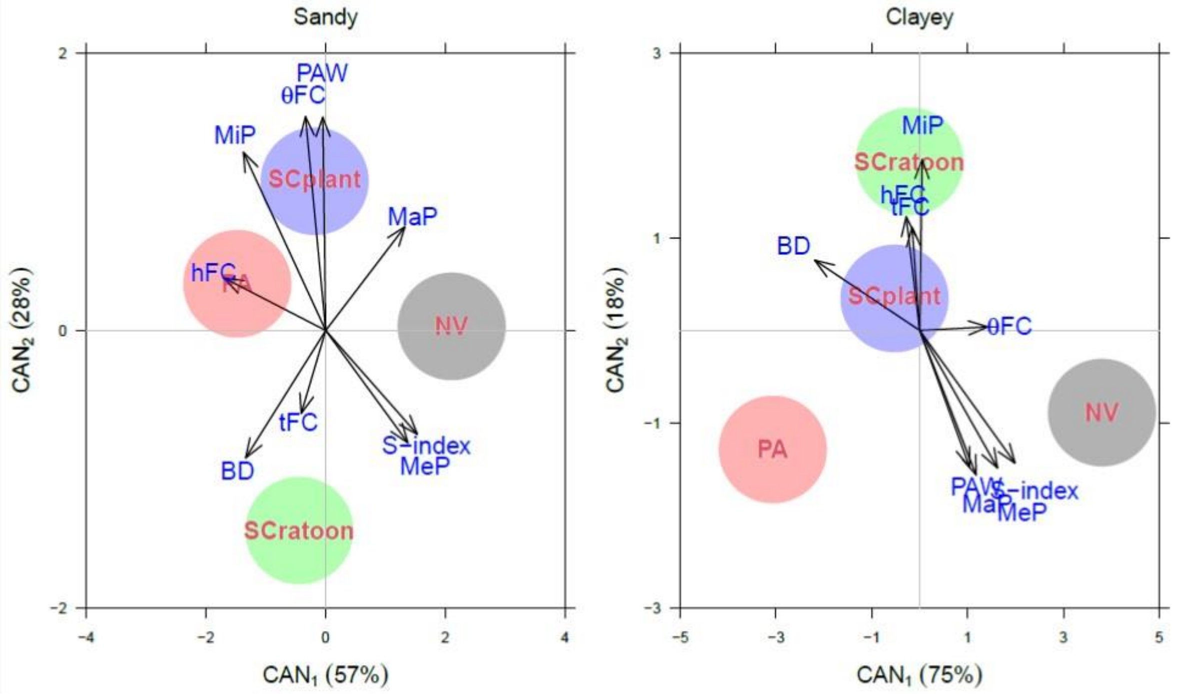


Figure 6. Dispersion of the canonical scores associated with soil porosity (MaP= macroporosity, MeP= mesoporosity, MiP= microporosity), bulk density (BD), parameters from soil water retention curve (*θ*FC= soil water content at field capacity, *h*FC= water tension at field capacity, *t*FC= drainage time to reach the field capacity, PAW= plant available water content, S-index) in four land-uses: (NV= native vegetation, PA= pasture, SCplant= sugarcane plant, SCratoon= sugarcane ratoon). n= 48.

2.4. Discussion

2.4.1. LUC impacts on soil physical quality and water dynamics

2.4.1.1. Land transition from native vegetation to pasture

The conversion from NV to PA substantially altered the soil physical properties, and consequently, the soil water dynamics. The reduction of soil macropores and mesopores due to the conversion from NV to PA (Figure 2) reduced soil water retention at lower *h* (e.g., < 10 hPa) (Figure 4). While PA reduced soil water retention in lower *h*, this conversion had positive effects on soil water retention in higher *h* (e.g., > 10 hPa) due to the transition from mesopores to micropores, as well as an increase in bulk density. As a consequence, the *h*FC (Figure 3c) and *t*FC (Figure 3e) were higher at PA in the Sandy soil. These results of *h*FC and *t*FC reflected the increment on soil compaction and agree with Cherubin et al. (Cherubin et al., 2016), who observed a reduction in field-saturated hydraulic conductivity in pasture areas. Although a higher bulk density in PA in comparison to NV was observed, this increase did not reflect in alterations in hFC and θFC in the Clayey soil. However, the lower stocking rate during grazing in the Clayey soil when compared to the Sandy soil (Table 2) can be an important aspect (de Andrade Bonetti et al., 2019) that attenuated water dynamics changes in this soil. In addition, it should be noted that excessive soil water retention at higher h in PA can impair grass growth, due to a limited supply of oxygen to plants, since macropores were < 0.10 m^3 m^{-3}, which is considered critical for air fluxes in the soil (Grable and Siemer, 1968). In addition, the association between hFC and θFC (Figure 6) showed that land-uses with higher hFC will be higher θFC (e.g., PA in comparison to NV) which might affect negatively air fluxes.

Furthermore, the increase in bulk density reached critical values in the Sandy soil (i.e., 1.60 Mg m^{-3}) according to Reynolds et al. (Reynolds et al., 2002), and did not reach critical values in the Clayey soil (i.e., 1.33 Mg m^{-3}) according to Reichert et al. (Reichert et al., 2009). Nevertheless, mesoporosity and macroporosity were reduced in the PA in the Clayey soil which indicates alterations in soil structure due to LUC as can be seen in Figure 6 by the association of these parameters with NV. The alterations in soil structure by LUC from NV to PA in tropical regions were described by several authors. First, conventional soil tillage used at land conversion breaks soil aggregates (Hunke et al., 2015), leading to increased soil C oxidation to the atmosphere (Reichert et al., 2009; Hunke et al., 2015). Secondly, after conversion external drivers such as soil compaction due to continuous cattle trampling, influence negatively the soil structure (Canisares et al., 2020; Huang & Hartemink 2020; Franco et al., 2015), water movement (Cherubin et al., 2016a), and consequently, important ecosystem services, such as grass productivity (Costanza et al., 1997), soil biodiversity and C sequestration (Franco et al., 2020), and erosion control. Therefore, the poor soil structure in PA and reduced vegetation cover in poorly managed pastures make the soil more susceptible to runoff (Youlton et al., 2016b) and soil erosion (Hunke et al., 2015), mainly in months with higher precipitation, i.e., from October to March in the studied region (Figure 1).

In addition, the S-index was able to confirm alterations in soil water dynamics where conversion from NV to PA reduced soil structure quality by about 50% (Figure 5c, Figure 5d) and θFC was reduced in Clayey soil. Despite those reductions, PAW was not altered in this scenario being considered ideal (> 0.20 m3 m-3) for maximum root growth in the Clayey soil and good (≥ 0.15 ≤ 0.20 m3 m-3) in the Sandy soil according to Reynolds (Reynolds et al., 2009).

Our findings showing soil physical degradation and its consequent negative implications on water dynamic in extensive PA soils confirm what previous studies with a broader scope have reported, namely that those areas are characterized by poor overall soil quality (Cherubin et al., 2016b) and provision of soil-related ecosystem services (Oliveira et al., 2019), low productivity and stocking rate (Strassburg et al., 2014), and low economic developments to farmers, workers and the surrounding urban centers (Oliveira et al., 2019). Due to all these environmental and socio-economic aspects the prevalent scenario of sugarcane and other annual crops expansion has been and will continue to be, over areas previously occupied with extensive pasture (Adami et al., 2012; Oliveira et al., 2019; Youlton et al., 2016). The full monitoring of PA soil conditions is fundamental to evaluate if sugarcane cultivation is degrading, sustaining, or even enhancing soil quality compared to the pasture baseline.

2.4.1.2. Conversion from pasture to sugarcane cultivation

The transition from PA to sugarcane cultivation did not impact negatively water dynamic in both soils, refuting our initial hypothesis. Conventional tillage by plowing and disking (Table 2) break up soil structure (Cavalcanti et al., 2020) what sometimes reduce bulk density and increases soil porosity as compared to the previous use (Awe et al., 2020). Therefore, in the sandy soil, where bulk density was considered critical in PA, the conversion to SCplant alleviated soil compaction mainly on the soil surface making the soil structure in SCplant similar to the one observed in NV. As a consequence of that, an increase in soil water retention at lower *h* (Figure 4a, Figure 4c, e Figure 4e), coupled with an increase of S-index (e.g., 0-10 cm layer), reduction of *h*FC (e.g., 10-20 cm layer) and *t*FC, and association with PAW and θFC (Figure 6) were observed. In a previous study by Cherubin et al. (2016a), conversion from pasture to sugarcane was able to increase the field-saturated hydraulic conductivity and decrease bulk density.

In the clayey soil, where PA did not reach the critical bulk density the conversion from PA to SCplant affected negatively soil porosity and reduced PAW only in the 10-20 cm layer. In that case, soil macropores were reduced to lower than 0.10 $m^3\ m^{-3}$ (Figure 2c), consequently, PAW decreased from 0.23 $m^3\ m^{-3}$ to 0.17 $m^3\ m^{-3}$ (Figure 5b). Similar results were observed by Cavalcanti et al. (2020) when soil tillage at the sugarcane replanting degraded soil structure and altered soil porosity. Despite the critical value of macroporosity (<0.10 $m^3\ m^{-3}$) (Grable and Siemer, 1968) being reached in SCplant, no limitation was observed for available water content (Reynolds et al., 2009) as shown in Figure 5b. Furthermore, the initial impact after conversion from PA did not cause substantial alterations in soil structure and soil water dynamics, as previously expected.

A negative impact induced by conversion from pasture to sugarcane was found by Youlton et al. (Youlton et al., 2016a) in a Quartzipsamments with 12% clay, who reported that runoff was increased in sugarcane just after the conversion due to soil disturbance and absence of soil cover. However, results from soil porosity and bulk density in SCplant showed a higher potential of water infiltration in comparison to PA, considering that about 3% of the amount of total rainfall might cause runoff near the city of Brotas-SP (Youlton et al., 2016b). Besides, during sugarcane ratoon cultivation there is no additional soil disturbance, and plant canopy plus crop residues could reduce substantially the risks of soil erosion and soil losses (Youlton et al., 2016b; Cherubin et al., 2016b).

Results from SCratoon showed that sugarcane cultivation altered the soil structure mainly in 10-20 cm layer where the observed θFC values were lower than PA (Figure 3a), and the PAW values were limited (Figure 5a) (Reynolds et al., 2009) in the Sandy soil. After soil disturbance by conversion from pasture to sugarcane, machinery traffic by harvesters, tractors and loaded trailers during harvesting intensifies soil compaction (Guimarães Júnnyor et al., 2019; Keller et al., 2019; Lima et al., 2020), mainly in the subsurface layer (Keller et al., 2019). Soil compaction induced by machinery traffic likely explains the reduction of the

PAW, of the soil water retention at lower h (Figure 4c), and alterations in soil porosity in the 10-20 cm layer in SCratoon in both soils (Figure 2a and Figure 2c). Despite that, SCratoon not only did not display altered bulk density in comparison to PA (Figure 2) but showed an increased S-index in this soil layer (Figure 5c). These results alleviate the negative impacts related to θFC in SCratoon and concur to the findings of Cherubin et al. (2016a) and Luz et al. (2019), who did not find increases in bulk density due to conversion from pasture to sugarcane.

Soil compaction by traffic can positively affect soil water retention due to rearrangement of pore-size distribution in sandy soils, as reported by Moraes et al. (2018) in a Typic Paleudult with 25% of clay and 55% of sand. However, our findings indicated an inverse pattern in the Sandy soil, in which there was a reduction in PAW in SCratoon that has experienced successive machinery traffic. In this case, the soil with a lower amount of clay and a higher amount of sand (Table 1) responded differently to machinery traffic, when compared to the results reported by Moraes et al. (2018), and tillage followed by traffic altered soil pore-size distribution in SCratoon (e.g., 10-20 cm layer) (Figure 2a). Nonetheless, a positive effect on soil water retention due to compaction could be confirmed when macroporosity does not reach critical values. Macroporosity reached critical values not only in sugarcane fields but also in pasture soils (Figure 2a). This compaction reinforces the poor structural stability of sandy soils, mainly in deeper layers (Barbosa et al., 2019).

Despite alteration in the 10-20 cm layer, conversion from PA to sugarcane did not change PAW and soil pore-size distribution in the soil surface and the lowest layer. In addition, about 60-90% of the sugarcane root system is distributed in the 0-40 cm layers [Keller et al., 2014; Tenelli et al., 2019) which allows sugarcane to explore soil layers with no limited water uptake. This means that no alterations in the soil water uptake by plants is expected as a result of the conversion from PA to sugarcane during the annual cycle, especially in periods of high-water deficit (Figure 1). Besides, our data showed that the management adopted in sugarcane cultivation (SCplant and SCratoon) did not induce water (PAW) and mechanical (bulk density) limiting conditions to plant growth in the Clayey soil. The S-index values corroborate it, indicating that those soils present good physical quality. Additionally, the principal component analysis demonstrated a positive correlation between S-index and mesoporosity (Figure 6), which was not altered in sugarcane fields.

As a result of the previous conditions of extensive pasture characterized by compacted soils, conventional tillage for planting sugarcane did not induce additional degradation on soil structure and soil water dynamics. During the sugarcane cycle, comparing SCplant and SCratoon, soil water retention was reduced in the Sandy soil, but only in the 10-20 cm layer, and it was not altered in the Clayey soil. In addition, θFC and PAW were increased and reduced, respectively, in the 10-20 cm layer in the Sandy soil. Thus, the Sandy soil was shown to be more prone to physical degradation by machinery traffic than the Clayey soil. On the other hand, the increased water retention promoted by SCratoon in the 0-10 cm layer (Figure 4b) did not change bulk density, soil porosity, and water dynamics when compared to SCplant.

2.4.2. Sustainable management practice to enhance water dynamics in sugarcane fields

Despite the similar conditions observed in SCplant and SCratoon related to soil water dynamics, sugarcane fields are still susceptible to soil compaction (Jabro et al., 2016; Keller et al., 2014) mainly in the 10-20 cm layer. The risk of compaction in sugarcane fields is dependent not only on machinery traffic but also on the management system (Guimarães Júnnyor et al., 2019). Therefore, soil management such as a no-tillage system (Barbosa et al., 2019) and reduced tillage (Jabro et al., 2016) can be promising strategies for reducing tension transmission through the soil profile (Keller et al., 2014), and consequently reduce the negative impact on soil structure. Additionally, keeping sugarcane straw on the soil surface after harvesting increases soil carbon content (Tenelli et al., 2019), reduces the negative impact of the raindrop splash effect, and reduce the negative impact on soil structure caused by traffic (Keller et al., 2014; Esteban et al., 2019). Therefore, these practices have the potential to improve soil water retention, field capacity, and PAW and make the soil more resistant to soil erosion processes.

The benefits of soil management practices which reduce soil disturbance, keep the soil surface covered, and promoted balanced water and air contents in the soil should be accompanied by other important conservation practices such as crop rotation or cover crops during sugarcane planting (Oliveira et al., 2019b) and controlled traffic in sugarcane fields (Esteban et al., 2020). The latter is fundamental to minimize soil compaction (Guimarães Júnnyor et al., 2019) preserving appropriated soil hydro-physical conditions to sugarcane growth (Esteban et al., 2019), and reducing sugarcane yield losses (Dias and Sentelhas, 2018).

We expect that our findings can be useful for a better understanding of the impacts of sugarcane expansion in contrasting soils in the central-southern region of Brazil. Furthermore, this information can serve as a scientific basis to design better soil management practices, that increase soil water conservation by reducing runoff and soil erosion. Finally, our findings can also be valuable for an array of modeling purposes, such as prediction of plant growth, hydrological processes, and broader ecosystem services assessments.

2.5. Conclusions

Long-term LUC from native vegetation to extensive pasture induced the degradation of the soil physical quality and soil water dynamics. This leads pasture soils to a vicious cycle, in which poor soil hydro-physical functioning leads to pasture degradation, and then consequently pasture degradation and continuous grazing lead to further degradation of soil properties, functions, and services.

One strategy to reincorporate those pasturelands into a productive system is through converting those areas for sugarcane cultivation. Our data showed that even conventional tillage used during such conversion did not cause additional degradation on soil structure and soil water dynamics. Over time, sugarcane cultivation slightly impaired soil water and physical conditions, but only in the 10-20 cm layer in both soils. We highlight that sustainable management practices to enhance soil physical quality and water dynamics in sugarcane fields are needed to prevent limiting conditions to plant growth and synergically contribute to delivering other ecosystem services.

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Supplementary Materials

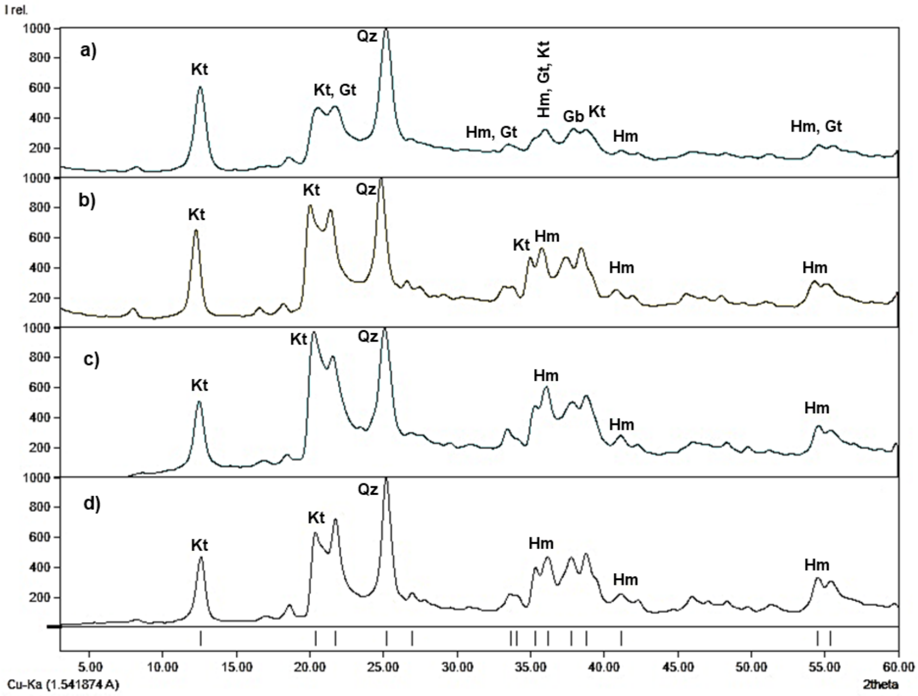

Figure S1. Difractograms of the soil+clay fraction for native vegetation (a), pasture (b), sugarcane plant (c), and sugarcane ratoon (d) for Sandy soil. Kt: kaulinite, Qz: quartz, Hm: hematite, Gt: Goethite, Gb: gibbsite.

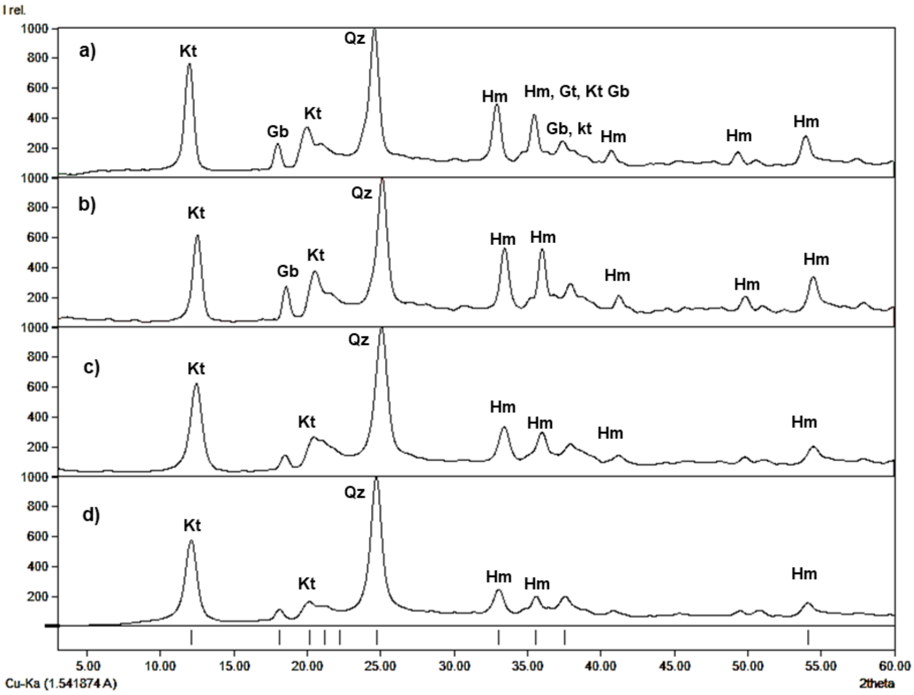

Figure S2. Difractograms of the soil+clay fraction for native vegetation (a), pasture (b), sugarcane plant (c), and sugarcane ratoon (d) for Clayey soil. Kt: kaulinite, Qz: quartz, Hm: hematite, Gt: Goethite, Gb: gibbsite.

Table S1. Adjustment parameters from Van Genuchten (1980) for the average soil water retention curves.

Site	Use*	α	n	θr	θs
		---hPa^{-1}--	-	-------m^3 m^{-3}-------	
Sandy soil		0-10 cm			
	NV	0.048	2.033	0.038	0.610
	PA	0.029	1.685	0.067	0.475
	SCplant	0.033	1.911	0.042	0.561
	SCratoon	0.025	2.325	0.054	0.496
		10-20 cm			
	NV	0.031	2.050	0.049	0.504
	PA	0.024	1.558	0.032	0.476
	SCplant	0.027	1.820	0.067	0.521
	SCratoon	0.019	3.585	0.050	0.442
		20-30 cm			
	NV	0.023	3.032	0.042	0.557
	PA	0.026	1.949	0.064	0.449
	SCplant	0.027	1.804	0.053	0.519
	SCratoon	0.023	1.874	0.065	0.451
Clayey soil		0-10 cm			
	NV	0.234	1.371	0.194	0.676
	PA	0.217	1.337	0.191	0.591
	SCplant	0.196	1.329	0.192	0.643
	SCratoon	0.162	1.298	0.240	0.582
		10-20 cm			
	NV	0.208	1.355	0.202	0.701
	PA	0.218	1.280	0.184	0.584
	SCplant	0.070	1.302	0.223	0.522
	SCratoon	0.102	1.304	0.239	0.531
		20-30 cm			
	NV	0.176	1.407	0.198	0.671
	PA	0.210	1.296	0.201	0.551
	SCplant	0.073	1.336	0.239	0.568
	SCratoon	0.203	1.282	0.242	0.592

3. SOIL TILLAGE AND MACHINERY TRAFFIC INFLUENCE SOIL WATER AVAILABILITY AND AIR FLUXES IN SUGARCANE FIELDS [2]

Abstract

Intensive soil disturbance by conventional tillage and heavy machinery traffic for planting, cultivation, and harvesting operations are the main causes of soil compaction and degradation of soil physical quality in sugarcane fields. However, the adoption of conservation soil tillage practices, such as no-till and reduced tillage associated with traffic control have been proposed as a key strategy to preserve soil physical quality, enhancing water availability and air fluxes. Nevertheless, the effects of reduced tillage associated with traffic control in sugarcane fields are still not well documented. A study was carried out to quantify soil water availability and air flux indicators in two soils with contrasting textures (named Sandy Loam and Clayey soil) under conventional and reduced tillage practices associated with and without controlled machinery traffic in central-southern Brazil. Soil physical parameters such as bulk density, total porosity, air-filled porosity, air permeability, pore continuity index, and the least limiting water range (LLWR) were measured. In both soils, there was no difference between conventional and reduced tillage in bulk density, air permeability, and LLWR. However, reduced tillage with non-traffic decreased bulk density and increased macroporosity, air-filled porosity, air permeability, pore continuity, and LLWR in Sandy Loam soil. In Clayey soil, the bulk density and LLWR did not change between tillage practices, but air permeability and pore continuity index were larger under reduced tillage with non-traffic. These results highlighted that soil disturbance by conventional tillage does not improve the water availability and air permeability during the crop cycle. However, the traffic control is essential to support the adoption of reduced tillage in sugarcane fields, preserving soil water availability and air fluxes for the subsequent ratoons. Reduced tillage and traffic control are two of the most important pillars for reducing soil compaction and promoting sustainability of sugarcane production in Brazil.

Keywords: Least limiting water range, Air permeability, Reduced tillage, Traffic control.

3.1. Introduction

Brazil is the world's leading producer of sugarcane, responsible for 39% of world production (FAO, 2019). In the last two decades, burning and manual harvesting of sugarcane has been replaced by mechanized harvesting in the central-south region of Brazil. Nevertheless, the introduction of intensive traffic of larger and heavier machines for sugarcane management operations has intensified soil compaction (Cavalcanti et al., 2019; Guimarães Júnnyor et al., 2019; Shukla et al., 2021) by increasing bulk density and penetration resistance and, decreasing macroporosity and water availability (Souza et al., 2015; Cherubin et al., 2016). Consequently, soil compaction leads to a decline in sugarcane yields (Pryor et al., 2017; Schossler et al., 2019) and threatens the sustainability of the sugarcane production (Bordonal et al., 2018). Water stress is the main cause of the sugarcane yield gap in Brazil; therefore, soil management practices that aim to promote proper soil structure conditions for root growth, deeper soil exploration, and higher water and nutrient uptake are vital to mitigate the water stress effects on the crop yield (Dias and Sentelhas, 2018).

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Conventional tillage practices (e.g., plowing) have been adopted as the main strategy to alleviate soil compaction preceding the sugarcane planting (Bolonhezi et al., 2019; Li et al., 2020a). However, the positive effects of mechanical disturbance are short lasting (Barbosa et al., 2019; Blanco-Canqui and Wortmann, 2020), and the soil returns to the same or even a worse degree of compaction after one or two harvesting events (Barbosa et al., 2019; Cavalcanti et al., 2019) due to high pressure (e.g. 800-900 kPa (Jimenez et al., 2021)) applied by machinery traffic (Guimarães Júnnyor et al., 2019; Castioni et al., 2021). Alternatively, no-tillage or reduced tillage practices have been investigated (Oliveira et al., 2019; Awe et al., 2020; Naseri et al., 2020) as a strategy to reduce soil disturbance and soil carbon losses (Tenelli et al., 2019) without compromising the sugarcane yield (Barbosa et al., 2019; Tenelli et al., 2019; Shukla et al., 2020). Although reduced tillage prevents massive soil disturbance and makes the soil less susceptible to erosion and additional compaction, reducing or avoiding soil compaction is still challenging since random traffic from successive mechanized operations is the major cause of soil compaction (Guimarães Júnnyor et al., 2019). Positive effects of reduced tillage practices should be augmented by controlled or reduced machinery traffic in order to preserve the soil structure and soil physical quality for sugarcane production (Braunack and McGarry, 2006; Esteban et al., 2020; Barbosa et al., 2021; Tweddle et al., 2021).

Many soil physical properties have been individually used to evaluate soil compaction and physical quality in sugarcane fields, e.g., bulk density and soil porosity (Luz et al., 2020; Pinheiro et al., 2021), infiltration (Cherubin et al., 2016; Shukla et al., 2020), aggregate stability (Castioni et al., 2019), penetration resistance (Otto et al., 2011), and Sq score from visual evaluation of soil structure (Cherubin et al., 2017; Cavalcanti et al., 2020). However, physical quality of the soil should be assessed through an integrated approach using physical parameters directly associated with plant growth. The least limiting water range (LLWR) describes a range of soil water content between upper and lower limits in which plant growth is restricted by water availability or matric potential, aeration, and mechanical resistance (da Silva et al., 1994; Tormena et al., 1998). The LLWR has been used as an advanced tool for detecting soil physical quality changes (Li et al., 2020b; Oliveira et al., 2019; Tormena et al., 2017) by integrating soil properties which directly influence plant water uptake capacity, plant growth, and crop yield (Benjamin and Karlen, 2014; Ferreira et al., 2020). Other soil physical indicators such as soil air-permeability and air-filled porosity are also sensitive for detecting soil structure changes and the intensity that some critical physical processes occur in the soils (Betioli Junior et al., 2014; Daraghmeh et al., 2019).

Globally, the LLWR has been successfully applied to investigate the effects of management practices on soil physical quality under different cropping systems (e.g., Tormena et al., 1998; Lapen et al., 2004; Oliveira et al., 2019; Tavanti et al., 2019; Li et al., 2020b). In Brazil, only a few studies were conducted to evaluate the impacts of tillage (Oliveira et al., 2019) and machinery traffic (Souza et al., 2015) on LLWR in sugarcane fields. Those previous studies revealed the potential of LLWR to detect soil physical changes and their association with sugarcane yield, but there are no long-term studies under reduced tillage and machinery traffic control in soils with contrasting texture.

This study tested the hypothesis that the benefits of reduced tillage practices on soil structure, soil water availability, and air fluxes measured by the LLWR and air permeability are magnified by the machinery traffic control in sugarcane fields. Without traffic control, reduced tillage does not mitigate soil physical degradation in the long-term compared to conventional tillage. Thus, the aim of this study was to quantify the LLWR and air permeability in two sugarcane soils under conventional and reduced tillage practices with random and without machinery traffic in central-southern Brazil.

3.2. Material and Methods

3.2.1. Study sites and experimental design

The study was carried out in two field experiments under contrasting edaphoclimatic conditions within central-southern Brazil: i) Clayey soil, located in the municipality of Quirinópolis, Goiás state (18°32' S and 50°26' W), classified as a Rhodic Eutrudox (Soil Survey Staff, 2014) with 547 g kg $^{-1}$ clay, 186 g kg $^{-1}$ silt, and 267 g kg $^{-1}$ sand; ii) Sandy Loam soil, located in the municipality of Quatá, São Paulo state (22°14' S and 50°42' W), in a soil classified as Arenic Kandiudult (Soil Survey Staff, 2014) with 87 g kg $^{-1}$ clay, 60 g kg $^{-1}$ silt, and 853 g kg $^{-1}$ sand. In both areas, the experiments were established in March 2013.

The Clayey soil was cultivated with pasture until 2006 when it was converted to sugarcane production, while the conversion from pasture to sugarcane occurred in 1995 in the Sandy Loam soil. In Clayey soil, the sugarcane harvesting was always performed through mechanized operations. In Sandy Loam soil, the harvesting was made through burning between 1995-2009 and the mechanical harvesting operations were established since then. In both sites, sugarcane renovation occurred in October 2012. After sugarcane harvesting, both areas were desiccated with glyphosate (5 L ha^{-1}), followed by a surface lime (2 Mg ha^{-1}) and gypsum (1 Mg ha^{-1}) application. The cover crop (*Crotalaria spectabilis*) was planted in December 2012 at seed rate of 25 kg ha^{-1}, then desiccated in April 2013. After fifteen days following cover crop desiccation, three treatments: conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN) were established. The CTT treatment was carried out by subsoiling at 40 cm soil depth with a five-shank subsoiler and a light harrowing using a harrow of 36 disks at 20 cm depth. Planting furrows were opened at 30 cm depth through a two-row planter with a spacing of 150 cm between furrows. The RTT and RTN treatments were characterized by a single operation of planting furrows opened at 30 cm soil depth using the same planter. The main differences between the RTT and RTN treatments were the machinery traffic along the crop cycle, since in RTT all operations were performed mechanically, and in RTN all field operations after planting were carried out manually without machinery traffic (Fig. 1). Each field experiment was arranged in randomized block design with three treatments and four replications. Each plot was composed of 10 sugarcane rows, 10-m in length spaced at 1.5-m.

As previously described in Barbosa et al. (2021), the RTN treatment was performed to evaluate the establishment of seedbeds and permanent traffic zones resulting from the use of machinery with a long distance between axes and controlled traffic operations. This practice has been adopted in several companies in Brazil in recent years, therefore our experiments aim to reproduce the reality observed in the field.

However, since we had no harvester or prototype available for the experiment conduction, the sugarcane harvesting was performed manually to simulate the potential production of sugarcane in seedbed zones without machinery traffic. More details about sugarcane variety, fertilization management, and pest and disease control in the experimental areas can be found in Barbosa et al. (2019) and Tenelli et al. (2019).

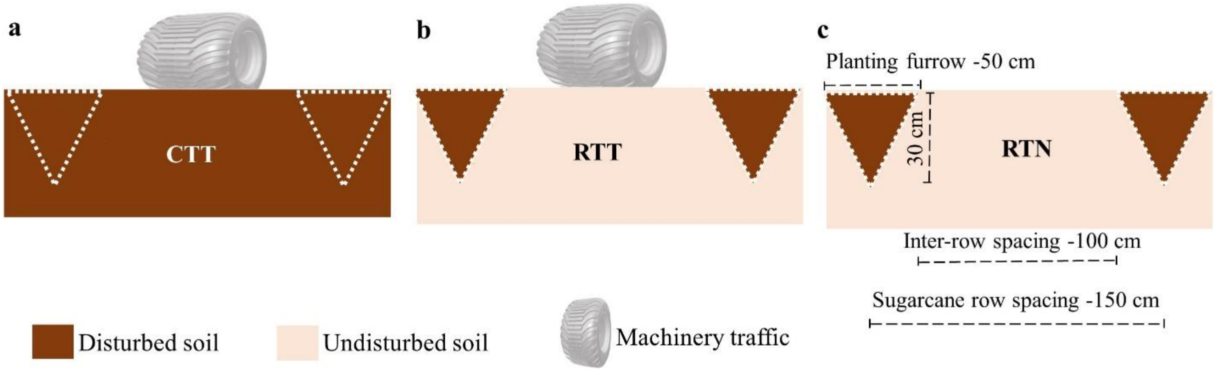

Figure 1. Description of conventional tillage with regular traffic (CTT) (a), reduced tillage with regular traffic (RTT) (b), and reduced tillage without traffic (RTN) (c) adopted in the sugarcane field trial

In the CTT and RTT treatments, the sugarcane was harvested using a harvester with treadmill wheels of 47 cm width, track width of 190 cm, and total mass of 20.6 Mg. In addition, the harvested sugarcane stalks were transported in wagons pulled by a tractor. The wagons had a weight of 6.5 Mg, capacity to transport 8.5 Mg of sugarcane, track width of 300 cm, and 600/50-22.5 tires. The tractor had a weight of 10.5 Mg, track width of 300 cm, 600/60-30.5 front tires, and 710/70 R38 rear tires. In the RTN treatment, the sugarcane harvesting was performed manually to preserve soil structure and to represent the adoption of traffic-free seedbed zones, as detailed by Barbosa et al. (2021).

3.2.2. Sampling and soil physical measuremnts

Undisturbed soil samples were taken in July 2018, after the fifth harvesting event. In each treatment, 10 samples per block, totaling 40 undisturbed samples, were randomly (e.g., within row and inter row position) collected at a depth of 0-10 cm. Therefore, considering the two sites, the total dataset was composed of 240 samples (10 samples x 4 blocks x 3 treatments x 2 sites). The samples were collected using metallic cylinders of 5 cm x 5 cm (~100 cm^3). After sampling, samples were carried to the laboratory and stored at 5^o C to avoid biological activity.

The soil water retention curve was determined according to da Silva et al. (1994). For each treatment, soil samples were divided into 10 groups of four samples corresponding to matric potentials (ψ) of -0.004, -0.006, -0.008, -0.01, -0.03, -0.07, -0.1, -0.5, and -1.5 MPa. The soil samples were water saturated and submitted to matric potentials using table tension and pressure plates. After samples reached an equilibrium in each matric potential, they were weighed to determine water content and subjected to soil penetration resistance (SPR) measurement using a static bench penetrometer according to Tormena et al.

(1999). Then, samples were oven-dried at 105 °C for 48 h, weighed again and the volumetric water content (θ) and bulk density (BD) were finally determined, according to Grossman and Reinsch (2002). Total porosity (TP) was determined by using BD and particle density: TP= 1- BD/2.65, where 2.65 Mg m^{-3} is the assumed value of particle density. The micropore volume was estimated as the water content retained in the ψ = -0.006 MPa. Soil macroporosity (MaP) was determined by the difference between TP and microporosity (MiP).

The soil water retention curve data were fitted through the proposed model by Ross et al. (1991) using the procedure described by da Silva et al. (1994) as in Equation 1.

$$\theta = a\psi^{b} \tag{1}$$

or alternatively

$$\ln \theta = \ln a + b \ln \psi \tag{2}$$

where θ is the soil water content (m^3 m^{-3}), ψ is the soil water potential (MPa), and *a* and *b* are model-fitting parameters. To characterize the influence of BD in each tillage/traffic treatment on *a* and *b* parameters, multiple regression analysis was carried out following the procedure described by da Silva and Kay (1997) using SAS software as in Equation 3.

$$\ln \theta = \ln (a + b\,\mathrm{BD}) + \ln \psi \tag{3}$$

Plant available water (PAW) was calculated using the soil water content between the ψ of -0.01 and -1.5 MPa.

The SPR curve was adjusted taking into account SPR as a function of BD and θ using the equation proposed by Busscher (1990) which is described in Equation 4.

$$SPR = aBD^{b}\theta^{c} \tag{4}$$

or alternatively

$$\ln \mathrm{SPR} = \ln a + b \ln \mathrm{BD} + c \ln \theta \tag{5}$$

where *a, b*, and *c* are the parameters of the model.

The LLWR was computed using the procedure described by da Silva et al. (1994). The upper limit was defined as soil water content at field capacity (θ_{fc}) at ψ= -0.01 MPa or by the soil water content in which the air-filled porosity (θ_{afp}) reached 0.10 m^3 m^{-3}, whichever is smaller. For each sample, θ_{afp} was calculated according to Equation 6.

$$\theta_{afp} = [(1 - \mathrm{BD}/2.65) - 0.10] \tag{6}$$

The lower limit was taken as the higher soil water content at the permanent wilting point (θ_{pwp}) soil water content at ψ= -1.5 MPa or by soil water content in which SPR reached 2.5 MPa (θ_{SPR}) (Taylor et al., 1966) which was obtained from Equation 7.

$$\theta SPR = \left(\frac{2.5}{aBD^{b}}\right)^{1/c} \tag{7}$$

The soil air permeability (Ka) was determined after sample equilibration at ψ = -0.006 ($Ka_{-0.006MPa}$) and -0.01 MPa ($Ka_{-0.01MPa}$) using a constant air head permeameter described by Figueiredo (2010) and following the recommendation of Ball and Schjønning (2002). The calculation of Ka (μm^2) was performed according to Equation 8.

$$Ka = \frac{Q\eta}{As}\left(\frac{z}{p}\right) \tag{8}$$

where Q is the air conductivity ($m^3 s^{-1}$), η is viscosity of air at 20 °C ($N s^{-1} m^{-2}$), As is the perpendicular area to the air movement (m^2), z is the height of soil column (m), and p is the differential air pressure (Pa).

The air-filled porosity (α_{air}) was calculated as the difference between TP and soil volumetric water content after equilibrium at ψ = -0.01 MPa.

Pore continuity index (K_1) was taken from the relationship $Ka_{-0.01MPa}$ /α_{air} according to Groenevelt et al. (1984).

The soil water retention and soil penetration resistance fitting curves were carried out using the Proc GLM routine on Statistical Analysis System SAS 9.3 software (SAS Inc., Cary, USA). The fitting curves were completed individually for each treatment and for each soil. Also, the effects of tillage practices and machinery traffic on LLWR, BD, TP, MiP, MaP, PAW, $Ka_{-0.006MPa}$, $Ka_{-0.01MPa}$, α_{air}, and K_1 were evaluated by the Proc ANOVA procedure and the means comparison test was performed according to the Tukey HSD test ($p < 0.05$).

3.3. Results

The BD values did not differ among soil tillage treatments in Clayey soil (Table 1), with mean values ranging from 1.27 Mg m^{-3} to 1.29 Mg m^{-3}. However, BD was lower in RTN (1.67 Mg m^{-3}) than CTT and RTT, which showed an average BD=1.75 Mg m^{-3} in Sandy Loam soil (Table 1). The value of TP also did not differ among soil treatments, but RTT treatment showed lower MaP (0.10 cm^3 cm^{-3}) and higher MiP (0.41 cm^3 cm^{-3}) in Clayey soil. Such results for porosity were not observed in Sandy Loam soil, where TP and MaP were higher in RTN than CTT and RTT (Table 1). In addition, these treatments presented higher values of MiP (0.22 cm^3 cm^{-3} and 0.23 cm^3 cm^{-3}, respectively). The PAW did not differ among treatments in both soils. The mean values of PAW were 0.13 m^3 m^{-3} and 0.10 m^3 m^{-3} in the Clayey soil and Sandy Loam soil, respectively (Table 1).

The high MaP and α_{air} and low BD in RTN reflected on the air permeability values in the Sandy Loam soil (Table 1). The $Ka_{-0.006MPa}$, $Ka_{-0.01MPa}$, and K_1 were higher in RTN than CTT and RTT which presented similar values. In addition, $Ka_{-0.006MPa}$ was lower than 1 μm^2 in CTT (0.95 μm^2) and RTT (0.83 μm^2) (Table 1), hence it can be considered an impermeable soil (McQueen and Shepherd, 2002) at this soil water matric potential. Furthermore, in Clayey soil, $Ka_{-0.01MPa}$ and K_1 were higher in RTN, whereas α_{air}, $Ka_{-0.006MPa}$, and K_1 had similar values in CTT and RTT (Table 1).

The LLWR estimation depends on variability of soil structure which can be described by BD (Letey, 1985). Therefore, as can be seen in Table 2, BD varied from 1.05 Mg m^{-3} to 1.52 Mg m^{-3} in the Clayey soil and from 1.45 Mg m^{-3} to 1.92 Mg m^{-3} in the Sandy Loam soil. Consequently, BD affected soil water retention curve and soil penetration resistance curve for all treatments, except for CTT in the Sandy Loam soil (Table 3).

Table 1. Average values of soil bulk density (BD), microporosity (MiP), macroporosity (MaP), total porosity (TP), plant available water (PAW), air-filled porosity (α_{air}), air permeability at ψ= -0.006 MPa ($Ka_{-0.006MPa}$), air permeability at ψ= -0.01 MPa ($Ka_{-0.01MPa}$), and pore continuity index (K_1) from 0-10 cm layer under conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT) and reduced tillage without traffic (RTN) at the Clayey soil and Sandy Loam soil.

Treatment	BD	MiP	MaP	TP	PAW	α_{air}	$Ka_{-0.006MPa}$	$Ka_{-0.01MPa}$	K_1
	(Mg m^{-3})	-----------------(m^3 m^{-3})----------------					---(μm^2)---		
	Clayey soil								
CTT	1.29 a*	0.38 c	0.13 a	0.51 a	0.16 a	0.14 a	11.07 a	13.70 b	103.38 b
RTT	1.29 a	0.41 a	0.10 b	0.51 a	0.13 a	0.12 a	14.06 a	13.97 b	106.89 b
RTN	1.27 a	0.40 b	0.12 ab	0.52 a	0.12 a	0.14 a	14.38 a	27.37 a	189.61 a
	Sandy Loam soil								
CTT	1.75 a	0.22 b	0.11 b	0.33 b	0.11 a	0.18 b	0.95 b	2.45 b	10.77 b
RTT	1.75 a	0.23 a	0.10 b	0.33 b	0.10 a	0.17 b	0.83 b	2.24 b	10.37 b
RTN	1.67 b	0.19 c	0.18 a	0.37 a	0.09 a	0.23 a	2.59 a	4.35 a	17.38 a

Moreover, not only BD, but also θ and SPR data (Table 2) were used for calculating the soil water retention curve and soil penetration resistance curve. The BD had a positive effect on soil water retention curve and consequently in the θ_{fc} and θ_{pwp} in all treatments for Clayey soil (Table 3). This influence was not observed in the Sandy Loam soil, in which BD had a negative effect on soil water retention under RTT. However, soil penetration resistance varied positively with BD and negatively with θ regardless of soils and treatments.

Table 2. Descriptive statistical parameters of soil physical parameters measured in conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN) at Clayey soil and Sandy Loam soil. Standard deviation (SD), coefficient of variation (CV).

Variable	Maximum	Minimum	Mean	SD	CV (%)
Clayey soil					
			CTT		
BD (mg m^{-3})	1.52	1.11	1.29	0.11	8.19
θ (m^3 m^{-3})	0.54	0.20	0.36	0.08	22.05
SPR (MPa)	9.10	0.16	1.61	1.66	103.07
			RTT		
BD (mg m^{-3})	1.49	1.05	1.29	0.10	7.40
θ (m^3 m^{-3})	0.58	0.26	0.37	0.08	22.69
SPR (MPa)	5.54	0.23	1.51	1.17	77.28
			RTN		
BD (mg m^{-3})	1.47	1.07	1.28	0.08	6.62
θ (m^3 m^{-3})	0.54	0.23	0.36	0.07	20.01
SPR (MPa)	6.50	0.18	1.45	1.37	94.50
Sandy Loam soil					
			CTT		
BD (mg m^{-3})	1.89	1.45	1.75	0.08	4.50
θ (m^3 m^{-3})	0.32	0.05	0.15	0.09	58.41
SPR (MPa)	13.88	0.70	4.37	3.25	74.47
			RTT		
BD (mg m^{-3})	1.92	1.48	1.75	0.08	4.72
θ (m^3 m^{-3})	0.33	0.06	0.15	0.08	53.44
SPR (MPa)	12.92	0.35	4.20	3.15	74.96
			RTN		
BD (mg m^{-3})	1.80	1.52	1.67	0.07	4.28
θ (m^3 m^{-3})	0.36	0.05	0.14	0.10	68.29
SPR (MPa)	13.27	0.29	3.11	2.96	95.19

Table 3. Soil water retention and soil penetration resistance curves models from conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN) in the Clayey soil and Sandy Loam soil. Coefficient of determination (R^2), root- mean- square error (RMSE).

Treatment	Model	R^2	RMSE
Clayey soil			
	Soil Water Retention Curve		
CTT	$\theta = \exp(-2.0486+0.4611\ BD)\ \psi^{-0.1141}$	0.91	0.0732
RTT	$\theta = \exp(-1.8780+0.3742\ BD)\ \psi^{-0.1090}$	0.90	0.0723
RTN	$\theta = \exp(-2.0339+0.4887\ BD)\ \psi^{-0.1001}$	0.87	0.0724
	Soil Penetration Resistance Curve		
CTT	$SPR=0.0069\ BD^{10.4898}\ \theta^{-2.2692}$	0.81	0.4401
RTT	$SPR=0.0342\ BD^{7,5815}\ \theta^{-1.6059}$	0.65	0.3647
RTN	$SPR=0.0153\ BD^{8.7866}\ \theta^{-1.9736}$	0.50	0.6578
Sandy Loam soil			
	Soil Water Retention Curve		
CTT	$\theta = \exp(-2.9732)\ \psi^{-0.2687}$	0.85	0.2248
RTT	$\theta = \exp(-1.2289-0.9045\ BD)\ \psi^{-0.2423}$	0.88	0.1814
RTN	$\theta = \exp(-5.4207+1.3349\ BD)\ \psi^{-0.3047}$	0.87	0.2401
	Soil Penetration Resistance Curve		
CTT	$SPR=0.0013\ BD^{11.4368}\ \theta^{-0.7123}$	0.74	0.4005
RTT	$SPR=0.0008\ BD^{11,8220}\ \theta^{-0.8454}$	0.78	0.4131
RTN	$SPR=0.0002\ BD^{13.2802}\ \theta^{-1.0362}$	0.80	0.4354

Therefore, after fitting soil water retention curve and soil penetration resistance curve equations, they were used for calculating the θ_{fc}, θ_{pwp}, and θ_{SPR} for each sample. In addition, θ_{afp} was calculated, and then, the LLWR could be estimated. Soil water content at the critical limits indicated that θ_{fc} and θ_{pwp} were the upper and lower limits of LLWR until BD= 1.27 Mg m^{-3}, BD= 1.30 Mg m^{-3}, and BD= 1.29 Mg m^{-3} for CTT, RTT, and RTN, respectively, in Clayey soil (Fig. 2a, b, c). When BD reached values higher than those, θ_{SPR} replaced θ_{pwp}, and θ_{afp} replaced θ_{fc} in CTT, RTT, and RTN, respectively. In addition, a positive correlation was verified between BD and LLWR until these BD values (Fig. 3a).

In Sandy Loam soil, θ_{fc} and θ_{pwp} were the upper and lower limits of LLWR until BD= 1.63 Mg m^{-3} (CTT), BD= 1.48 Mg m^{-3} (RTT), and BD= 1.58 Mg m^{-3} (RTN) (Fig. 2d, e, f). For BD higher than those values, θ_{pwp} was replaced by θ_{SPR} in all treatments. For this data set θ_{afp} was not considered, limiting it to LLWR. Consequently, θ_{SPR} can be considered the most important physical limitation to root growth due to its higher frequency as a lower limit than θ_{pwp} in sandy soils as previously identified by Benevenute et al. (2020).

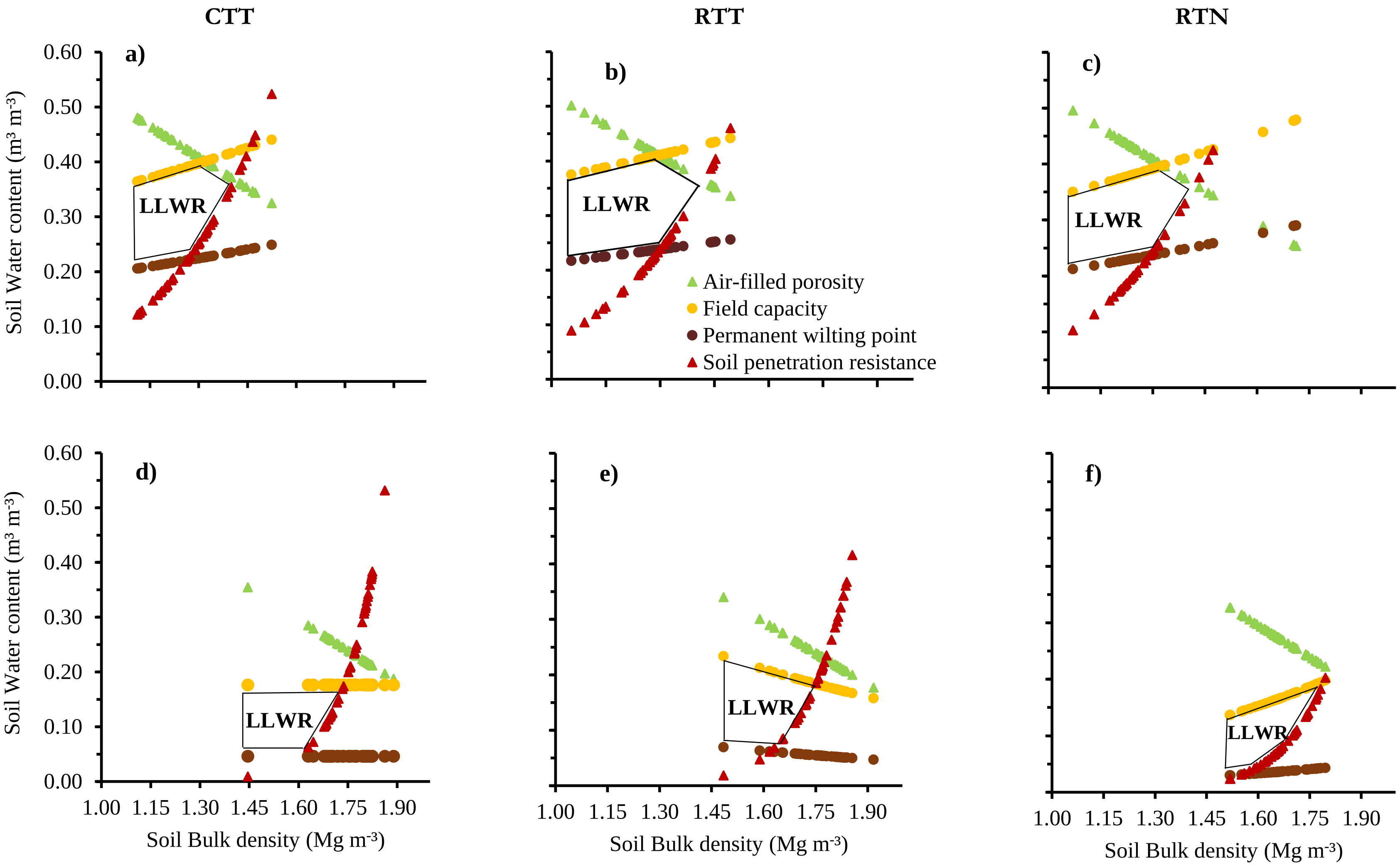

Figure 2. Variation of soil water content in relation to soil bulk density at the air-filled porosity (0.10 m^3 m^{-3}), field capacity, permanent wilting point, and soil penetration resistance (2.5 MPa) under conventional tillage with regular traffic (CTT), reduced tillage with regular traffic (RTT), and reduced tillage without traffic (RTN) at Clayey soil (a, b, c) and Sandy loam soil (d, e, f). The delimited area represents the least limiting water range (LLWR).

When the upper limit is crossed by the lower limit, the LLWR becomes null and BD in which LLWR=0 is taken as the critical BD (BDc), suggesting severe physical limitation to plants for DB>BDc. BDc was 1.43 Mg m^{-3} for all treatments in the Clayey soil (Fig. 2a, b, c). However, in Sandy Loam soil, BDc= 1.74 Mg m^{-3}, BDc= 1.75 Mg m^{-3}, and BDc= 1.79 Mg m^{-3} for CTT, RTT, and RTN respectively (Fig 2d, e, f).

The LLWR ranged from 0.170 to 0 m^3 m^{-3}, 0.172 to 0 m^3 m^{-3}, and 0.153 to 0 m^3 m^{-3} in CTT, RTT, and RTN, respectively (Fig. 3a), which reflected on LLWR average values of 0.118 m^3 m^{-3} (CTT), 0.136 m^3 m^{-3} (RTT), and 0.119 m^3 m^{-3} (RTN) in Clayey soil (Fig. 3b). For the Sandy Loam soil, LLWR ranged from 0.130 to 0 m^3 m^{-3}, 0.164 to 0 m^3 m^{-3}, and 0.112 to 0 m^3 m^{-3} in CTT, RTT, and RTN respectively (Fig. 3c). However, in this soil, the average LLWR was higher in RTN (0.077 m^3 m^{-3}) compared to CTT (0.025 m^3 m^{-3}) and RTT (0.033 m^3 m^{-3}) (Fig. 3d).

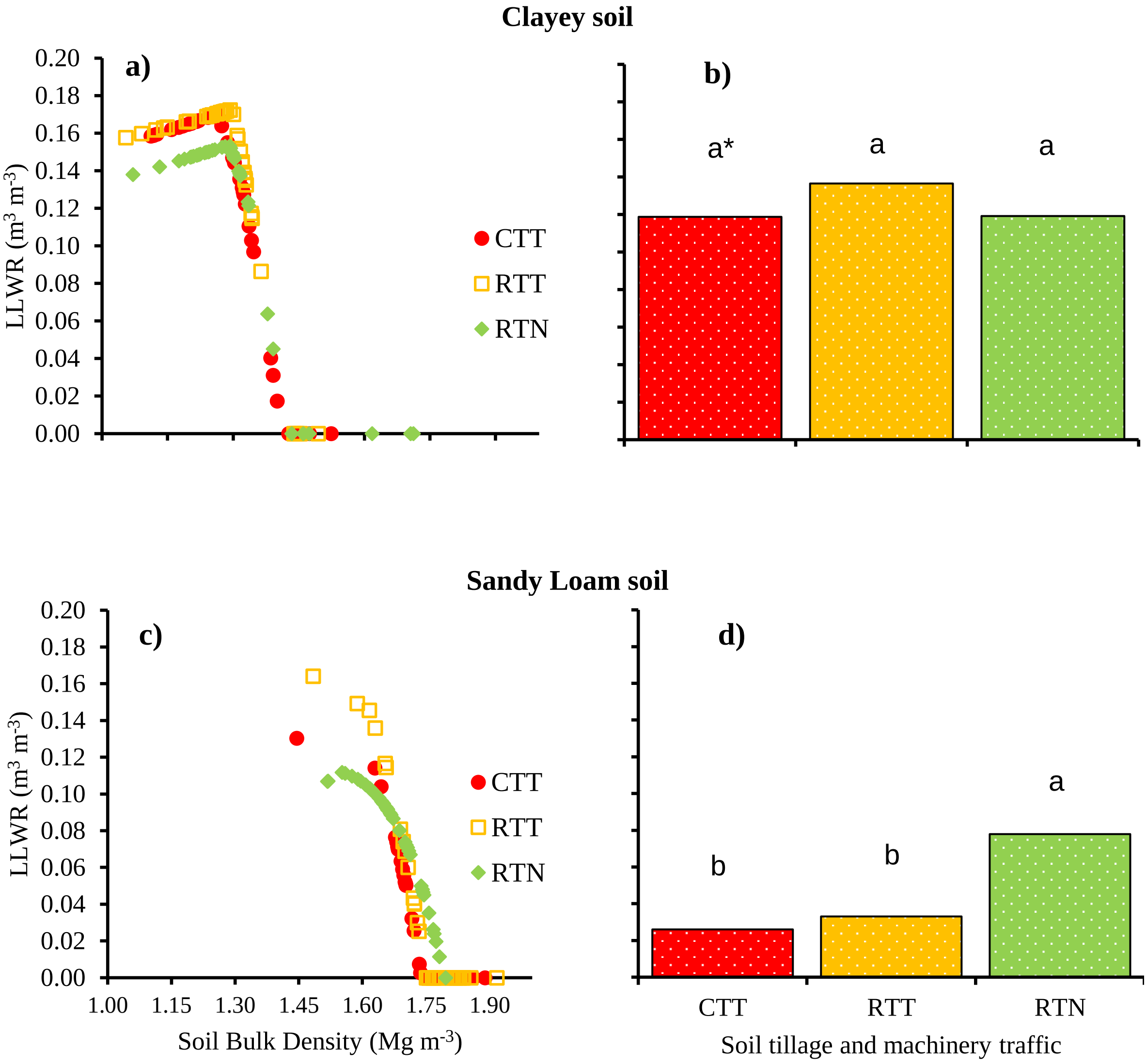

Figure 3. The least limiting water range (LLWR) variation (a, c) and average values (b, d) under conventional tillage with regular traffic (CTT), reduced tillage with regular traffic (RTT), and reduced tillage without traffic (RTN) at Clayey soil (a, b) and Sandy Loam soil (c, d). *Mean values within each site followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$).

3.4. Discussion

The BD and TP values measured in Clayey soil and Sandy Loam soil (Table 1) are similar to those found in Oliveira et al. (2019), Barbosa et al. (2019), and Pinheiro et al. (2021). Those authors did not find differences between conventional tillage and reduced tillage after the first ratoon in sugarcane fields in different regions of Brazil. Overall, the main reason for using conventional tillage in sugarcane fields is to alleviate soil compaction through mechanical mobilization (Bolonhezi et al., 2019). The results from α_{air}, $Ka_{-0.006MPa}$, and K_1 showed that there was no positive change by adopting conventional tillage instead of reduced tillage in sugarcane fields at the fourth ratoon. The effects of conventional tillage are temporary (Barbosa et al., 2019) not only in sugarcane fields, but also in annual crops, as reported by Moraes et al. (2016) and Anghinoni et al. (2019). Therefore, the soil returns to the previous state of compaction after the first harvesting event mainly due to intensive traffic of harvesters and loaded wagons (Morrison and Gawander, 2016; Awe et al., 2020; Luz et al., 2020). In addition, conventional tillage has been considered the main cause for a series of the soil processes that leads to a vicious cycle of degradation. Soil tillage causes soil organic carbon depletion (Tenelli et al., 2019), soil disaggregation, substantial decrease in water-stable aggregates, and macropore reduction (Cavalcanti et al., 2020). Along with machinery traffic, they are associated with a reduction of air permeability and pore continuity (Chen et al., 2014).

In Clayey soil, BD showed a positive effect on soil water retention curve in all managements (Table 2) which is related to an increase of MiP as a function of the BD increase. However, in CTT and RTT in Sandy Loam soil, BD had a negative or absence effect on soil water retention curve (Table 3). Those effects were a result of a higher level of compaction in these managements expressed by higher values of BD, MaP near to the critical value of $0.10\ m^3\ m^{-3}$ (Grable and Siemer, 1968), and $Ka_{-0.006MPa}$ lower than $1\ \mu m^2$ (Table 1). The poor structural stability of sandy soils (Huang and Hartemink, 2020) and higher susceptibility to compaction (Gregory et al., 2007; Jabro et al., 2016) explains the differences observed between Clayey and Sandy Loam soil. Weak soil's resilience makes it harder to recover its initial state after being compacted by machinery traffic (Obour and Ugarte, 2021) even after undergoing conventional tillage. In addition, the higher total porosity, pore continuity, and root dry biomass (Barbosa et al., 2021) which increases root channels found in Clayey soil resulted in higher air permeability in this soil (Table 1).

Our findings evidenced that the LLWR was similar between CTT and RTT in Clayey soil, where $BD < BDc$ was observed in almost all samples. The RTT treatment had a higher frequency (70%) of samples with SPR values below 2.5 MPa compared to CTT (50%) in Clayey soil. This result might be indicative of soil structure improvement in RTT. In addition, it is expected that reduced tillage will become more viable because of its long-term positive effects on organic matter accumulation (Segnini et al., 2013; Tenelli et al., 2019) and soil structure after several cycles of sugarcane, as reported by Martíni et al. (2021). Those authors reinforced that conventional tillage led to negative changes in the soil hydraulic and physical attributes while reduced tillage promoted a more stable environment in a clayey soil cultivated with sugarcane.

Recent studies have drawn attention to the low efficiency of conventional tillage, since it promotes soil disturbance at high costs and increases the risk of soil physical degradation, soil erosion, and soil organic matter depletion in sugarcane fields (Barbosa et al., 2019; Tenelli et al., 2019; Pinheiro et al., 2021; Tabriz et al., 2021). In the same way, our results revealed that RTT seems to be a viable alternative for a more sustainable sugarcane production. It could be taken as a conservation tillage practice for sugarcane, regardless of soil texture.

It is well known that soil structure and pore size, continuity, and connectivity are altered by soil, land use, and tillage practices (de Moraes et al., 2014; Lima et al., 2020). In addition, our results showed that RTN improved $Ka_{-0.01MPa}$ and K_1 in Clayey soil, and $Ka_{-0.006MPa}$, $Ka_{-0.01MPa}$ and K_1 in Sandy Loam soil. The absence of machinery traffic creates a functional porous system that enables the roots to explore a greater volume of soil (Gonçalves et al., 2014; Barbosa et al., 2021). Consequently, the root penetration creates a connected macropore pattern (Bodner et al., 2014) that positively affects the soil physical quality (Chen et al., 2014). Therefore, the values of Ka and K_1 indicated great air flux capacity in RTN. The adoption of controlled traffic had potential to preserve soil structure and soil physical quality (Reichert et al., 2016) and also, increase sugarcane yields (Esteban et al., 2019; Barbosa et al., 2021).

The increase of sugarcane root system in the reduced tillage without traffic was reported by Barbosa et al. (2021) in the same experimental areas. They reported that in the second ratoon cycle the root biomass increased 22% in RTN compared with RTT in the Sandy Loam soil. Besides showing higher values of MaP, Ka, and K_1, RTN treatment showed higher LLWR which can explain higher root growth. Therefore, the higher MaP and α_{air} observed in RTN in Sandy Loam soil (Table 1) increased air and water fluxes. In addition, it is worth highlighting that the proportion of samples with $BDc > BD$ was 2.5% in RTN and more than 50% in CTT and RTT in the Sandy Loam soil.

Recently, Esteban et al. (2019) showed that the adoption of a controlled traffic system increases root biomass (17.9%) and macroporosity (39%) when compared to random traffic. It is important to notice that they evaluated areas under conventional tillage practice. However, our results showed that RTN increases the MaP and K_1 by 70% in Sandy Loam soil (Table 1). This result brought new insights about soil tillage practices in sugarcane, in which the adoption of conventional tillage is unnecessary and the improvement of soil structure in reduced tillage is conditioned to the complementary adoption of traffic-free seedbed zones by the controlled traffic practices.

The results also suggested that LLWR can be used as an integrative indicator of tillage impacts on water availability in sugarcane fields due to its greater sensitivity in relation to PAW, measured as the difference between θ_{fc} and θ_{pwp} (Table 1). In addition, Silva et al. (2021) highlighted that the soil physical quality affected by machinery traffic can be evaluated by LLWR. Therefore, the LLWR was efficient to evaluate the effects of machinery traffic mainly in Sandy Loam soil. Evaluating sugarcane yield changes in 28 field experiments under different edaphoclimatic conditions in Brazil, Carvalho et al. (2019) observed that sandy soils produce 40% less biomass (stalks and crop residues) than clayey soils due to lower soil fertility and water holding capacity. Consequently, the low amounts of crop residues make it more prone to compaction by machinery traffic (Vischi Filho et al., 2015; Cherubin et al., 2021). Therefore, reduced tillage without traffic affected the LLWR more in Sandy Loam than in Clayey soil (Fig. 3). The values of LLWR, total porosity, $Ka_{-0.006MPa}$ lower than 1.0 μm^2, and BD higher than 1.70 Mg m^{-3} in CTT and RTT treatments in Sandy Loam soil indicated that this soil was more susceptible to negative impacts of conventional tillage and machinery traffic in relation to Clayey soil. Our results are according to Barbosa et al. (2021) who previously reported that the impact of machine traffic on soil structure quality was more evident in the Sandy Loam soil. Therefore, reduced tillage and the adoption of traffic-free seedbed zones are essential to preserve soil structure and maximize the yield potential of sandy soils cultivated with sugarcane. Although LLWR did not differ among tillage practices in the Clayey soil, the highest K_1 in RTN reflected the higher $Ka_{-0.01MPa}$ (Table 1). These results are indicative of a better soil structure and physical quality in RTN in the Clayey soil.

There are two ways to improve soil physical quality and water availability based on LLWR measurements. The first one is to manage water content within LLWR to avoid physical restriction for plant water uptake (Lima et al., 2020), and the second one is associated with tillage practices capable of keeping the BD within a range in which the LLWR is wider. In Sandy Loam, RTN treatment is an efficient practice for achieving the water availability due to its lower BD and SPR. Therefore, the highest degree of compaction found in CTT and RTT compared to RTN increases the SPR which was responsible for the LLWR differences among the treatments in Sandy Loam soil (Fig. 3d). Similar results were found by Benevenute et al. (2020) and Silva et al. (2021) who reported that soil penetration resistance is a key indicator of physical degradation in Brazilian soils.

Lastly, our results showed that the improvement of soil physical quality was conditioned by the adoption of reduced tillage with non-traffic in these field experiments. Nevertheless, some additional management practices can be encouraged in Brazilian sugarcane fields. For instance, adjusting crop spacing based on machinery track width as well as widening harvester tracks can minimize soil compaction induced by traffic and create traffic-free seedbed zones. It can also increase the LLWR mainly near planting rows in the untrafficked region as described by Souza et al. (2015). In addition, the adoption of controlled traffic practices by automatic steering systems associated with double-combined row spacing can reduce the trafficked area (Esteban et al., 2020) and then, preserve the soil physical quality and crop yield (Esteban et al., 2019; Barbosa et al., 2021).

3.5. Conclusions

The adoption of reduced tillage practice did not negatively impact the soil physical quality assessed LLWR, air permeability, and air-filled porosity in relation to conventional tillage practice in both soils. Therefore, our results reinforce that conventional tillage could be replaced by reduced tillage to improve soil water availability and air fluxes in sugarcane fields.

However, the soil benefits provided by reduced tillage are conditioned by the adoption of traffic-free seedbed zones. It increased LLWR, air permeability, and pore continuity in Sandy Loam soil and air permeability and pore continuity in Clayey soil. Finally, we concluded that adoption of reduced tillage and traffic control practices are two of the most important pillars for reducing soil compaction and improving the sustainability of sugarcane production in Brazil.

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4. SOIL STRUCTURE CHANGES INDUCED BY TILLAGE AND REDUCTION OF MACHINERY TRAFFIC ON SUGARCANE – A DIVERSITY OF ASSESSMENT SCALES [3]

Abstract

Conventional tillage disturbs soil structure, increasing the soil's susceptibility to compaction by machinery traffic in sugarcane fields. In this sense, the adoption of reduced tillage or no-tillage practices associated with traffic control has been proposed to preserve the functionality of soil structure, thus reducing soil compaction and plant growth restrictions. A long-term sugarcane experiment was carried out to evaluate the effects of conventional and reduced tillage practices with random and without machinery traffic on soil structure in southeastern Brazil. The soil structural quality was evaluated using a diversity of assessment scales, including on-farm Visual Evaluation of Soil Structure (VESS) in the "macroscale", aggregate stability (e.g., mean weight diameter-MWD) in the "mesoscale" and 2D micro-morphometric image analysis (size and shape of pores, and total pore area) in the "microscale". The conventional tillage and reduced tillage with random traffic treatments showed a similar soil structure after the fourth cycle of sugarcane ratoon in the macro (i.e., VESS Sq), meso (i.e., MWD), and micro scale (shape and total pore area). However, the reduced tillage without traffic improved soil structure (e.g., lower VESS Sq, higher total pore area, and greater percentage of complex pores) when compared to the treatments with random traffic in the 0-10 cm soil layer. While conventional tillage does not bring additional benefits in alleviating soil compaction compared to reduced tillage, the preservation of soil structure under reduced tillage is conditioned by the adoption of traffic-free seedbed zones. A diversity of assessment scales showed that different methods and scales are related to specific soil functions and have a distinct objective, but it is an advisable strategy to assess the soil structural quality.

Keywords: Reduced tillage, Traffic control, Soil health, VESS, 2D micro-morphometric image analysis, Aggregation

4.1. Introduction

Soil structure is defined by the shape, size, and spatial arrangement of primary soil particles and aggregates (Warkentin, 2008), as well as the spatial configurations of the pore network produced by processes of root growth, faunal activity, swell-shrink dynamics, and wetting-drying cycles (Vogel et al., 2021). There are two different perspectives to quantify the structure of soils, one focused on aggregates of the solid phase and the other on the pore space (Rabot et al., 2018; Schlüter et al., 2020). Better soil structure and high aggregate stability are imperative for supporting soil functions such as carbon storage (Meurer et al., 2020), biomass production, water storage and filtering, soil fertility, and soil physical stability (Bronick and Lal, 2005, Rabot et al., 2018). However, soil structure can be changed by land use, mainly cultivation, and management practices such as soil tillage (Pires et al., 2017) and machinery traffic (Keller et al., 2019). Both soil tillage and machinery traffic are largely used in sugarcane cultivation (e.g., crop planting) on every cycle (Cavalcanti et al., 2020; Li et al., 2020; Toledo et al., 2021).

Soil tillage in sugarcane planting followed by random machinery traffic such as harvesters, wagons, and tractors in sequential sugarcane cycles has increased soil compaction and impaired soil structure

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(Jimenez et al., 2021a). Despite that, conventional tillage by subsoiling and plowing operations before sugarcane planting is widely adopted as the main strategy to alleviate soil compaction (Li et al., 2020). Typically, soil returns to the same or even worse compaction degree after the first harvesting event, mainly when performed during the rainy periods from October to March in Brazil (Cherubin et al., 2017; Barbosa et al., 2019). Conventional tillage is an annual practice adopted in about 1.37 million hectares (i.e. 14% and 70% of the sugarcane total area every year and every five years respectively) by sugarcane farmers in Brazil (Cursi et al., 2021). On the other hand, no-tillage or reduced tillage practice has been shown to be as a target conservationist strategy to preserve soil structure quality in sugarcane fields (Barbosa et al., 2019; Li et al., 2020; Martíni et al., 2021). Evidence revealed the benefits of reduced tillage on increasing biological activity and consequently carbon accumulation (Tenelli et al., 2019), beyond to creating greater pores networks connected to the root growth environment while supporting biomass production (Li et al., 2020). Despite improving soil structural quality, reduced tillage is still affected by machinery traffic in sugarcane fields, which substantially weakens the positive effects of reduced tillage on soil structure. Therefore, management strategies to reduce or control the machinery traffic are imperative to mitigate soil structure degradation and maintain in fully operation soil physical processes and functions (Techen et al., 2020; Toledo et al., 2021; Tweddle et al., 2021). However, there is a paucity of studies that focus on reduced tillage and reduction of machinery traffic as a joint strategy in sugarcane production (Martíni et al., 2020).

Modifications in soil structure can be assessed from the perspectives of the solid phase (bulk density) and pore space architecture (Rabot et al., 2018), as well as at the macro- and microscales. The methods range from practical and quick field observations to detailed and time-consuming laboratory analysis. A wide number of methods are currently used to evaluate soil structure, however direct analysis such as visual and imaging techniques are more relevant for several soil functions (Rabot et al., 2018). In addition, soil structure indicators composed by a visual assessment, provide a more detailed description of changes in soil structure through morphological examination of aggregates (Boizard et al., 2013; Rabot et al., 2018). On the macroscale, the Visual Evaluation of Soil Structure (VESS) (Ball et al., 2007; Guimarães et al., 2011) is considered a practical and efficient method to assess soil structure quality under contrasting soil, climate and management conditions around the world (Franco et al., 2019). The VESS is an effective on-farm method for assessing soil structural quality under different land uses (Cherubin et al., 2017) and tillage practices (Tormena et al., 2016; Çelik et al., 2020). However, the VESS is not recommended to assess the potential of soil structure to resist disaggregation (i.e., aggregate stability). In this case, the physical stability of soil structure can be evaluated through aggregate distribution and stability by wet sieving (Rabot et al., 2018; Liu et al., 2021).

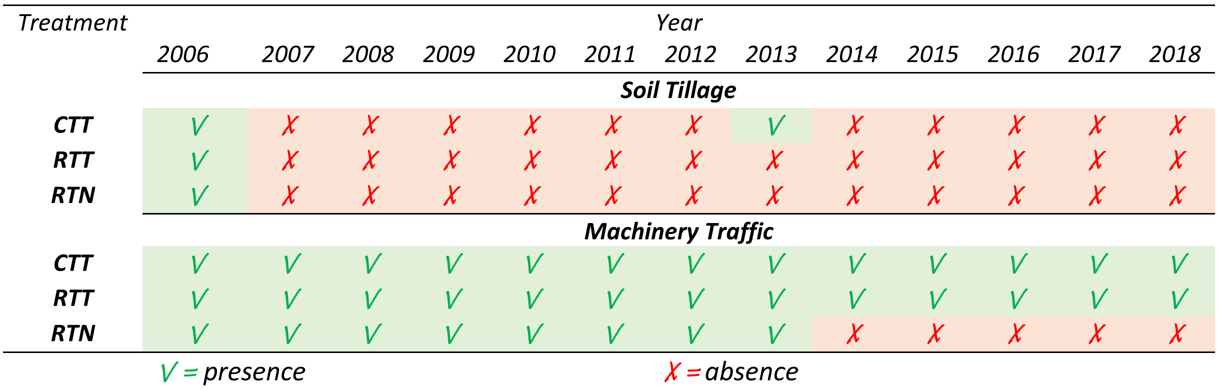
Both VESS and aggregate distribution and stability measure the solid phase arrangement and they are not efficient indicators of pore space. In this case, 2D micro-morphometric pore images (Murphy et al., 1977; Ringrosevoase, 1991; Cooper et al., 2016) and thin section (Bullock et al., 1985) analyses are more accurate tools to identify and quantify the soil pore space by direct geometric visualization. They can be used to understand mechanical and biological structuration factors that occur on a more detailed scale in different soil managements (Hubert et al., 2007; Silva et al., 2015; Rabot et al., 2018). Under different management systems, image analyses proved to be sensitive to detect changes in the pore size distribution, interfacial area, pore types and connectivity (Silva et al., 2015). In addition, imaging instruments are the most reliable tools to measure porosity and its relationship with processes that occur in the soil such as water flow, matter fluxes, and gas exchange (Rabot et al., 2018; Schlüter et al., 2020; Vogel et al., 2021). Thus, soil structure changes caused by management strategies should be evaluated by a combination of methods that incorporate both the solid phase and pore space perspectives.

Soil structure changes in sugarcane fields conventionally tilled have been investigated by diverse direct and indirect indicators such as bulk density (Esteban et al., 2019; Li et al., 2020; Shukla et al., 2021), soil penetration resistance (Barbosa et al., 2019; Oliveira et al., 2019), soil water content (Oliveira et al., 2019; Li et al., 2020), infiltration rate (Shukla et al., 2020), aggregate size distribution (Braunack and McGarry, 2006), soil porosity by indirect methods (i.e., volumetric water content) (Li et al., 2020; Barbosa et al., 2021; Martíni et al., 2021), and soil consistency limits (Esteban et al., 2020). Nevertheless, there is a paucity of studies that integrate assessments in a diversity of scales (i.e., macro-, meso-, and microscales) to quantify soil structure under different soil management practices with and without random machine traffic (Martíni et al., 2020). In this context, we hypothesized that the benefits of reduced tillage compared to conventional tillage on soil structure are no longer detected, regardless of assessment scales, when the field is managed under random machinery traffic. This study aimed to assess the soil structure changes by a diversity of assessment scales through the VESS, aggregate distribution and stability, and 2D micro-morphometric image analysis under conventional and reduced tillage practices with and without random traffic in a clayey soil cultivated with sugarcane.

4.2. Material and Methods

4.2.1. Study sites and experimental design

A field experiment was conducted in a Rhodic Eutrudox (Soil Survey Staff, 2014) with clayey texture (547 g kg $^{-1}$ clay, 186 g kg $^{-1}$ silt, 267 g kg $^{-1}$ sand), located in the municipality of Quirinópolis, Goiás state, Brazil (18°32’ S and 50°26’ W). The soil was cultivated with pasture until 2006 when it was converted into sugarcane using soil tillage practices (Fig. 1). After the harvest in October 2012, the field was desiccated with glyphosate (5 L ha^{-1}), and lime (2 Mg ha^{-1}) and gypsum (1 Mg ha^{-1}) were applied to the soil surface after the harvesting. In December 2012, a cover crop (*Crotalaria spectabilis*) was planted and then was desiccated after four months (April 2013). Fifteen days later, the experiment was arranged in a randomized block design with three treatments and four replications. The treatments were as follows: conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN). Soil preparation in the CTT treatment was carried out by subsoiling with a subsoiler at 40 cm depth and rods spaced at 50 cm, and light hydraulic harrowing with a harrow of 36 disks at 20 cm depth. For all treatments, sugarcane planting consisted of a single operation of planting furrow opened to a 30 cm depth over the cover crop biomass using a 2-row planter with spacing of 150 cm. All practices were performed using a 4 x 4 tractor of 220hp. The treatments RTT and RTN were tested in order to evaluate the adoption of reduced tillage on sugarcane planting time, while CTT was used as a control treatment. The main differences between RTT and RTN treatments were the mechanized operations performed along the crop cycle (pesticides application and harvest), being therefore, on RTT all operations performed mechanically, while in RTN all field operations after planting were carried out manually (Fig. 1). RTN treatment was established to evaluate the potential reduced tillage associated with the creation of seedbeds (i.e., traffic-free zones) and permanent traffic zones and their effects on soil structure, simulating the use of transloaders and harvesters with long distances between axes. These practices have been recently adopted by sugarcane farmers in Brazil (Barbosa et al., 2021). Each plot was composed of 10 sugarcane rows with 10-m in length spaced at 1.5-m. More details about fertilization management, sugarcane variety, disease and pest control in the experimental areas can be found in Barbosa et al. (2019) and Tenelli et al. (2019).



Treatment	*Year*												
	2006	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*
	Soil Tillage												
CTT	V	✗	✗	✗	✗	✗	✗	V	✗	✗	✗	✗	✗
RTT	V	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
RTN	V	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
	Machinery Traffic												
CTT	V	V	V	V	V	V	V	V	V	V	V	V	V
RTT	V	V	V	V	V	V	V	V	V	V	V	V	V
RTN	V	V	V	V	V	V	V	V	✗	✗	✗	✗	✗

V = presence *✗ = absence*

Figure 1. Soil tillage practices and machinery traffic chronosequence at the sugarcane field trial. The green (*v*) and red (*x*) symbols represent the presence and absence of tillage practices and machinery traffic by tractors, wagons, and harvesters under conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN).

In CTT and RTT, the sugarcane harvesting was done with random traffic of a harvester (Model Case B8800) with 159 treadmill wheels 47 cm wide, track width of 190 cm, and total mass of 20.6 Mg. In addition, the harvested sugarcane stalks were transported in wagons pulled by a tractor (Model Case 220cv). The wagons weighed 6.5 Mg, had a track width of 300 cm, 600/50-22.5 tires, and the capacity to transport 8.5 Mg of sugarcane. The tractor weighed 10.5 Mg, had a track width of 300 cm, 600/60-30.5 front tires, and 710/70 R38 rear tires. In the RTN, the sugarcane was harvested manually to preserve soil structure and to represent sugarcane management with seedbed zones without traffic, as detailed in Barbosa et al. (2021).

4.2.2. Sampling and soil structure measurements

4.2.2.1. Visual Evaluation of Soil Structure – VESS (macro-scale) and mean weight diameter – MWD (meso-scale)

Soil samples were collected in July 2018, after the fifth harvesting event. In the field, a small trench (30 x 30 x 30 cm) was dug in the inter-row position (between rows, 20 cm apart from each sugarcane row) at each plot. The VESS assessment was done in the field according to Guimarães et al. (2011). Therefore, an undisturbed soil sample (25 cm depth x 20 cm wide x 10 cm thick) was collected in each plot (totaling 12 samples) using a shovel. The assessment included a manual breakdown of soil aggregates along their fracture planes for identification of the main structural units (i.e., shape, size, visible porosity, and tensile strength of soil aggregates), identification of contrasting soil layers, measurement of soil layer thickness, fragmentation of some aggregates higher than 2 cm, and then it was assigned a score (Sq) in each soil layer according to their structural quality as described in Guimarães et al. (2011).

An individual VESS Sq was assigned for each naturally formed and identified layer and an overall weighted Sq was calculated for each sample based on the individual Sq and thickness of each contrasting soil layer as shown in Equation 1:

$$\text{VESS Sq} = \sum_{i=1}^{n} \frac{SqiTi}{TT} \tag{1}$$

where, VESS Sq is the overall VESS score, *Sqi* and *Ti* are respectively the score and thickness of each identified soil layer, and *TT* is the total thickness of the soil sample.

In addition, the weighted average of VESS Sq was calculated for 0-10 and 10-25 cm soil layers and an overall VESS Sq was taken using the thickness and scores of the naturally formed first and second soil layers. The interpretation of VESS Sq was done according to Ball et al. (2007) and Guimarães et al. (2011). The VESS Sq ranges from 1 to 5 in which lower VESS Sq (1 and 2) indicates good soil structure quality due to the presence of roots, high porosity, and aggregates with lower tensile strength. The higher VESS Sq (4 and 5) indicates poor soil structure quality due to the absence of roots, low porosity, and aggregates with higher tensile strength. The VESS Sq = 3 was considered a threshold of soil structure quality. The Sq ≥ 3 means that soil structural quality begins to decline and changes in soil management practices are needed to improve it (Guimarães et al., 2011; Cherubin et al., 2017).

In the same trenches, a soil block (10 x 10 x 10 cm) was collected at the 0-10, 10-20, and 20-30 cm soil layer in each plot (totaling 36 samples) for aggregate stability assessment. The aggregate stability was determined through an adapted method from Elliott (1986). Therefore, field moist soil was passed through an 8-mm sieve by manually breaking up the soil along natural planes of weakness and then air-dried. The air-dried soil samples were rewetted for sixteen hours and then were wet sieved in a vertical Yoder-type sieve column at a speed of 30 cycles/ min for 10 minutes. Soil was separated into three fractions: i) large macroaggregates (LMac, > 2 mm), ii) small macroaggregates (Mac, 2 – 0.250 mm), and iii) microaggregates (Mic, 0.250 – 0.053 mm). All fractions were dried and then weighted. The mean weighted diameter (MWD) of water-stable aggregates was calculated according to Equation 2:

$$MWD = \sum_{i=1}^{n} WiXi \tag{2}$$

where *Xi* is the mean diameter of each size fraction and *Wi* is the proportional weight of the corresponding size fraction.

4.2.2.2. Micromorphological and 2D micro-morphometric image analyses (micro-scale)

One undisturbed and vertically oriented soil sample (12 x 7 x 5 cm) was collected in each treatment from the inter-row positions in two soil layers (0-12 cm and 12-24 cm), totaling six samples. Soil samples were air-dried and impregnated by capillarity with a polyester resin, styrene monomer, and fluorescent dye mixture in a vacuum chamber. After impregnation, one vertically oriented soil thin section (30 μm thick) per treatment and layer were cut and polished for qualitative and semi-quantitative description (micromorphological analysis) according to Bullock et al. (1985) and Castro and Cooper (2019). Also, one polished block (12 x 7 x 1.5 cm) per treatment and layer were cut for 2D micro-morphometric image analysis.

The thin sections were described using a polarizing optical petrographic microscope. The qualitative and semi-quantitative descriptions were performed according to the classification described in Bullock et al. (1985) and Castro and Cooper (2019).

In each polished block, 18 photomicrographs of 180 mm² (15 mm x 12 mm) were obtained randomly using a charged couple device photographic camera coupled to a petrographic microscope with a 10x optical lens. Ultraviolet light was used to enhance the contrast between the pore space and soil matrix. The images were digitized with a resolution of 1024 x 768 pixels in which each pixel corresponded to an area of 156.25 μm². Pore segmentation was undertaken in Noesis Visilog version 5.4 software, in which each image was submitted to the following steps: segmentation process (binarization) by grey-level thresholding considering the full gray-level range (0-255), erosion/dilation, opening/closing filtering, and labeling. After those steps, final binary images were obtained and the measurement of the total pore area for each image was calculated as the sum of all pores area using Visual Basic language macros in Microsoft Excel®. Pore shape was classified into three groups (i.e., rounded, elongated, and complex pores) according to Cooper et al. (2016). Two indices (Equations 3 and 4) were employed to determine the pore shape:

$$I1 = \frac{P^2}{4\pi A} \tag{3}$$

where *P* is the perimeter of the pore and *A* is the area

$$I2 = \frac{\frac{1}{m}\sum_i (NI)i}{\frac{1}{n}\sum_j (DF)j} \tag{4}$$

where *NI* is the number of intercepts of an object in four different directions *i* (*i* = 0°, 45°, 90°, and 135°), *DF* is the ferret diameter of an object in two directions *j* (*j* = 0° and 90°), *m* corresponds to the number of *i* directions and *n* to the number of *j* directions.

The *I2* index was used as a complement to the *I1* for better pore segregation between elongated and complex pores' shapes. The distinction of the pore shapes followed the criteria: if $I1 \leq 5$ shape was rounded (channels and isolated vughs), if $5 < I1 \leq 25$ and $I2 \leq 2.2$ shape was elongated (planar pores), if 5

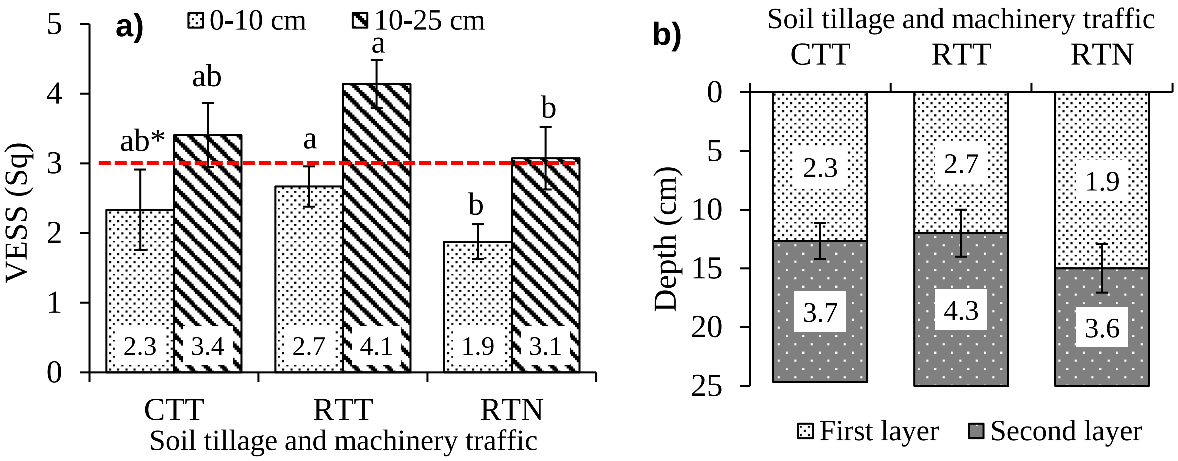
< $I1 \leq 25$ or and $I2 > 2.2$ shape was complex (packing pores and chambers). Pore size was classified according to small (0.000156 - 0.0156 mm^2), medium (0.0156 - 0.156 mm^2), and large (> 0.156 mm^2).

The mean soil porosity of each treatment was derived from 18 subsamples (every photomicrograph) which were used as replicates to analyze the effect of treatments in the pore shape and total pore area.

The data were subjected to analysis of variance by Proc ANOVA procedure, and when significant (Test F $p < 0.05$) means comparison was performed according to the Tukey's test ($p < 0.05$). ANOVA was performed separately for each soil layer and scale. All statistical analyses were performed using Statistical Analysis System – SAS 9.3 software (SAS Inc., Cary, NC, USA).

4.3. Results

After the fifth sugarcane harvesting, the soil structure was changed by tillage practices and machinery traffic. The RTN treatment showed a VESS Sq of 1.9 in the 0-10 cm layer, average lower than the VESS Sq observed in RTT (2.7) and similar to VESS Sq observed in CTT (2.3) (Fig. 2a). RTN treatment exhibited a structure composed of rounded aggregates easy to break with one hand, visible porosity, and the presence of roots throughout the soil. In the 10-25 cm layer, VESS scores were higher than of 3.0 in all treatments, with similar Sq in RTN and CTT, while the higher values were verified in RTT (4.3). Additionally, the data showed that naturally formed first layer has better structural quality than the naturally formed second layer for all treatments (Fig. 2b). However, in relation to overall VESS Sq (Fig. 2c) the higher mean values were observed in RTT (3.6) and CTT (3.0). The RTN treatment showed a VESS Sq of 2.6, average similar to VESS Sq observed in CTT and lower than the VESS Sq observed in RTT treatment. In addition, a greater presence and activity of macrofauna was also observed in RTN treatment during VESS evaluation (Fig. 3).



c) Overall (0-25 cm layer) VESS Sq

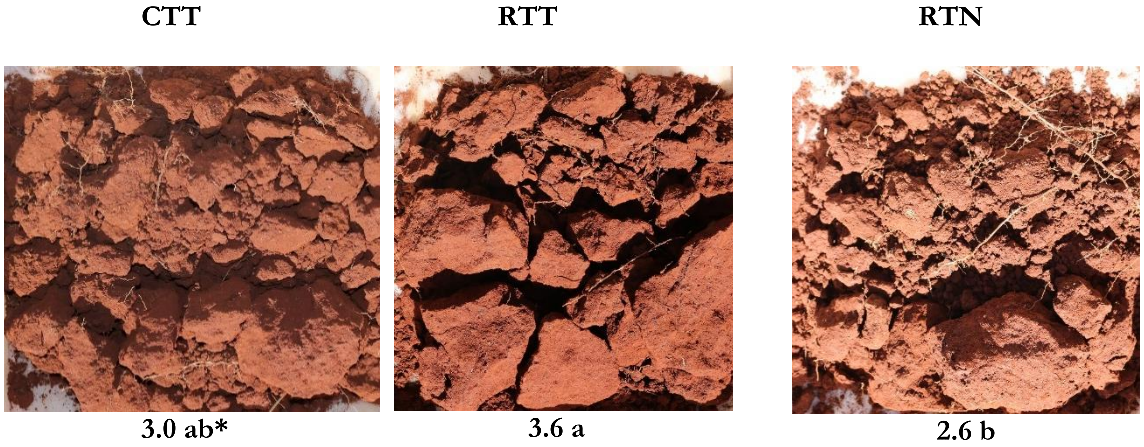


Figure 2. Mean scores of the Visual Evaluation of Soil Structure (VESS) under different soil tillage and machinery traffic practices in the 0-10 and 10-25 cm layers (a), scores of the naturally formed first and second layers depth (b), and overall (0-25 cm layer) VESS score (c) under conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN). * Means within the same layer followed by the same letter do not differ among themselves according to Tukey's test (p<0.05).

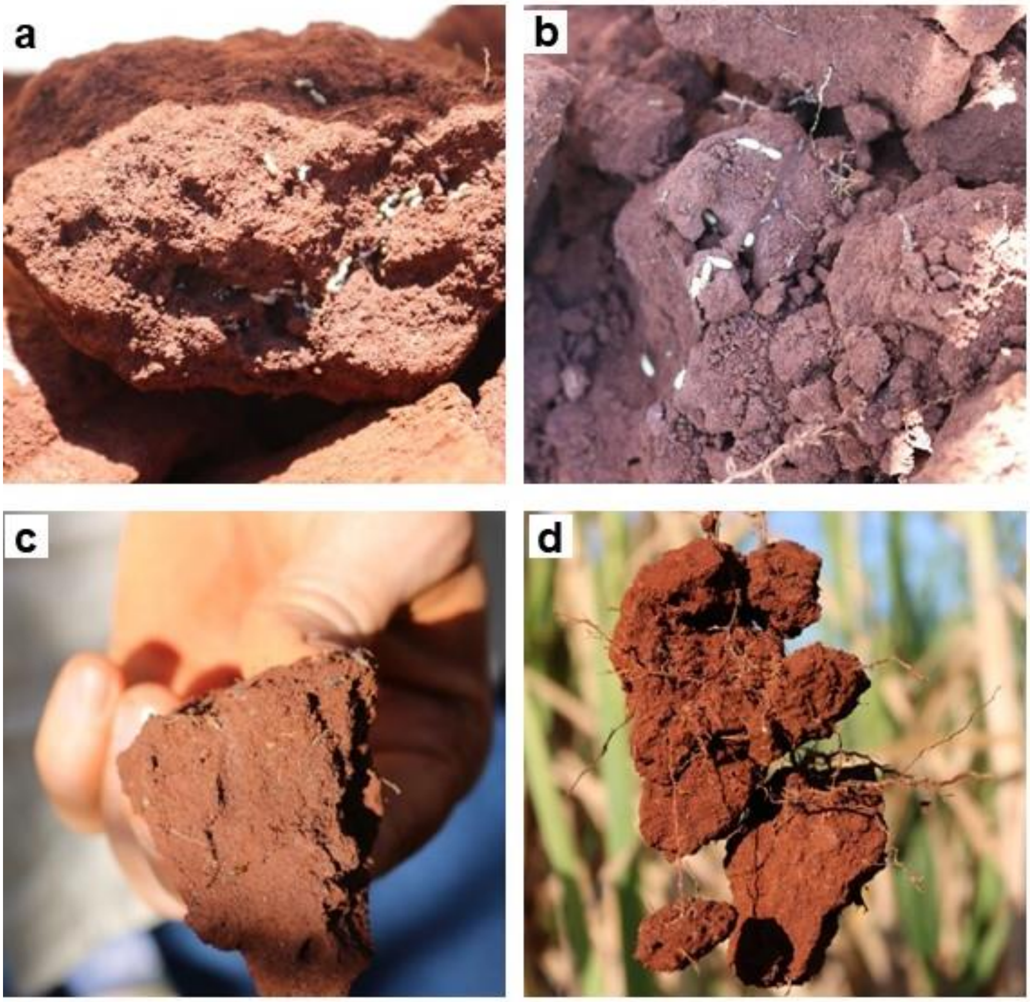


Figure 3. Presence of macrofauna (a, b, c) and roots (d) in soil aggregates in the RTN treatment. Images are taken in the VESS assessment at trial field.

The MWD was higher than 2.0 mm in all soil layers but was not influenced by the tillage and machinery traffic treatments (Figs. 4a, 4c, 4e). The results indicated that soil was highly aggregated because the LMac dominated the water-stable aggregate size distribution and accounted for more than 50% of the total mass of aggregates in all treatments and soil layers (Figs. 4b, 4d, 4f).

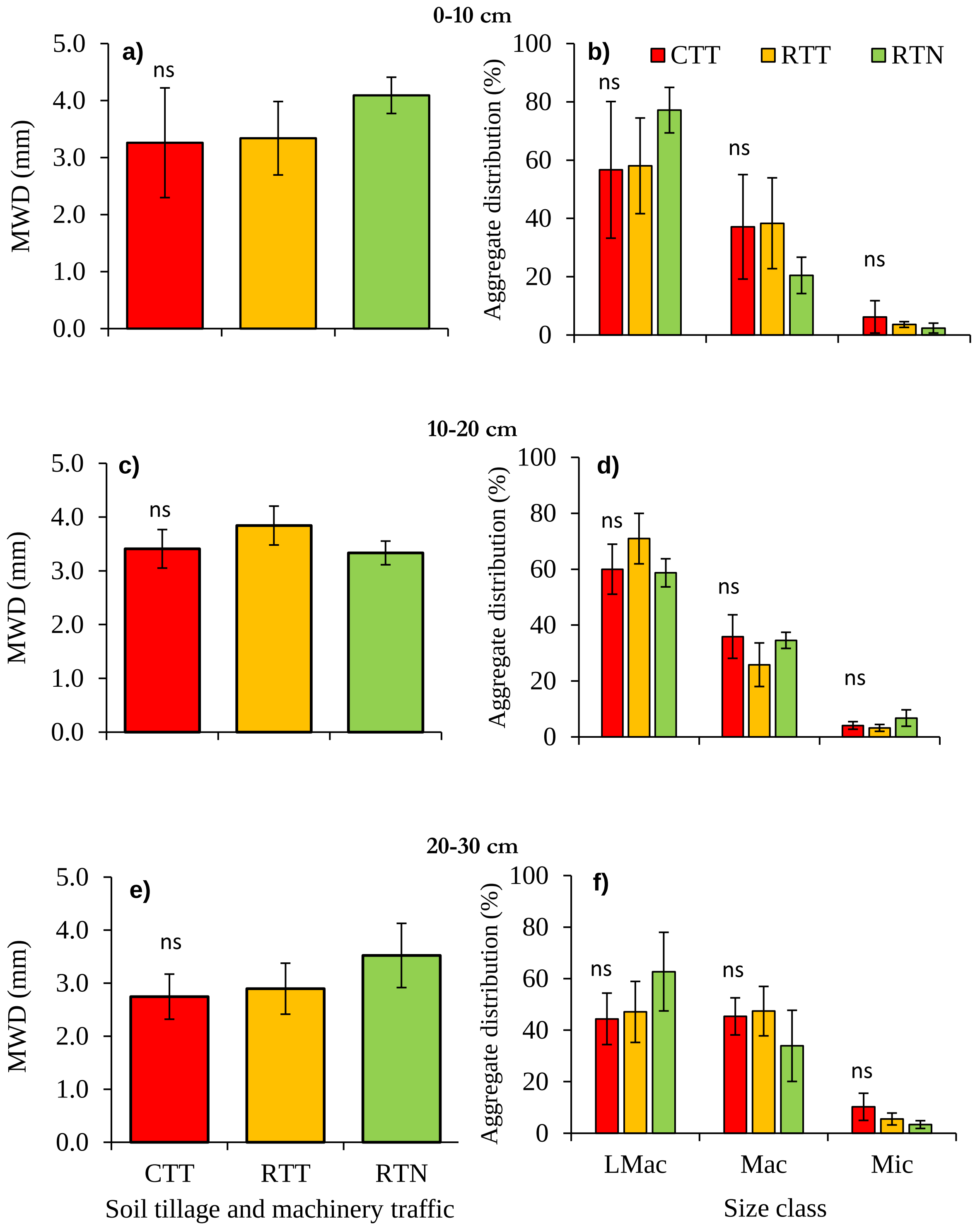


Figure 4. Mean weight diameter (MWD) (left) and water-stable aggregate size distribution (right) in soil layers under conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN). LMac (large macroaggregates, > 2 mm), Mac (macroaggregates, 2 – 0.250 mm), Mic (microaggregates, 0.250 – 0.053 mm). ^{ns} not significant according to Tukey's test (p<0.05). The horizontal bars denote the standard deviation of the mean (n= 4).

Tables 1 and 2 show the thin section's description for the 0-12 and 12-24 cm layers respectively. Overall, pores were classified as packing pores (i.e., complex pores that result from the loose packing of soil components), channel and planar pores, vughs (i.e., equidimensional, irregularly shaped, smooth, or rough, rarely connected). The related distribution was classified as enaulic (i.e., fine material appears as microaggregates between coarser particles), porphyric (i.e., coarser particles occur in a groundmass of fine material) or a combination of those. The microstructure was predominantly classified as granular structure (i.e., granules are separated by compound packing voids and do not accommodate each other) and subangular blocky structure (i.e., aggregates are separated by short planar voids on all or most sides).

Specific differences among treatments were observed. For example, a higher porosity accounting for complex packing and channel pores was observed in RTN treatment in 0-12 cm soil layer. The CTT and RTT treatments showed similar porosity in the 12-24 cm soil layer related to the 0-12 cm layer. On the other hand, there was a porosity reduction in RTN treatment in the 12-24 cm (Table 2) compared to the 0-12 cm (Table 1) soil layer. In addition, the microstructure was predominantly granular with strong pedality in RTN and moderately developed pedality in CTT and RTT in the 0-12 cm soil layer. Fig. 5 shows the aggregate coalescence in CTT and RTT in both soil layers and in RTN treatment in the 12-24 cm soil layer. Although roots were present in all treatments, excrements were observed only in RTN treatment which can be seen in Fig. 5.

Table 1. Micromorphological description of the treatments in the 0-12 cm soil layer under conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN).

CTT	RTT	RTN
Soil matrix composition		
Coarse material: 10 % Fine material: 65 % Porosity: 25 %	Coarse material: 10 % Fine material: 70 % Porosity: 20 %	Coarse material: 10 % Fine material: 50 % Porosity: 40 %
Related distribution		
Porphyric: 5% Enaulic: 95 %	Porphyric: 40 % Enaulic: 60 %	Porphyric: 20% Enaulic: 80 %
Coarse material		
Quartz subrounded, undulated, moderately selected with irregular linear alteration	Quartz subrounded, undulated, moderately selected with irregular linear alteration (98 %). Presence of magnetite and feldspars (2%)	Quartz subrounded, undulated, moderately selected with irregular linear alteration
Fine material		
Composed of clay and iron oxides and organic material. The color is predominantly red	Composed of clay and iron oxides and organic material. The color is predominantly red	Composed of clay and iron oxides and organic material. The color is predominantly red
Pores		
Complex packing (60 %), Spherical and policoncave vughs (40 %)	Complex packing (25 %), Spherical and policoncave vughs (65 %), and channels (10 %)	Complex packing (75 %), Spherical and policoncave vughs (5 %), channels (20 %)
Microstructure		
Predominant granular with moderately developed pedality and partially accommodated (95 %). Subangular blocks with strong pedality and partially accommodated (5 %)	Complex microstructure. Composed of granular with moderate pedality and partially accommodated (60 %). Subangular blocks with moderate pedality and partially accommodated (40 %)	Predominant granular with strong pedality and partially accommodated (80 %). Subangular blocks with strong pedality, accommodated, and partially accommodated (20 %)
Pedofeatures/Basic organic material		
Presence of roots Presence of charcoal	Typical ferruginous nodules Presence of roots	Typical ferruginous nodules Excrements Presence of roots

Table 2. Micromorphological description of the treatments in the 12-24 cm soil layer under conventional tillage with random traffic (CTT), reduced tillage with random traffic (RTT), and reduced tillage without traffic (RTN).

CTT	RTT	RTN
Soil matrix composition		
Coarse material: 15 % Fine material: 60 % Porosity: 25 %	Coarse material: 10 % Fine material: 70 % Porosity: 20 %	Coarse material: 15 % Fine material: 70 % Porosity: 15 %
Related distribution		
Enaulic: 20 % Enaulic-porphyric: 80 %	Porphyric-enaulic: 40 % Enaulic: 60 %	Porphyric: 90% Enaulic: 10 %
Coarse material		
Quartz subrounded, undulated, moderately selected with irregular linear alteration	Quartz subrounded, undulated, moderately selected with irregular linear alteration.	Quartz subrounded, undulated, moderately selected with irregular linear alteration
Fine material		
Composed of clay and iron oxides and organic material. The color is predominantly red	Composed of clay and iron oxides and organic material. The color is predominantly red	Composed of clay and iron oxides and organic material. The color is predominantly red
Pores		
Complex packing (35 %), Spherical and policoncave vughs (55 %), and fissures (10 %)	Complex packing (15 %), Spherical and policoncave vughs (75 %), fissures (10 %), and channels (10 %)	Complex packing (10 %), Spherical and policoncave vughs (70 %), channels (10 %), and fissures (10 %)
Microstructure		
Granular microstructure with moderately developed pedality and partially accommodated	Granular microstructure with moderately pedality and partially accommodated	Predominant subangular blocks with granular with weakly moderate pedality and partially accommodated. Showed a small zone with granular microstructure
Pedofeatures/Basic organic material		
Presence of roots Presence of charcoal	Presence of roots	Typical ferruginous nodules Presence of charcoal Presence of roots

The 2D morphometric image analysis revealed differences between treatments for the total pore area in the 0-12 cm soil layer (Fig. 6). For the CTT and RTT treatments, the total pore area was about 17% while for RTN was 37%. Hence, the total pore area was about 54% higher in the RTN as compared to the other two treatments. No changes in total pore area were detected in the 12-24 cm soil layer for all treatments. Averaged values of total pore area ranged between 13% and 18% in this soil layer (Fig. 6).

In the 0-12 cm soil layer, complex pore shape contributed to the total pore area more than rounded and elongated pore shapes (Figs. 6a, 6c, 6e). There was a reduction in complex pore shape in CTT (Fig. 4a; Fig. 5a) and RTT (Fig. 6c; Fig. 7c) when compared to RTN (Fig. 6e; Fig. 7e). In the same layer, rounded and elongated pore shapes represented about 5% and 2% of the pore area in all treatments, respectively. However, RTN showed a greater percentage of large pores than that of the CTT and RTT treatments (Fig. 6e). For the CTT and RTT treatments, rounded pore shape was composed by a higher percentage of medium-size pores.

The CTT treatment had a similar pore shape and size distribution in both soil layers (Figs. 6a, b). The same tendency was not observed in RTT and RTN, in which a reduction of complex pore shape in the

12-24 cm soil layer was observed. However, in RTN treatment, rounded pore shape was mainly composed by large pores (Fig. 6f). Therefore, the treatments modified pore shape and size distribution without changing the total pore area in the 12-24 cm soil layer (Fig. 6).

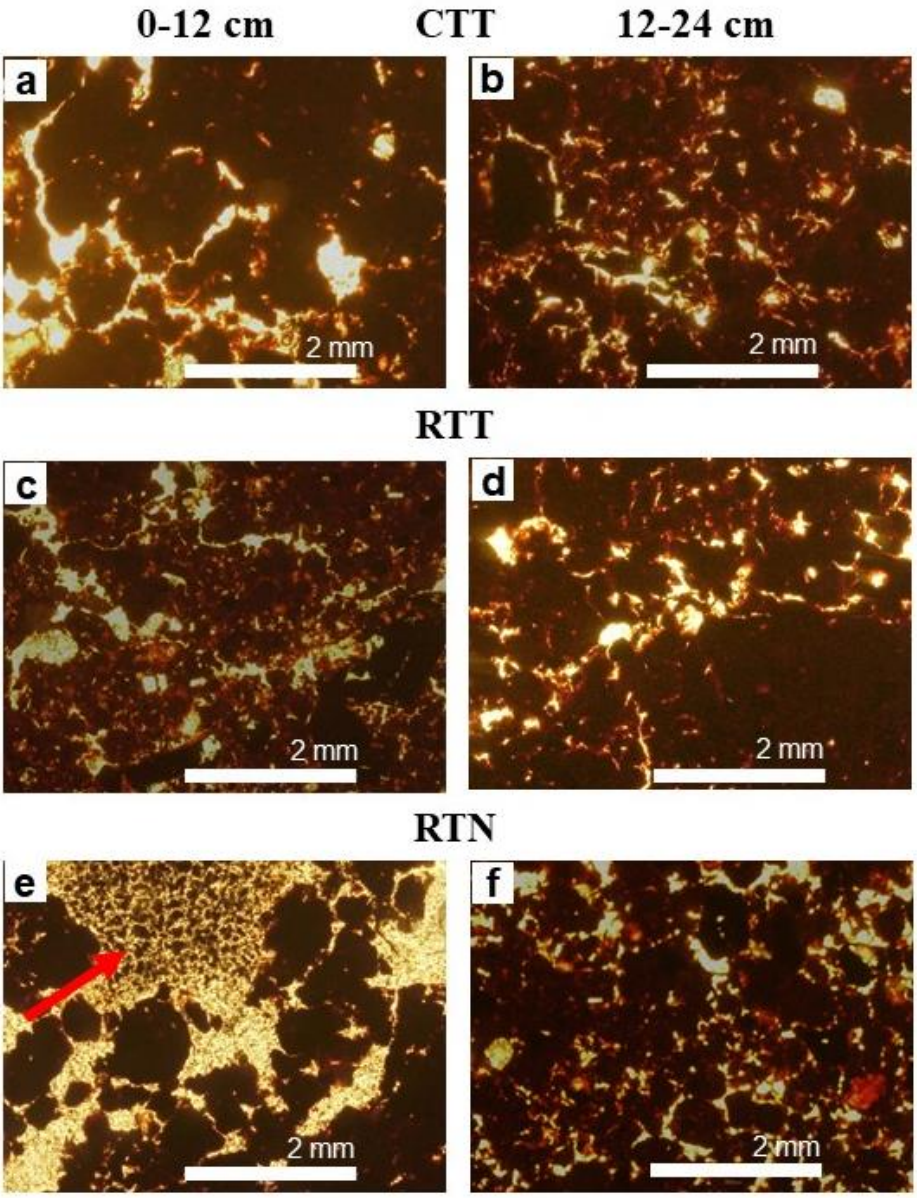


Figure 5. Microphotographs of representative thin section in the 0–12 cm (a, c, e) and 12-24 cm (b, d, f) soil layers under conventional tillage with random traffic (CTT) (a, b), reduced tillage with random traffic (RTT) (c, d), and reduced tillage without traffic (RTN) (e, f). Images were taken in an optical petrographic microscope with a 25x optical lens. The white dashes represent a scale of 2 mm. The red line arrow indicates the presence of excrements in RTN treatment.

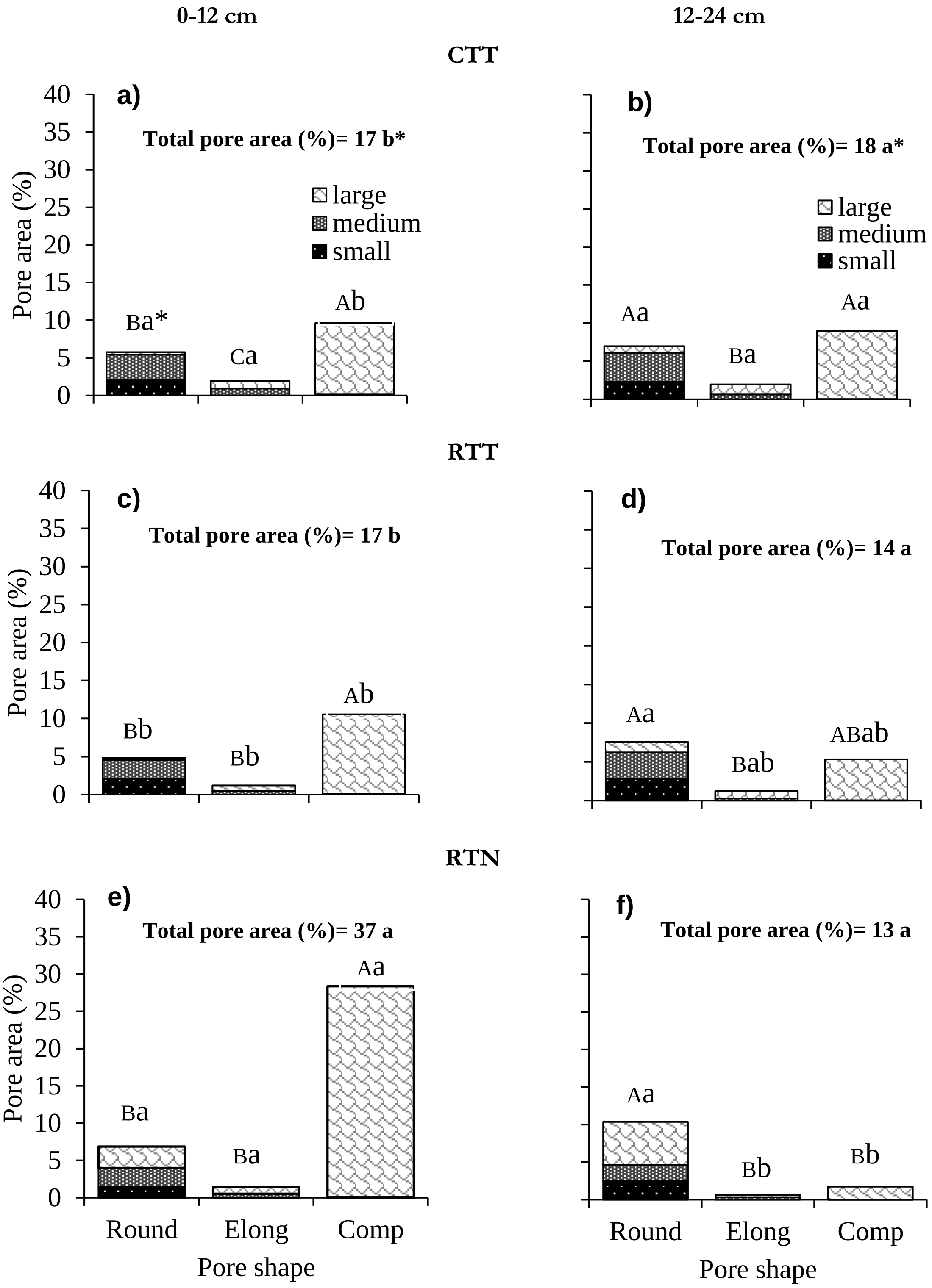


Figure 6. Total pore area (%), pore shape and size distribution in the 0–12 cm (a, c, e) and 12-24 cm (b, d, f) soil layer under conventional tillage with random traffic (CTT) (a, b), reduced tillage with random traffic (RTT) (c, d), and reduced tillage without traffic (RTN) (e, f). Round= rounded (channels and isolated vughs), Elong= elongated (planar pores), Comp= complex (packing pores and chambers). Small= 0.000156 - 0.0156 mm^2, medium= 0.0156 - 0.156 mm^2, large= > 0.156 mm^2. * Means within the same layer followed by the same capital letter among pore shape and lowercase letter among treatments do not differ among themselves according to Tukey's test (p<0.05).

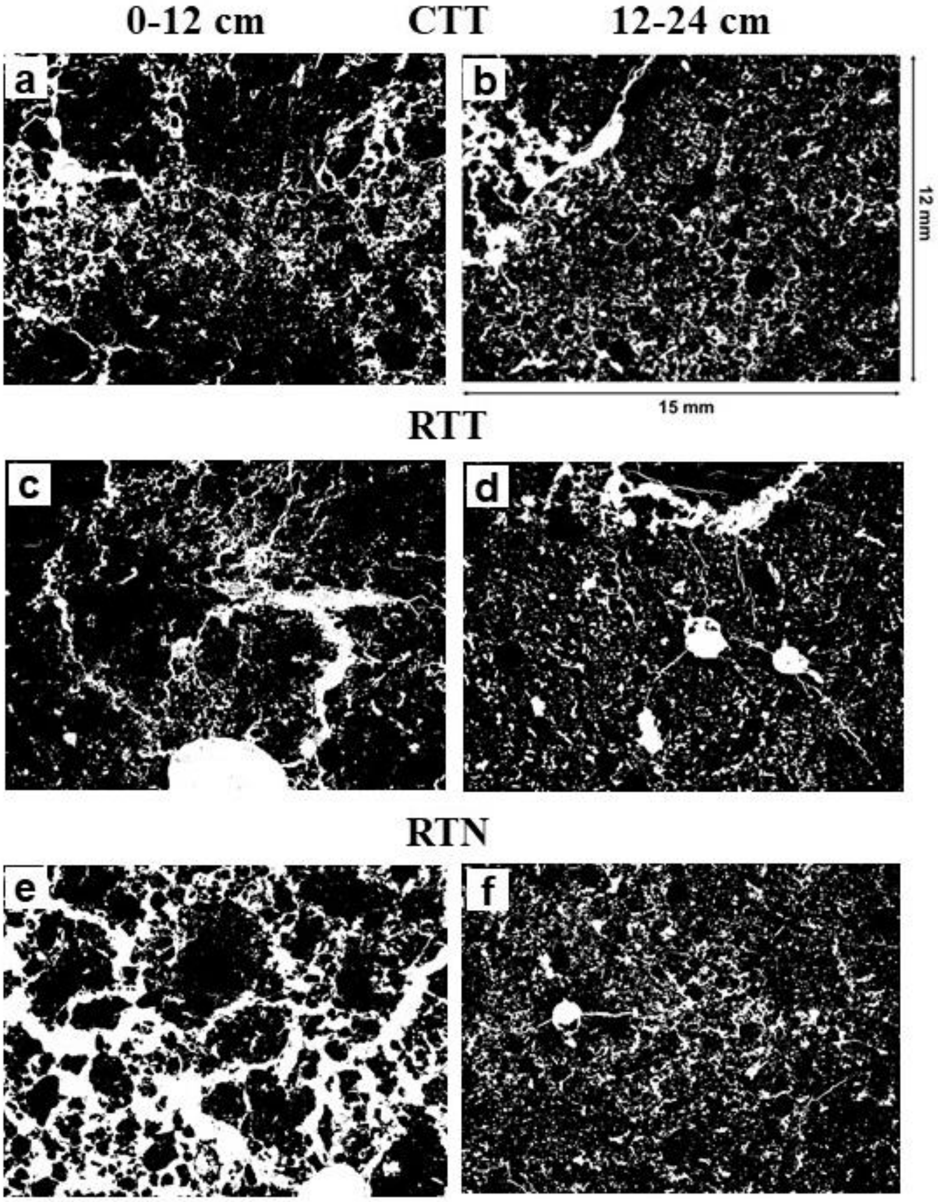


Figure 7. Binary microphotographs of representative thin section (black) and pore area (white) in the 0–12 cm (a, c, e) and 12-24 cm (b, d, f) soil layers under conventional tillage with random traffic (CTT) (a, b), reduced tillage with random traffic (RTT) (c, d), and reduced tillage without traffic (RTN) (e, f). The area of each binary microphotograph is 180 mm^2 (15 mm x 12 mm).

4.4. Discussion

4.4.1. Soil structure changes induced by reduction of tillage and random traffic

The data of VESS, MWD, aggregate size distribution, and total pore area showed that soil structure quality was similar in CTT and RTT after the fifth sugarcane harvesting. Those results are consistent with recent studies, such as Barbosa et al. (2019) and Tabriz et al. (2021), who reported that conventional tillage did not bring additional benefits to alleviate soil compaction in sugarcane fields and thus can be replaced by reduced tillage. The latter disturbs around 13% of the soil surface area in planting furrows (Tenelli et al., 2019), showing similar effects in CTT and RTT in planting furrows. Conventional tillage has negative effects on soil structure in sugarcane fields (Barbosa et al., 2019), since the soil mobilization causes a reduction in total porosity (Cavalcanti et al., 2020), disrupting the continuity or narrowing pore size and distribution (Lucas et al., 2019), breaking up soil macroaggregates, modifying the environment to microorganisms and increasing soil organic carbon losses through soil organic matter oxidation (Oliveira et al., 2017; Tenelli et al., 2019). In addition, conventional tillage makes the soil structure more susceptible to soil re-compaction. Although conventional tillage continues to be used in sugarcane production systems to alleviate soil compaction before planting our data support that reduced tillage is a viable alternative compared to the conventional tillage at the fourth ratoon cycle.

Although reduced tillage in sugarcane fields has reportedly numerous advantages in provisioning of ecosystems services such as enhancing soil carbon contents (Segnini et al., 2013; Tenelli et al., 2019), lowering soil disturbance and greenhouse gas emissions (Halpin et al., 2015), and improving soil hydro-physical functioning (Martíni et al., 2021), the reduced tillage as one isolate management practice is not able to improve soil structure quality over time. Not only in a reduced tillage practice but also in all tillage practices, soil structure is dependent on present and past compaction intensity (Boizard et al., 2013), and in sugarcane fields the stress applied by transloaders and harvesters can be greater than 800 kPa at the superficial layers (Jimenez et al., 2021b) due to excessive load of machines, high inflation pressure and small tire-soil contact area (Guimarães Júnnyor et al., 2019). Those factors make load pressure capable of exceeding the load support bearing capacity of most soils, which promotes short-term impacts in soil structure by reducing total and macroporosity (Reichert et al., 2016). The overall VESS scores in RTT, ranging from 3.6 and 4.1, indicated that the creation of traffic-free zones (i.e., seedbeds) are essential to support soil structure in this treatment. Recent studies have indicated that traffic control practices are extremely necessary to minimize superficial soil compaction in sugarcane fields (Techen et al., 2020; Toledo et al., 2021). However, a strategy ensemble is required to properly implement a seedbed zone and traffic control management in the field, including the use of autopilot (Esteban et al., 2020), widening harvester tracks, high-flotation tires with adequate inflation pressure (Guimarães Júnnyor et al., 2019), and adjusting crop spacing based on machinery track width (Sousa et al., 2019).

Our results showed that random traffic was the main factor that changed the shape and size of the soil porosity. The arrangement of microaggregates results in the formation of packing and complex pores that result in higher macroporosity in Oxisols (Juhász et al., 2007). However, the pore area was changed by tillage and machinery traffic in CTT and machinery traffic in RTT (Fig. 6). The total pore area found in RTN is similar to the total pore area found by Canisares et al. (2019) in native vegetation in the same region. Therefore, the smaller amount of large and complex pores as well as the total pore area found in CTT and RTT as compared to RTN, showed the negative influence of tillage (CTT) and machinery traffic (CTT and RTT) in the soil structure in the 0-12 cm soil layer. Along with soil porosity reduction soil compaction create large elongate pores in a horizontal preferred orientation (Murphy et al., 1977). Although the small variation in elongated pores among CTT, RTT, and RTN, there was large amount of small and medium pores in CTT and RTT than RTN (Fig. 6), which could be a result of mechanical stresses, as reported by Reis et al. (2021).

The RTN treatment showed a potential to recover soil structure functioning on the surface layer (Fig. 6e; Fig. 7e). After five years without tillage and machinery traffic (Fig. 1), RTN increased the total pore area (Fig. 6e) in the 0-12 cm soil layer and reduced the VESS Sq in the naturally formed first layer (Fig. 2b). The higher complex porosity found in RTN (Fig. 6e, Table 1) can be attributed to faunal (Fig. 3, Fig. 7e) and root activity (Barbosa et al., 2021). In addition, the large pores could be the result of more sugarcane root development on the surface layer (Barbosa et al., 2021). The root development reorganizes the spatial arrangements of soil particles (Lucas et al., 2019) that change the structural pores and create a functional porous system (Gonçalves et al., 2014). In an environment without soil compaction, the persistence of existing pores would improve their continuity in the soil profile (Carof et al., 2007; Alvarez et al., 2018), which results in higher pore connectivity (Fig. 7e), complex packing pores, and air permeability, as well as in the development of microstructure with strong pedality in RTN (Table 1). Therefore, the creation of traffic-free zones provides the conservation of the soil structure, especially in the regions with the highest proportion of plant roots (i.e., 0-10 cm soil layer close to the planting row), which may contribute to the increase of sugarcane productivity (Sousa et al., 2019). However, VESS Sq above 3 in RTN (e.g., 10-25 cm soil layer) and similar total pore area among the treatments in the 12-24 cm soil layer occur due to the tillage practices (e.g., soil tillage and machinery traffic; Fig. 1) adopted before the establishment of RTN treatment in the trial area. In addition, an uniformity in soil matrix composition (Tables 1 and 2) and pore shape (Figs. 6a, b) as well as total pore area (Fig. 6) found in both soil layers can be associated with the subsoiling process (Pires et al., 2017; Galdos et al., 2019) in the CTT treatment.

The VESS Sq (Figs. 2a, 2b) and total pore area found in RTN treatment in the 0-12 cm soil layer (Fig. 6e) are related with soil resilience, which occurs because clayey soils are more resilient than other soils (Corstanje et al., 2015; Bonetti et al., 2017; Obour and Ugarte, 2021), and can recover their initial state of aggregation upon disturbance by tillage and machinery traffic. In a study performed by Bonetti et al. (2017), an Oxisol cultivated under no-tillage was able to recover from soil disturbance and compaction after three wetting-drying cycles. The authors found that total porosity and macroporosity recovered initial values after the cycles. However, the soil will respond differently when subjected to wetting-drying cycles under contrasting tillage practices (Oliveira et al., 2021), such as conventional and reduced tillage practices. Therefore, the reduction of tillage and random traffic are extrinsic practices that can promote soil resilience (Boizard et al., 2013) due to increases in soil organic matter (Figueiredo et al., 2015), biological activity (Galdos et al., 2019; Tenelli et al., 2019), root biomass (Barbosa et al., 2021), and biopores (Lucas et al., 2019).

4.4.2. A diversity of methods used to describe soil structure changes

Although the wet sieving procedure is widely accepted as a standard method to measure the soil aggregate stability (Liu et al., 2021), it was not sensitive to detect alterations in the soil structure (Fig. 4). This result indicates that soil structure evaluation should be made by either using different energy in the sieving or using multiple methods (Pulido Moncada et al., 2015). A diversity of assessment scales is fundamental to provide a more comprehensive evaluation of soil structure changes. Relations among the different scales, measurement methods, analysis features, and their relationship with soil functions are shown in Fig. 8. Globally, there is a tendency to use methods that allow faster, more practical and cheaper evaluation of soil structure (Franco et al., 2019) and soil health (as a whole) (Bünemann et al., 2018). Our data support that VESS can be used directly in the field to have a fast and suitable diagnosis of soil structural quality to root growth in sugarcane areas, corroborating previous results of Cherubin et al. (2017), Castioni et al. (2018), and Cavalcanti et al. (2020). In addition, the VESS allowed detecting biologic activity (e.g., macrofauna community) (Fig. 3), which corroborated with results found by Franco et al. (2017) and Demetrio et al. (2022). However, as a practical on-farm method, the VESS was not developed to evaluate the distribution and functionality of the soil porosity (Fig. 8). On the other hand, determination of 2D micro-morphometric analysis is high-time consuming and accounts for a small soil sample but its indicators are complex with higher detailing level that represents a higher number of soil functions, e.g., plant growth, physical stability and support, water retention and soil aeration, and habitat for biological activity (Fig. 8). According to Rabot et al. (2018), 2D micro-morphometric analysis was considered efficient in characterizing soil structure due to its relationships with a wide range of soil functions.

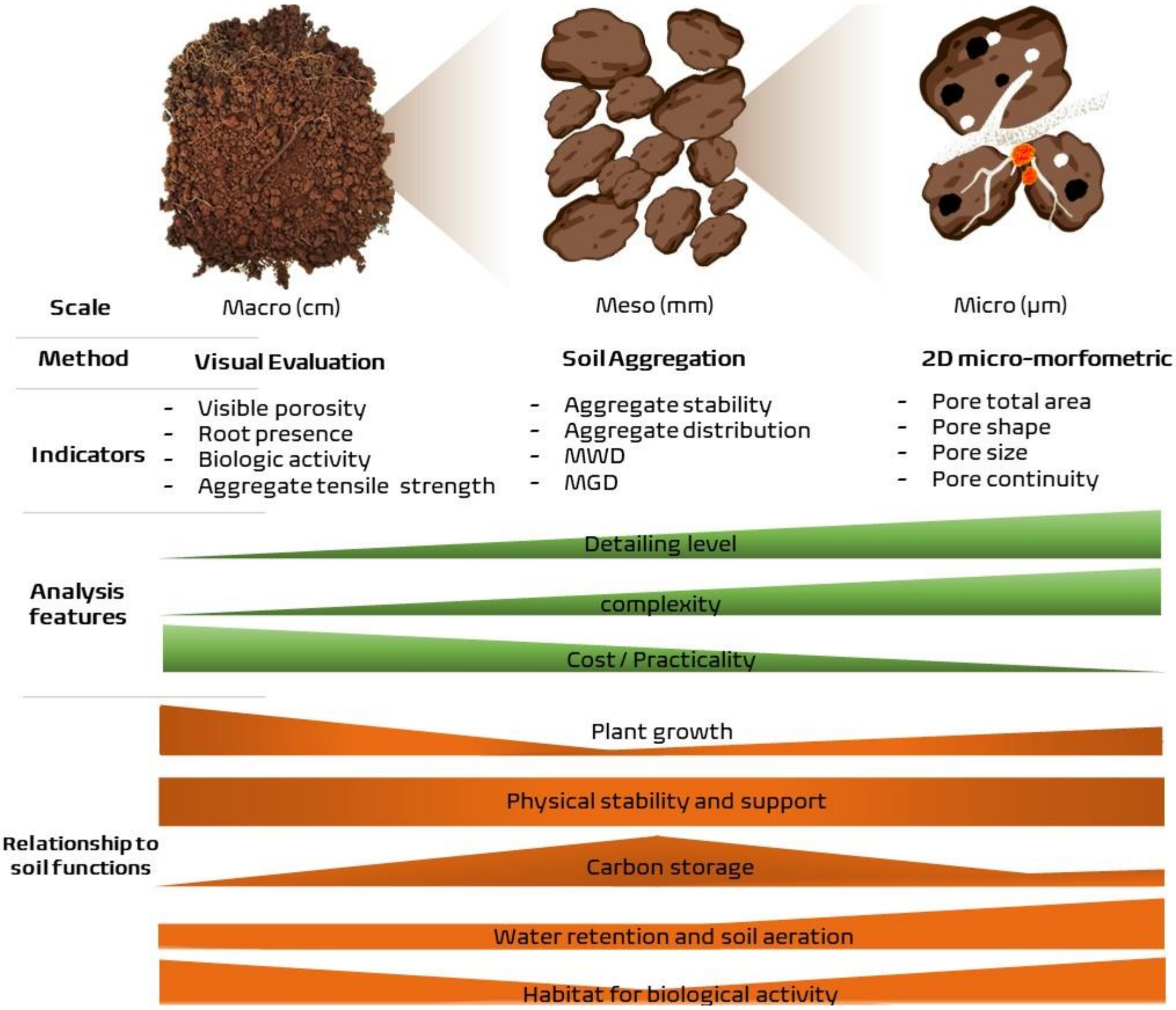


Figure 8. A diversity of methods (macro-, meso-, and micro-scales) for assessing soil structure and the relationships among scales, methods, indicators, analysis features, and soil functions. MWD: mean weight diameter, MGD: mean geometric diameter. The bar thickness represents high (thick bar) and low (thin bar) relationship between the scale/methodologies with analysis features (in green) and soil functions (in brown).

Our findings show high convergence between VESS and micro-morphometric method, despite the contrasting scale and level of details in the methods. This indicates that the macro-scale criteria used in the visual evaluation reflected in somehow the micro-scale feature of the soil structure. Even though the VESS assessment does not allow a complete pore network analysis (Fig. 8), the structural porosity of the soil is related to the boundaries and weakness planes of its aggregates. This could explain the relationship between complex pores and VESS scores observed in RTN (Fig. 2b; Fig. 7e). Therefore, our results are according to Bullock et al. (1985), who highlighted that combined field and micromorphological descriptions are advisable. Soil tillage practices that prioritize the minimum soil disturbance (e.g. RTN) associated with cumulative crop residues and diversified cropping systems, usually result in lower VESS Sq (Tormena et al., 2016; Tuchtenhagen et al., 2018; Demetrio et al., 2022). This is likely related to the greater exploration of roots in the soil (Fig. 3d), which results in different patterns of pores in the soil and bonding of primary particles forming aggregated units. Thus, in these conditions are found fewer aggregates with diameter > 1 cm and higher porosity. Those aspects were found in RTN treatment (Fig. 2).

The most common sugarcane cultivation system in Brazil consists of a five-year cycle with annual harvests (Luz et al., 2020). The stalks gathered in the first harvest are from the planted sugarcane cuttings, whereas subsequent harvest gather stalks regrow from sprouts. Therefore, sugarcane field is renewed once every five years, when a new cycle is established. The main reasons for sugarcane renewal are associated with yield reduction and soil compaction over the cycles (Li et al., 2020). The assessment of soil structure at the different scales showed that RTN treatment had the potential to make the sugarcane yield more stable (Barbosa et al., 2021) and consequently it could extend the cultivation cycle (longevity) to six or more years. It represents a significant reduction of production costs (Martins et al., 2021; Amorim et al., 2022). In addition, the presence of excrements (Table 1, Fig. 5) and higher pore area (Fig. 7) found in RTN treatment are associated with carbon accumulation (Tenelli et al., 2019), which in turn provides enhanced stability to the pore walls and also contributes to mitigate greenhouse gas emissions (from the soil and fossil fuel combustion) (Bordonal et al., 2018). Furthermore, beyond RTN treatment improves soil functions related to carbon storage (Tenelli et al., 2019) and physical stability and support (Barbosa et al., 2019; Barbosa et al., 2021), this treatment has potential to increase other critical soil functions such as plant growth and production of biomass (Barbosa et al., 2021), water retention and soil aeration (Luz et al., 2022), and habitat for a myriad of organisms (Fig. 3).

4.5. Conclusion

After the fourth cycle of sugarcane ratoon, conventional tillage and reduced tillage resulted in similar soil structure conditions and functioning, regardless of the soil structure assessment scales. Based on that, conventional tillage did not bring additional benefits in alleviating soil compaction compared to reduced tillage in this field experiment. However, the adoption of reduced tillage by itself was not able to improve soil structure. In sugarcane fields under a reduced tillage practice, the preservation and/or recovery of soil structure is conditioned by the additional adoption of seedbeds (i.e., traffic-free zones).

A diversity of assessment scales showed that different methods and scales are related to specific soil functions and have a distinct objective, however, a diversity of assessment scales is an advisable strategy to assess the soil structure quality. The aggregate stability by wet sieving was not sensitive enough to detect alterations among treatments. The VESS assessment was practical, sensitive, and had a fast and suitable diagnosis of soil structure in the field. Lastly, the 2D micro-morphometric analysis allowed a higher detailing level of soil structure which represents a larger number of processes and soil functions.

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5. LONG-TERM CONTROLLED TRAFFIC FARMING MAINTAINS SOIL PHYSICAL FUNCTIONALITY IN SUGARCANE FIELDS [4]

Abstract

The disorderly machinery traffic has been one of the main causes of soil physical degradation in sugarcane fields. In this sense, the adoption of strategies for field traffic control has been a viable alternative to reduce the risk of soil compaction and minimize physical restrictions to plant growth. However, the impact of traffic control on soil physical properties is still unknown in sugarcane fields. In this study, we investigated the impacts of agricultural traffic control on soil physical properties and functions under contrasting soil textures (clayey and sandy clay), assessed at row and inter-row sugarcane planting positions. Bulk density, soil porosity, soil penetration resistance, the weighted average diameter of aggregates, in addition to visual assessment of soil structure (VESS), were measured and integrated into a soil physical quality index (SPQI) for the assessment of the following soil functions: root growth support, ability to resist erosion and physical degradation, water supply for plants, edaphic fauna, and its relationship with the exchange of gases between soil and atmosphere. The results revealed that uncontrolled traffic farming increased bulk density, soil penetration resistance, and VESS scores as well as reduced total porosity mainly in the 0-10 cm soil layer. Controlled field traffic supported soil functions in relation to uncontrolled traffic. Uncontrolled traffic caused a reduction by 12% on the SPQI at row position in both clayey and sandy clay soils, whereas for inter-row position, no difference was observed between controlled and uncontrolled traffic. Controlled traffic in sugarcane fields was able to reduce soil physical degradation induced by agricultural field traffic, whose mitigation of compaction occurs mainly at row-position. These results suggest that controlled traffic may be a strategy to reduce soil physical restrictions for root growth, supporting structural stability and soil functions related to the flow of water and gases.

Keywords: Soil physical quality index, Soil functions, Soil compaction, Soil structure

5.1. Introduction

Brazil is the major and influential global player in sugarcane production (Hughes et al., 2020), accounting for 39% of world production (FAO, 2019). As sugarcane is a semi-perennial crop, the cumulative compaction by mechanized operations (e.g., disordered traffic at harvesting events) (Guimarães Júnnyor et al., 2019; Jimenez et al., 2021) is considered the primary cause of the loss of soil's ability to sustain its essential physical functions (Cherubin et al., 2016; Keller et al., 2022), able to reduce sugarcane yield not only in Brazil (Dias and Sentelhas, 2018) but also worldwide (Tweddle et al., 2021). Consequently, the yield decline due to soil compaction has accelerated the needed for sugarcane re-planting over a shorter cultivation time (Bernardo et al., 2019).

Controlled traffic and permanent seedbed positions can offer an opportunity to physically separate wheel zones from row cultivation positions without harming yield, which can be an interesting strategy for the sustainability of mechanized farming in sugarcane fields (McHugh et al., 2009; Mouazen and Palmqvist, 2015). The concept of controlled traffic involves either the matching of crop row spacing with

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equipment track width or having crop row spacing as a multiple of track width, which ensures that all traffic always occurs in the same position (Braunack and McGarry, 2006), keeping a proportion of soil spacing that is not impacted by traffic (McPhee et al., 2020). Traffic lanes are concentrated in permanent zones that according to the row spacing (150 cm), establish 70 cm for wheeling, and traffic-free seedbed zones of 80 cm. The way wheel zones remain in the same place for all crop cycles (i.e., 5 or 6 ratoons), creating untrafficked positions across the field (Esteban et al., 2020; Barbosa et al., 2021).

Due to soil compaction, plant roots are exposed to a multi-stress environment, including higher soil resistance to penetration, lower air capacity, and lower water storage and availability (Colombi and Keller, 2019). In this sense, the diagnosis of compaction in sugarcane fields has been made traditionally by verification of soil physical indicators such as bulk density (Jimenez et al., 2021), pore distribution (Cavalcanti et al., 2020; Luz et al., 2020), aggregate stability (Castioni et al., 2018), soil penetration resistance (Barbosa et al., 2019), and Visual Evaluation of Soil Structure – VESS (Ward et al., 2021; Luz et al., 2022). However, soil compaction can impair other soil functions such as the ability to resist erosion and physical degradation and their related ecosystem services such as water purification and regulation (Vogel et al., 2018; Adhikari and Hartemink, 2016). Therefore, soil functionality can be measured by an integrated approach of soil physical indicators that provides a soil physical quality index (Cherubin et al., 2016; Cavalcanti et al., 2020).

Recent studies related to controlled traffic in sugarcane fields focused on isolated physical indicators such as bulk density and soil porosity (Esteban et al., 2019), soil penetration resistance (Barbosa et al., 2021), compression index (Sousa et al., 2019), and tensile strength (Esteban et al., 2020). Those studies did not provide a comprehensive response of controlled traffic adoption on soil physical functions such as the ability to resist erosion and physical degradation and supplying water for plants and edaphic fauna in soils with contrasting textures. Thus, we carry out a study to measure the impacts of controlled traffic farming adoption on the physical functionality of soils with contrasting textures (clayey and sandy clay) in central-southern Brazil. Our hypothesis is that controlled traffic over the years creates permanent compaction wheeling, improving soil biological activity and increasing structural stability and soil functions related to the flow of water and gases, and supporting root growth under untrafficked zones compared to random traffic farming.

5.2. Material and Methods

5.2.1. Study sites and experimental design

The study was carried out in a commercial sugarcane field located in the Lençóis Paulista region, São Paulo state (22°29' S and 48°47' W), central-southern of Brazil. This area of study has adopted controlled traffic farming (CTF) in soils of contrasting textures since 2012. To compare the CTF and random traffic farming (RTF) were selected adjacent areas under the RTF system with the same textural class (Clayey and Sandy Clay soils). The description of the climate, soil classification, and soil particle size distribution is presented in Table 1. On the experimental sites, sugarcane has been cultivated since 1970 in both soils. The last sugarcane re-planting occurred six and five years before the soil sampling in Clayey soil and Sandy clay soil respectively. Soil tillage was characterized by cross subsoiling with a subsoiler at 40 cm depth and light hydraulic harrowing at 20 cm depth in all areas. Sugarcane planting furrows were opened at 30 cm depth using a two-row planter with a spacing of 150 cm. The planting was carried out manually in Clayey soil and mechanically in Sandy clay soil. In the bottom planting furrow, fertilizers were applied according to the crop nutritional requirement, following the recommendations described by van Raij et al. (1997). In Clayey soil, vinasse was applied at an amount of 120 m^3 ha^{-1} every year after the first harvest.

The CTF was characterized by the adoption of GPS in planting (Sandy clay soil) and harvesting. The harvester (Model A8810) was characterized by treadmill wheels of 47 cm in width, the track width of 190 cm, and a total mass of 18.5 Mg. Sugarcane stalks were transported in a wagon truck model ATR 216X 6 × 4 by Grunner® with 17.5 Mg weight, a wheel size of 300 cm, 405/70R20, and 400/70R20 high flotation in front and rear tires, respectively, and the capacity to transport 16 Mg of sugarcane. Both harvester and truck worked using an automatic steering system with permanent traffic lines at the inter-row center. In RTF, the harvesting was done with a similar harvester, however, the stalks were transported in wagons pulled by a tractor (model 6190M). The wagons weighed 9.5 Mg, had a track width of 240 cm, 600/50 x 22.5 tires, and had a capacity to transport 16 Mg of sugarcane. The tractor weighed 14 Mg, track width of 270 cm, 600/60-30.5 front tires, and 710/70 R38 rear tires. All operations were done without an automatic steering system in RTF.

Table 1. Climate and soil characterization of experimental location in Lençóis Paulista, state of São Paulo, Brazil.

Description	Clayey soil		Sandy clay soil	
	CTF	RTF	CTF	RTF
Elevation (m)	550	550	550	550
Mean annual rainfall (mm)	1230	1230	1230	1230
Mean annual temperature (°C)	21.8	21.8	21.8	21.8
Climate	Cwa	Cwa	Cwa	Cwa
Previous land use	Pasture	Pasture	Pasture	Pasture
Last sugarcane renewal	2013	2013	2014	2014
Sugarcane variety	RB96 6928	RB96 6928	CTC 16	RB96 6928
Soil classification	Oxisol	Oxisol	Ultisol	Ultisol
Clay/silt/sand (g kg^{-1})				
0-10 cm	533/67/402	617/83/301	281/151/569	300/172/528
10-20 cm	525/56/426	619/97/284	311/141/550	360/97/545
20-40 cm	575/69/359	644/94/264	381/97/529	379/103/519
Fertilizer inputs	Mineral + organic	Mineral + organic	Mineral	Mineral

Cwa: humid subtropical climate characterized by dry winter and hot summer

5.2.2. Sampling and soil physical measurements

Soil sampling was carried out at the fifth and fourth ratoon cycle in Clayey and Sandy clay soils respectively in 2018. The sampling consisted of four sample points spaced 50 m apart in each field (with and without traffic control). Undisturbed soil cores using cylindrical rings of ~100 cm^3 were collected to measure soil bulk density (BD), total porosity (TP), macroporosity (MaP), microporosity (MiP), and soil penetration resistance (SPR). A soil block (10 × 10 × 10 cm) was collected to measure aggregate stability by mean weight diameter (MWD). Besides that, disturbed soil samples were collected to measure the soil organic carbon (SOC). All samples were taken from the center of soil layers 0-10, 10-20, and 20-40 cm on trenches opened crosswise the cultivation row, from the center to the middle of the seedbed (i.e., at row and inter-row positions). Each trench had a dimension of 150 × 40 cm (width x depth). Considering the two sites, a total of 96 samples were taken (i.e., 2 farming systems × 4 repetitions × 2 sampling positions × 3 soil layers).

The undisturbed soil cores were saturated with water by capillarity for 48 h and subjected to a water tension of 0.006 MPa using a table tension. After samples reached the hydraulic equilibrium, they were weighted to determine water content and subjected to SPR measurement using an electronic penetrometer with a 4-mm diameter cone, 30° of angle tip, and a constant penetration speed of 10 mm s^{-1}. After SPR determination, the soil samples were oven-dried at 105 C for 48 h to quantify the BD according to Grossman and Reinsch (2002). The MiP was estimated as the water content retained at 0.006 MPa. TP was determined by using BD and 2.65 Mg m^{-3} as the value of particle density: TP = 1- (BD/2.65). The MaP was determined by the difference between TP and MiP.

For the evaluation of MWD, the samples were passed through an 8-mm sieve by manually breaking up the soil along natural planes of weakness and then air-dried. Then, soil samples were rewetted for sixteen hours and wet sieved in a vertical Yoder-type sieve column at a speed of 30 cycles/ min for 10 minutes following an adapted method from Elliott (1986). The soil was separated into the following classes: I - (8.0 – 2.0 mm), II - (2.0 – 0.250 mm), and III - (0.250 – 0.053 mm). The content of each sieve was dried and then weighted. The MWD of water-stable aggregates was calculated according to Equation 1:

$$MWD = \sum_{i=1}^{n} WiXi \qquad (1)$$

where *Wi* is the proportional weight of the corresponding size fraction and *Xi* is the mean diameter of each size fraction.

For SOC analysis, the samples were air-dried, passed through a 0.150 mm sieve, and then analyzed by dry combustion using a carbon analyzer – LECO CN 628.

In the field, the Visual Evaluation of Soil Structure (VESS) was performed according to Guimarães et al. (2011). An undisturbed soil sample (25 cm depth × 20 cm wide × 10 cm thick) was collected in both row and inter-row positions (totaling 32 samples) using a shovel. The assessment included identification of contrasting soil layers, measurement of soil layer thickness, a manual breakdown of soil aggregates along their fracture planes for identification of the main structural units (i.e., shape, size, visible porosity, and tensile strength of soil aggregates), verification of root distribution and biological activity, and fragmentation of some aggregates higher than 2 cm. A structural quality score (Sq) was assigned according to Guimarães et al. (2011).

An individual Sq was assigned for each layer and an overall weighted Sq was calculated for each sample based on the individual Sq and thickness of each contrasting soil layer as shown in Equation 2:

$$\text{VESS Sq} = \sum_{i=1}^{n} \frac{\text{SqiTi}}{\text{TT}} \tag{2}$$

where VESS Sq is the overall VESS score, *Sqi* and *Ti* are respectively the score and thickness of each identified soil layer, and *TT* is the total thickness of the soil sample.

In addition, the weighted average of VESS Sq was calculated for 0-10 and 10-25 cm soil layers according to Cherubin et al. (2017). The VESS Sq ranges from 1 to 5 in which lower VESS Sq (1 and 2) indicates good soil structure quality due to the presence of roots, high porosity, and aggregates with lower tensile strength. The higher VESS Sq (4 and 5) indicates poor soil structure quality because of the absence of roots, low porosity, and aggregates with higher tensile strength. In addition, the Sq = 3 was considered a threshold of soil structure quality. The Sq ≥ 3 means that soil structural quality begins to decline (Guimarães et al., 2011).

In the field, the soil moisture was quantified using the sensor H2-12 Decagon Devices© in all soil layers. Mean, maximum, and minimum values of soil moisture and soil organic carbon (SOC) are presented in Table S1.

In all soil layers, soil monoliths of 25 × 25 cm were collected at the row position for the quantification of earthworm abundance according to Anderson and Ingram (1993). In the laboratory, earthworms were manually separated from the soil and stored in 70% alcohol for subsequent counting. The earthworm abundance was calculated as the number of individuals per m^2.

5.2.3. Soil physical quality index - SPQI

The effects of CTF and RTF on soil physical quality were assessed by an overall SPQI according to Cherubin et al. (2016). To perform an overall evaluation for 0-40 cm soil layer, soil indicators from the 0-10, 10-20, and 20-40 cm layers were grouped to an average value for each physical indicator. A three-step procedure: selection of indicators, interpretation of selected indicators, and integration of soil physical indicators were adopted. In the first step, appropriate soil physical indicators were selected to represent four soil physical functions: *f(i)* support root growth, *f(ii)* ability to resist erosion and physical degradation, *f(iii)* supply water for plants and edaphic fauna, and *f(iv)* allow gases exchange between soil and atmosphere. Based on the published literature and author experience, a set of seven indicators were selected from our dataset to compose the index: *f(i)* – BD and VESS, *f(ii)* – MWD and SOC, *f(iii)* – MiP and soil moisture, and *f(iv)* – MaP. In the second step, a linear procedure was used to transform the indicators into unitless values ranging from 0 to 1 (Andrews et al., 2002). The indicators were ranked in ascending or descending order depending on whether a higher value was considered "good" or "bad" in terms of each soil function. For "more is better" indicators, such as MWD, SOC, MiP, soil moisture, and MaP, each observation was divided by the highest observed value, such that the highest value received a score of 1. For "less is better" indicators, such as BD and VESS, the lowest observed value received a score of 1. In the third step, the transformed values were combined into the SPQI by multiplying the scores of each indicator by the function weight (Equation 3).

$$SPQI = \sum f(\text{scores})\ W \qquad (3)$$

where SPQI is the soil physical quality index, f(scores) is the scores obtained for each soil physical function, and W is the weight (i.e., 0.25) of each soil physical function.

5.2.4. Statistical analysis

The analysis of variance (ANOVA) was calculated through the PROC GLM (SAS) routine to test farming systems (CTF and RTF) effects on BD, TP, MiP, MaP, SPR, MWD, VESS, soil functions, and SPQI within each soil texture (clayey and Sandy clay) and position (row and inter-row). When the values of the ANOVA results were significant ($p < 0.05$), the means were separated using T-test ($p < 0.05$). The correlation between soil physical indicators was performed based on Pearson's correlation coefficients. A regression analysis was performed to explore the relationship between SPQI and earthworm abundance. All statistical procedures were performed using Statistical Analysis System—SAS 9.3 software (SAS Inc., Cary, NC, USA).

5.3. Results

In the Clayey soil, the BD values varied from 1.26 Mg m^{-3} to 1.56 Mg m^{-3}. The higher BD was verified in RTF in relation to CTF at both positions (i.e., row and inter-row) at the 0-10 cm layer (Fig. 1a, 1b). BD was 6% and 13% higher at row and inter-row positions, respectively, in RTF. However, in the 10-20 and 20-40 cm layers, both CTF and RTF showed similar DB at both positions. The TP was lower under RTF in the 20-40 cm layer at row position (Fig. 1c) and in the 0-10 cm layer at inter-row position (Fig. 1d). In those soil layers, TP was higher under CTF influenced by higher MaP at the row position, and higher MiP at the inter-row position. Although the similar TP between farming systems in other soil layers, the MaP was higher under CTF in 10-20 cm at the row position (Fig. 1c), while MiP was higher under CTF in 0-10 and 10-20 cm soil layers at the inter-row position (Fig. 1d).

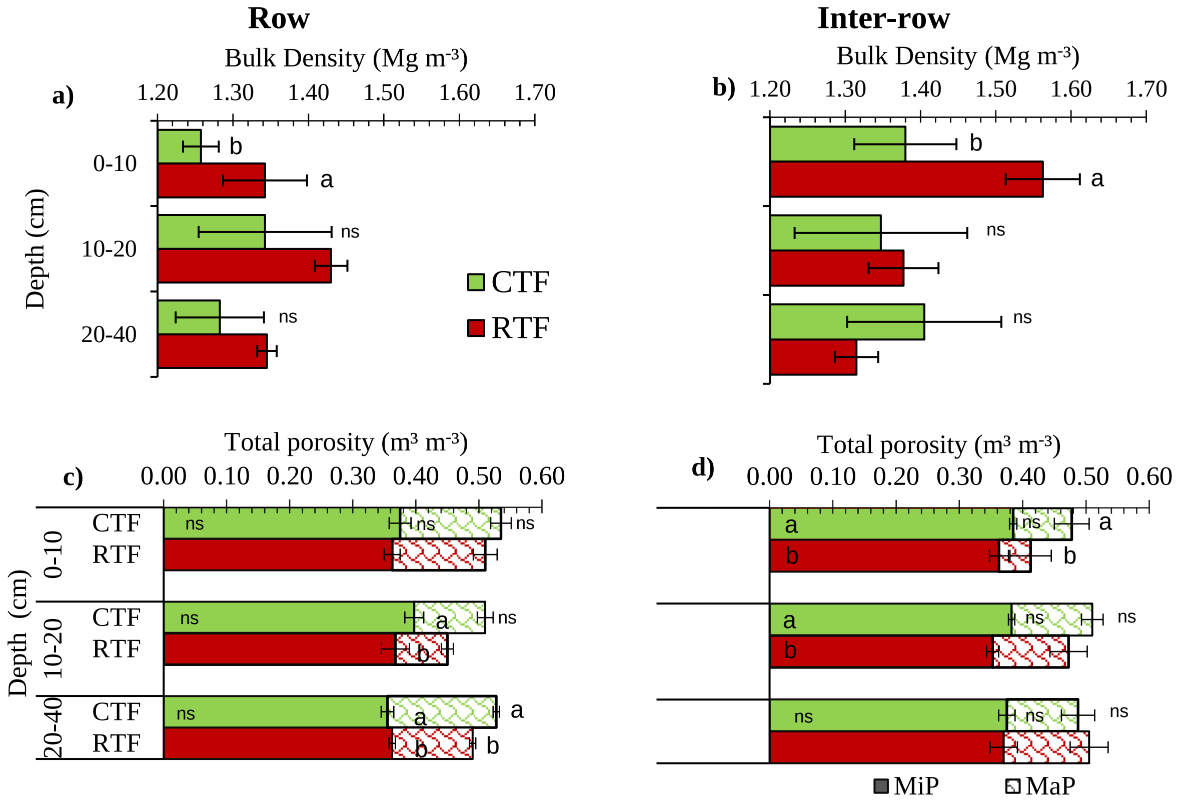

Figure 1. Bulk density – BD (a, b) and Total porosity - TP (MiP= microporosity, MaP= macroporosity) (c, d) from 0-10, 10-20, and 20-40 cm layers at the row (a, c) and inter-row (b, d) positions at **Clayey soil** managed under controlled traffic farming (CTF) and random traffic farming (RTF). * Mean values within each pore-size distribution in the same depth and position (row and inter-row) followed by the same letter do not differ between themselves according to T-test ($p < 0.05$). ^{ns} Not significant. The horizontal bars denote the standard deviation of the mean (n= 4).

In the Sandy clay soil, the BD values varied from 1.38 Mg m^{-3} to 1.83 Mg m^{-3}. The difference between farming systems in BD was evidenced only at the row position in the 0-10 and 20-40 cm soil layers. In those layers, BD was higher under RTF (Fig. 2a), for instance in the 0-10 cm layer, BD was 26% higher in RTF (Fig. 2a) at the row position. On the other hand, BD was higher than 1.65 Mg m^{-3} in both farming systems in all soil layers at the inter-row position (Fig. 2b). RTF reduced TP in the 0-10 and 20-40 cm soil layers at the row position (Fig. 2c). Such results were due to lower MaP and MiP in 0-10 cm soil layer, and lower MiP in 20-40 cm soil layer (Fig. 2c). However, both CTF and RTF showed similar TP at the inter-row position (Fig 2d). Overall, RTF did not change pore distribution at the inter-row position (Fig. 2d).

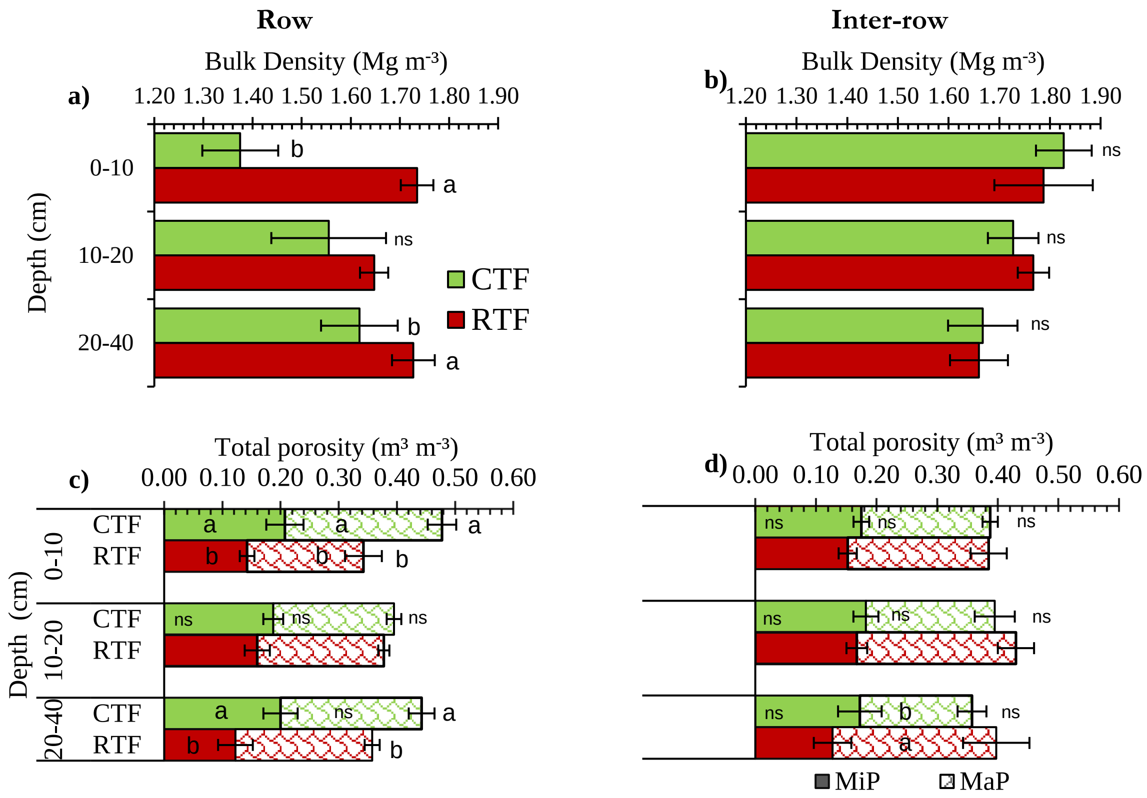

Figure 2. Bulk density - BD (a, b) and Total porosity - TP (MiP= microporosity, MaP= macroporosity) (c, d) from 0-10, 10-20, and 20-40 cm layers at the row (a, c) and inter-row (b, d) positions at **Sandy clay soil** managed under controlled traffic farming (CTF) and random traffic farming (RTF). * Mean values within each pore-size distribution in the same depth and position (row and inter-row) followed by the same letter do not differ between themselves according to T-test ($p < 0.05$). ^{ns} Not significant. The horizontal bars denote the standard deviation of the mean (n= 4).

In Clayey soil, after four years of cultivation RTF did not increase the SPR in the 0-10 and 10-20 cm soil layers at the row position (Fig.3a). However, SPR was higher in RTF in the 20-40 cm soil layer (Fig. 3a). At the inter-row position, RTF showed SPR = 2.1 MPa which was higher than SPR in CTF (1.5 MPa) in the 0-10 cm soil layer (Fig. 3b). At the same position, SPR was higher in CTF (1.55 MPa) than RTF (1.18 MPa) in the 20-40 cm soi layer. RTF altered the MWD only at the row position in the 0-10 cm soil layer. In this layer and position, MWD was lower in RTF (1.2 mm) than in CTF (2.1 mm) (Fig. 3c).

In Sandy clay soil, SPR was lower than 2.0 MPa under CTF at row position in all soil layers. In addition, RTF increased the SPR in 0-10 and 20-40 cm soil layers at the row position (Fig. 4a). Although both farming systems showed SPR higher than 2.0 MPa in all soil layers, at the inter-row position the SPR was higher under RTF than CTF in 0-10 and 20-40 cm soil layers. Concerning the MWD in Sandy clay soil, the RTF did not reduce the aggregate stability in both positions and soil layers (Fig. 4c, Fig. 4d). The MWD values range from 0.6 mm to 1.4 mm in this soil.

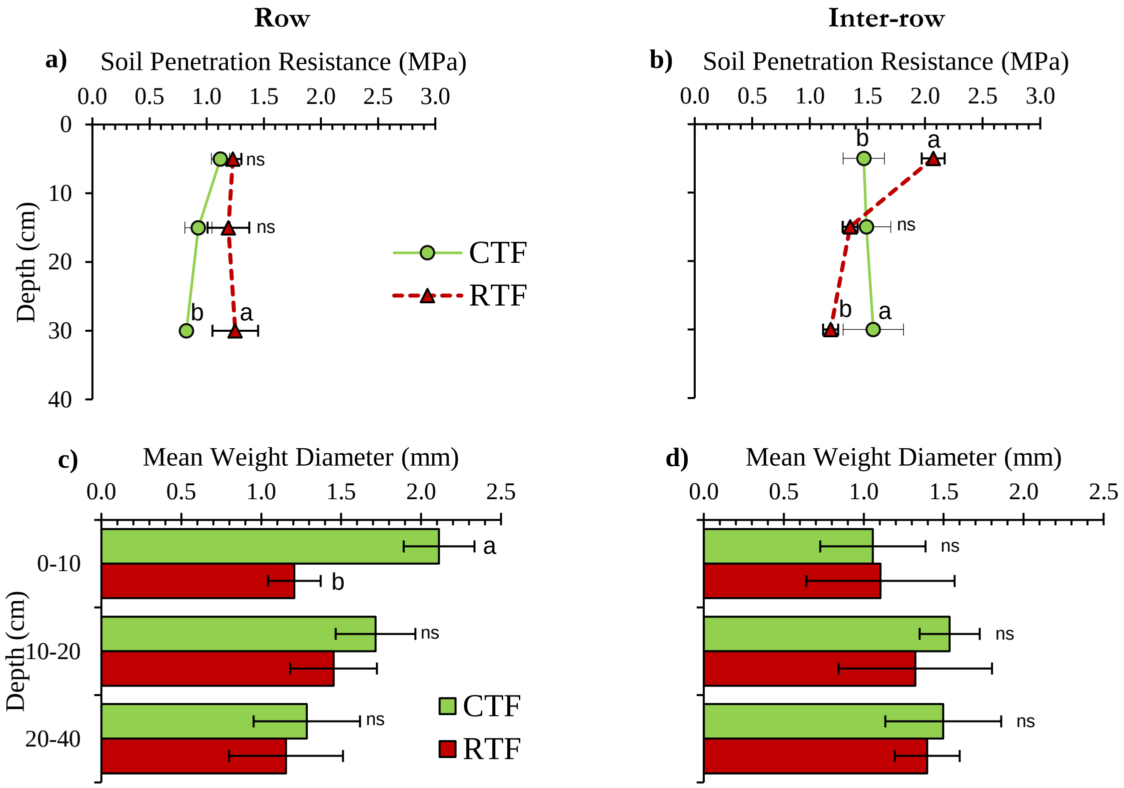

Figure 3. Soil penetration resistance - SPR (a, b) and mean weight diameter - MWD (c, d) from 0-10, 10-20, and 20-40 cm layers at the row (a, c) and inter-row (b, d) positions at **Clayey soil** managed under controlled traffic farming (CTF) and random traffic farming (RTF). * Mean values in the same depth and position (row and inter-row) followed by the same letter do not differ between themselves according to T-test ($p < 0.05$). ^{ns} Not significant. The horizontal bars denote the standard deviation of the mean (n= 4).

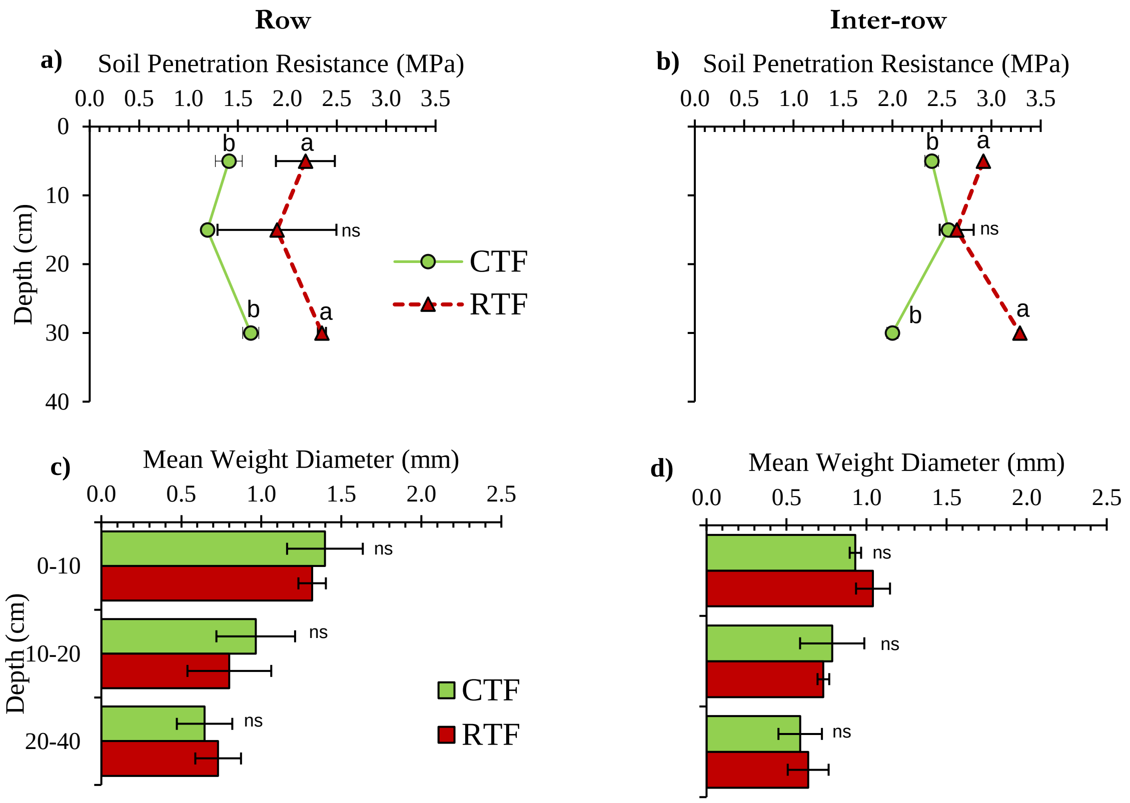

Figure 4. Soil penetration resistance - SPR (a, b) and mean weight diameter - MWD (c, d) from 0-10, 10-20, and 20-40 cm layers at the row (a, c) and inter-row (b, d) positions at **Sandy clay soil** managed under controlled traffic farming (CTF) and random traffic farming (RTF). * Mean values in the same depth and position (row and inter-row) followed by the same letter do not differ between themselves according to T-test ($p < 0.05$). ^{ns} Not significant. The horizontal bars denote the standard deviation of the mean (n= 4).

At the row position, it was verified a VESS sq lower under CTF in both soils (Fig. 5a, 5c). Under this farming system, values of VESS sq were near 2.0. These values were lower than values in RTF which reached 2.5 in 0-10 cm, 10-25 cm, and 0-25 cm (overall) soil layers (Fig 5a, Fig. 5b). However, at the inter-row position, there was a difference between farming systems about the VESS sq only in Sandy Clay soil. In this soil, values of VESS sq were near 2.0 under CTF, meanwhile, VESS sq were either near or higher than 3.0 under RTF in 0-10 cm, 10-25 cm, and 0-25 cm soil layers (Fig. 5d).

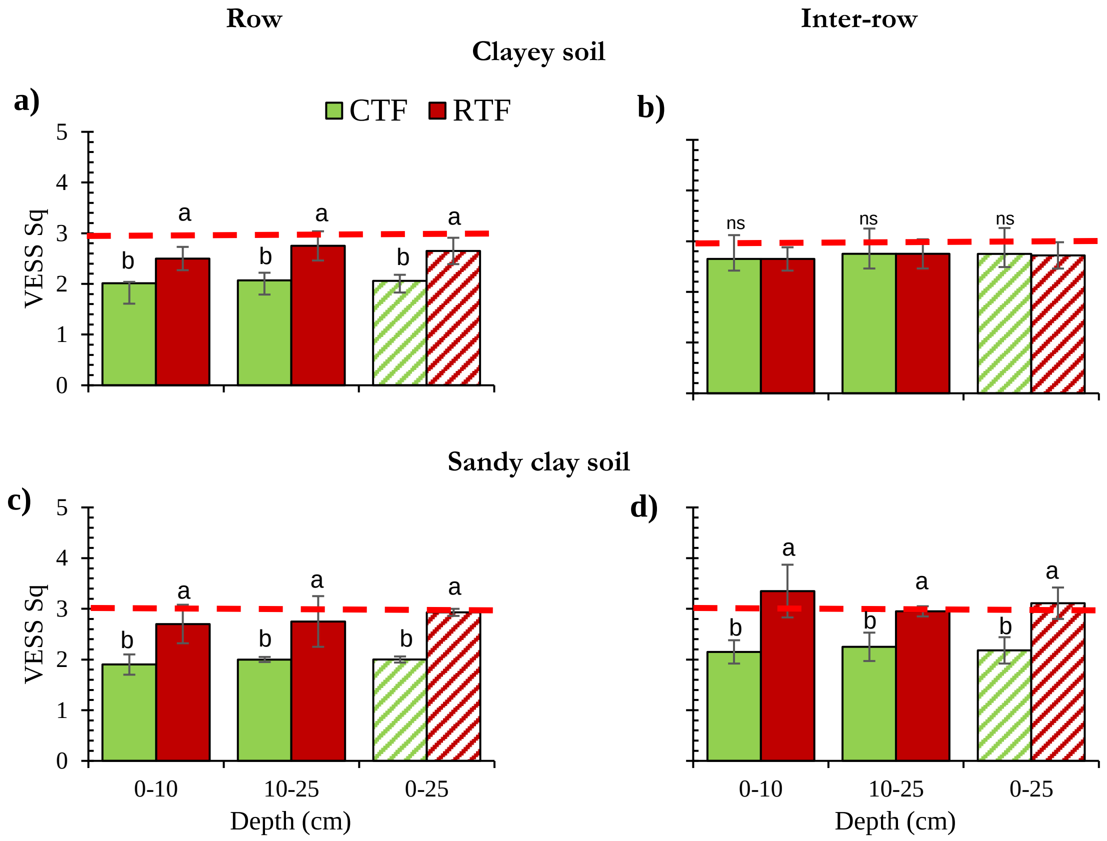

Figure 5. VESS scores from 0-10, 10-25, and 0-25 cm (overall) layers at the row (a, c) and inter-row (b, d) positions at Clayey soil and Sandy clay soil managed under controlled traffic farming (CTF) and random traffic farming (RTF). * Mean values in the same depth and position (row and inter-row) followed by the same letter do not differ between themselves according to T-test ($p < 0.05$). ^{ns} Not significant. The horizontal bars denote the standard deviation of the mean (n= 4). The red dashed line indicates the threshold value for suitable root growth.

A positive correlation was observed between BD and SPR ($p < 0.01$) (0.69 and 0.58 for Clayey and Sandy clay soil, respectively) as well as between BD and VESS ($p < 0.05$) (0.35 and 0.46 for Clayey and Sandy clay soil, respectively) and SPR and VESS ($p < 0.05$) (0.39 and 0.49 for Clayey and Sandy clay soil, respectively) (Table 2). On the other hand, a negative correlation was observed between TP and BD in both Clayey (-0.83) and Sandy clay (-0.39) soils. There was a negative correlation between MWD and BD (-0.31), MWD and SPR (-0.28), MWD and VESS (-0.37), and a positive correlation between MWD and TP (0.31) in Clayey soil. However, there was a correlation only between MWD and SPR (-0.29) in Sandy clay soil (Table 2).

Table 2. Pearson's correlations coefficients and probability of error among soil physical indicators at Clayey soil and Sandy Clay soil managed under controlled traffic farming (CTF) and random traffic farming (RTF).

		BD*	SPR	MaP	MiP	TP	MWD	VESS
					Clayey soil			
BD		1	**0.69^b** <0001	**-0.82** <0001	0.004 0.977	**-0.83** <0001	-0.31 0.033	0.35 0.045
SPR		**0.58** <0001	1	**-0.62** <0001	-0.031 0.833	**-0.64** <0001	-0.28 0.046	0.39 0.028
MaP	**Sandy clay soil**	-0.18 0.222	0.13 0.37	1	-0.24 0.095	**0.75** <0001	0.19 0.184	-0.33 0.058
MiP		**-0.41** 0.004	**-0.53** <.0001	0.08 0.604	1	-0.02 0.919	**0.38** 0.007	-0.29 0.101
TP		**-0.39** 0.006	-0.24 0.098	**0.77** <0001	**0.69** <0001	1	0.31 0.031	-0.21 0.255
MWD		-0.24 0.09	-0.29 0.044	-0.07 0.633	0.12 0.406	0.03 0.854	1	-0.37 0.039
VESS		**0.46** 0.007	**0.49** 0.004	0.07 0.691	**-0.57** 0.0007	-0.24 0.182	-0.16 0.364	1

*Abbreviations: BD – bulk density, SPR – soil penetration resistance, MaP – macroporosity, MiP – microporosity, TP – total porosity, MWD – mean weight diameter, VESS – visual evaluation of soil structure.

^{b} Pearson's correlation coefficients significant ($p < 0.01$) are in bold. n= 48 (BD, SPR, MaP, MiP, TP, MWD), n= 32 (VESS).

The overall scores of each soil physical function and SPQI for both soils are presented in Fig. 6. In Clayey soil, soil functions such as support root growth – *f(i)*, ability to resist erosion and physical degradation – *f(ii)*, supply water for plants and edaphic fauna – *f(iii)* and allow gases exchange between soil and atmosphere – *f(iv)* showed higher scores under CTF which resulted in higher SPQI at the row position. SPQI was 0.84 under CTF and 0.72 under RTF. Although only the function related to supply water for plants and edaphic fauna – *f(iii)*, shows a higher score under CTF, SPQI was higher in this farming system than RTF at the inter-row position in Clayey soil. In Sandy clay soil, RTF reduced soil functions related to supporting root growth – *f(i)*, supplying water for plants and edaphic fauna – *f(iii)*, and allowing gases exchange between soil and atmosphere – *f(iv)* (21%, 22%, 6%, respectively) which resulted in a SPQI= 0.63 at row position. This value was 12% lower than the value found in CTF (0.75). Although CTF showed a higher score in soil functions related to support root growth – *f(i),* the RTF showed a higher score in soil function related to allowing gas exchange between soil and atmosphere – *f(iv).* There was no difference between farming systems in SPQI at the inter-row position in Sandy clay soil. At this position, SPQI was 0.65 in both farming systems (Fig.6).

Soil function	Clayey soil				Sandy clay soil			
	Row		**Inter-row**		**Row**		**Inter-row**	
	CTF	RTF	CTF	RTF	CTF	RTF	CTF	RTF
f(i)	0.95 a*	0.82 b	0.81 ^{ns}	0.80	0.91 a	0.70 b	0.82 a	0.69 b
f(ii)	0.74 a	0.60 b	0.67 ^{ns}	0.60	0.61 ^{ns}	0.63	0.54 ^{ns}	0.58
f(iii)	0.92 a	0.88 b	0.92 a	0.87 b	0.80 a	0.57 b	0.67 ^{ns}	0.60
f(iv)	0.74 a	0.60 b	0.55 ^{ns}	0.50	0.69 a	0.63 b	0.58 b	0.74 a

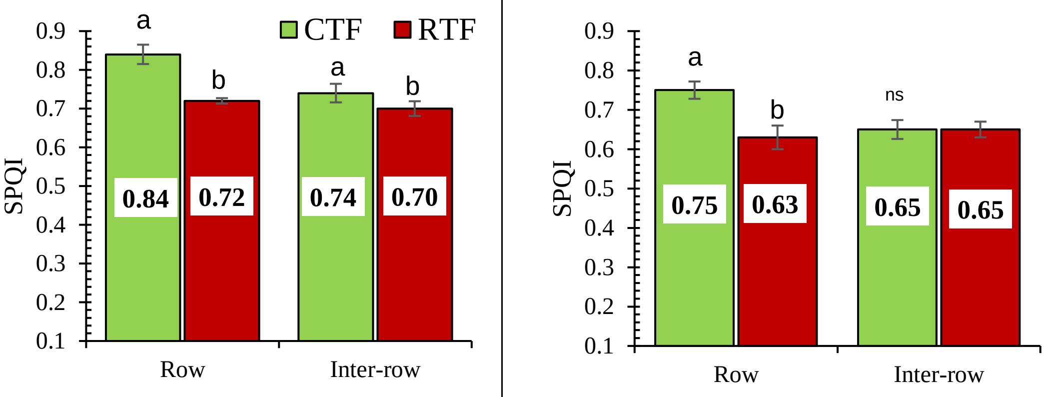

Figure 6. Scores of soil functions (*f(i)*: support root growth, *f(ii)*: ability to resist erosion and physical degradation, *f(iii)*: supply water for plants and edaphic fauna, *f(iv)*: allow gases exchange between soil and atmosphere) and soil physical quality index (SPQI) at 0-40 cm soil depth in rows and inter-rows positions at Clayey soil and Sandy Clay soil managed under controlled traffic farming (CTF) and random traffic farming (RTF). * Mean values within each soil function at the same position (row and inter-row) followed by the same letter do not differ between themselves according to T-test ($p < 0.05$). ^{ns} Not significant. The horizontal bars denote the standard deviation of the mean (n= 4).

A relationship between SPQI and the abundance of earthworms can be seen in Fig. 7. There was a trend of increasing SPQI in function of earthworm abundance increasing. Although Sandy clay soil showed a lower abundance of earthworms than Clayey soil there was an increase in earthworm abundance due to the adoption of CTF in both soils (according to the fitted curve). Therefore, the adoption of CTF supported soil biological activity and consequently, the higher biological activity increased SPQI.

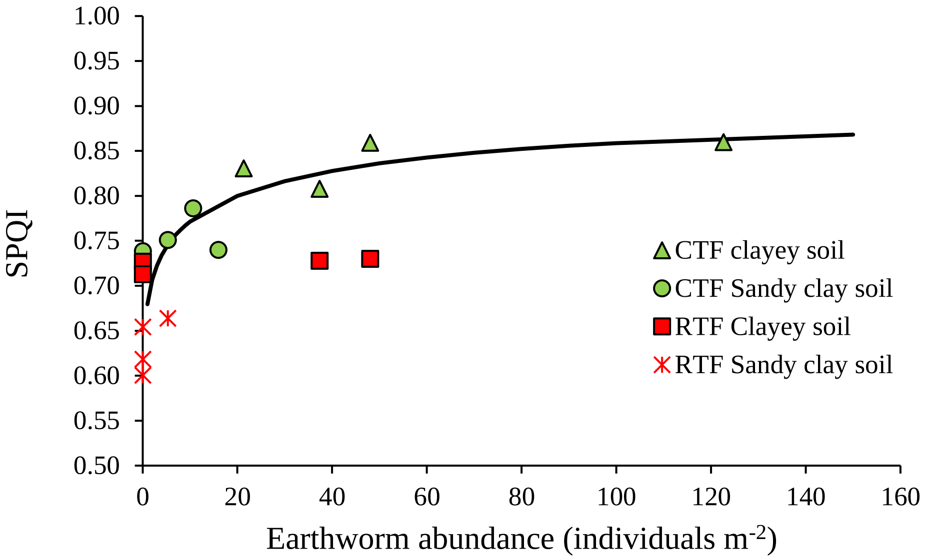

Figure 7. Relationship between soil physical quality index (SPQI) and abundance of earthworm in a Clayey soil and Sandy clay soil managed under controlled traffic farming (CTF) and random traffic farming (RTF). The curve was fitted with dataset from CTF.

5.4. Discussion

5.4.1. Implications of controlled traffic farming on soil physical indicators

There was a trend of better physical quality of both studied soils under CTF than RTF mainly in the 0-10 cm soil layer. In Sandy clay soil, the effect of CTF adoption was more evident at the row position, whereas in Clayey soil, soil physical indicators were beneficiated by CTF at both row and inter-row positions. In the 0-10 cm layer, CTF showed lower BD and VESS Sq at the row position in both soils. Those results are in accordance with results found by Braunack et al. (2006) and Esteban et al. (2019) who highlighted the improvement in soil physical indicators due to the adoption of controlled traffic practices. In the topsoil layer, along with no compaction due to CTF, there is a higher root concentration (Lovera et al., 2021) and biological activity which increase soil organic matter fluxes and consequently accelerate the structural formation and improve soil functionality (Colombi and Keller, 2019). In addition, successive renovation of sugarcane ratoon growth and decomposition of root systems in the row position are beneficial to soil aggregation and the formation of interconnecting biopores (Barbosa et al., 2021). The controlled traffic based on the adjustment of the track width of the tractor-trailer set and the use of an autopilot preserved the soil physical quality (e.g. increased water availability and porosity) in the plant rows and resulted in greater compaction at the inter-row position in a study led by Souza et al. (2014). In addition, in the same experimental area, controlled traffic increased sugarcane root dry mass by 44% (Souza et al., 2015). According to Esteban et al. (2020), the concentration of traffic at the inter-row center by controlled traffic provided high trafficability areas as well as places with better soil physical conditions at the row position.

Although there was a significant correlation between BD and TP (Table 2) there was no difference between CTF and RTF in soil porosity at the row position in Clayey soil. According to a study led by de Lima et al. (2022), total porosity and macroporosity are dependent on the compactness degree and texture. However, the magnitude of those changes is associated with particle size range. In their study, total porosity and macroporosity decrease with increasing compaction, mainly for soils with silt + clay content lower than ~500 g kg^{-1}, while that decreases in response to compaction were substantially reduced for further increase in silt + clay content (>500 g kg^{-1}) due to greater soil aggregation in clayey soils. Therefore, the effect of CTF on soil porosity at the row position was higher in Sandy clay soil (Fig. 2c). In addition, values of BD (e.g., higher than 1.7 Mg m^{-3}) (Fig. 2a, 2b), SPR (e.g., higher than 2.0 MPa) (Fig. 4a, 4b), and VESS Sq either near or higher than the threshold of 3.0 (Fig. 5c, 5d) under RTF could limit root elongation at row and inter-row position in Sandy clay soil. In soil with similar texture, Braunack and McGarry (2006) found greater soil bulk density and penetration resistance under random traffic compared to controlled traffic.

The result of MWD found under CTF in 0-10 cm soil layer (Fig. 3c) indicated a better soil structure under controlled traffic at the row position. This finding is associated with the capacity of clayey soil to reorganize primary particles in secondary unities influenced by the highest soil root volume, and the excretion of light compounds in an environment without soil compaction (Bonetti et al., 2017). The root growth, biological activity, and wetting-drying cycles are processes associated with soil aggregation development (Rabot et al., 2018; Vogel et al., 2021). The higher MWD is also associated with other soil physical indicators, e.g., higher TP and lower BD and SRP (Table 2) in the Clayey soil. In addition, the VESS Sq showed better soil structure under CTF (Fig. 5) due to the presence of roots, visible porosity, and aggregates with rounded shapes at the row position. Those results are according to a previous study in which controlled traffic increased root biomass by about 17.9% and enabled sugarcane yield gains in 8.2 and 10.3 Mg ha^{-1} in the third and fourth harvesting respectively (Esteban et al., 2019).

A study led by Guimarães Júnnyor et al., (2019) drew attention that the compressive stresses applied to the soil extend vertically and horizontally, which may cause soil compaction at the sugarcane planting lines when traffic control is adopted. Our findings did not show degradation of soil structure under CTF compared to RTF at row position. Although there have been increased BD, SRP, and VESS Sq in CTF at the inter-row position compared to row-position this farming system did not cause additional degradation of soil structure when compared to RTF at the inter-row position in all soil layers after four ratoon and three ratoon cycles in Clayey and Sandy clay soil respectively. The reasons for those results are related to the soil load-bearing capacity (Esteban et al., 2020) and straw maintenance on the soil surface mainly in the first ratoon cycle (Castioni et al., 2021; Carvalho et al., 2022) which increases the tire-soil contact area and decreases soil compaction risk (Vischi Filho et al., 2015; Keller et al., 2019). In addition, straw maintenance increases multiple benefits such as the source of carbon which enhances the biological activity and soil structure and alleviates the negative effects of soil compaction to plant growth (Cherubin et al., 2021). Although our results did not show an increase in soil compaction under CTF as compared to RTF at the inter-row position, a higher amount of roots focuses at the ratoon position/planting furrows

(Otto et al., 2011; Esteban et al., 2019). Machinery traffic in the sugarcane production system is set at 70 cm intended for transit and 80 cm for the traffic-free seedbed zones, in this sense, if the traffic is directed to the center of the interrow, more space is created for root growth. With this in mind, we encourage further long-term experiments should be carried out to measure the impacts of controlled traffic on root growth at the inter-row position.

Overall, soil physical indicators showed a better soil physical condition under CTF at the row position, on the other hand, RTF did not show a better soil physical environment at the inter-row position after four and three ratoon cycles in Clayey soil and Sandy clay soil respectively. Those findings reinforced previous results carried out by Esteban et al. (2019) and Barbosa et al. (2021) in other experimental conditions.

5.4.2. Implications of controlled traffic farming on SPQI and soil functionality

The higher difference found in soil functions such as supporting root growth - *f(i)*, ability to resist erosion and physical degradation - *f(ii)*, and allowing gases exchange between soil and atmosphere - *f(iv)* show that soil structure is benefited from controlled traffic practices at the row position which can improve root growth (Esteban et al., 2019) and sugarcane yield (Barbosa et al., 2021). On the other hand, the reduction in function related to the supply of water for plants and edaphic fauna - *f(iii)* at the inter-row position (Fig. 6) decreased soil physical quality under RTF in this position in Clayey soil. Also reinforces the fact of no difference found in other soil functions between CTF and RTF at inter-row position occurs due to higher resistance and resilience of clayey soils (Gregory et al., 2007) and the maintenance of straw on the soil surface (Blanco-Canqui et al., 2010). In Sandy clay soil, RTF decreased soil structure quality by reducing the soil's capacity to support root growth and supplying water for plants and edaphic fauna at the row position. However, the low ability to recover from compaction impact (Huang and Hartemink, 2020) reduced the soil's physical capacity in both CTF and RTF at the inter-row position in Sandy clay soil (Fig. 6).

Therefore, the reduction of soil compaction (i.e., under CTF) at row-position supported soil functions and related nature's contributions to people. For instance, the maintenance of soil function *f(i)* is related to the provision of fuel (e.g., source of green energy) and carbon sequestration regulation. In addition, the higher amount of sugarcane roots due to an environment without soil compaction can improve biological activity. In Fig. 7, the relation between SPQI and the abundance of earthworms indicated that CTF benefited biological activity and consequently soil physical quality. This finding highlights the soil's multifunctionality is related to the biological processes that occur in the soil (Bünemann et al., 2018; Ploeg et al., 2018). The benefits of earthworm abundance are related to infiltration, storing and supply of water, nutrient cycling (Lima et al., 2013), as well as earthworms are of crucial importance to decreasing the yield gap (Groenigen, 2014) and increasing the resilience of soil carbon to natural or anthropogenic disturbances

(Angst et al., 2019). In this sense, CTF is an advisable strategy to achieve both soil physical quality and soil biological activity, reducing ecological damage (Keller et al., 2022).

If CTF maintains the soil structure quality, better will be the root environment, and quickly the whole biological and physical system interacts moving toward the soil's functional structure, able to freely conduct water and gases (McHugh et al., 2009). Those processes result in benefits in nature's contributions related to water filtering and purification, improved infiltration capacity, sediment regulation (Masters et al., 2013), and erosion control (Mouazen and Palmqvist, 2015) which are related to function *f(ii)* mainly in Clayey soil (Fig. 6). In addition, the maintenance in soil functions *f(iii)* and *f(iv)* under CTF beneficiate nature's contributions relating to water and nutrient availability, fresh-water supply, air availability, and gas fluxes in both Clayey and Sandy clay soils (Fig. 6). Furthermore, uncontrolled traffic caused a reduction by 12 % in SPQI at row position in both Clayey and Sandy clay soils and the adoption of traffic-free seedbed zones creating a more stable and functional soil structure (Fig. 6).

The benefits of controlled traffic farming on soil physical quality in sugarcane fields would increase with time (Braunack and McGarry, 2006; Latsch and Anken, 2019). However, the soil environment at the inter-row position could be improved by the adoption of additional practices in both Clayey and Sandy clay soils. The use of traffic control techniques, primarily involves an efficient planting project, including parallelism between traffic lines, tires with high-flotation, and the use of autopilot. Soil management practices such as reduced or no-tillage (Tweddle et al., 2021; Luz et al., 2022) and cover crops cultivation on sugarcane renewal (Farhate et al., 2022) are efficient strategies to attenuate soil physical degradation, increase soil organic matter, and improve soil structure creating an environment more resistant to physical degradation by external pressure. On the other hand, the better soil physical quality obtained by soil tillage and the use of cover crops can be weakened by the compaction caused in harvesting operations if controlled traffic not be adopted (Guimarães Júnnyor et al., 2022). In this sense, creating traffic-free seedbed zones (Barbosa et al., 2021) decreases the risk of soil re-compaction related to conventional management (Colombi and Keller, 2019). In addition, as previously mentioned by Dias and Sentelhas (2018), controlled traffic practices and reduced tillage can be adopted by farmers to improve yield and reduce both water deficit and crop management yield gaps (e.g., yield variability (Ward et al., 2021)). Such practices are one of the most important pillars to achieving the best soil functional capacity and sustainability of sugarcane production, which faces future challenges related to the continuing trend toward heavier machinery and the projected increase in extreme weather events (Keller et al., 2022).

5.5. Conclusion

In this chapter, it was measured the impact of controlled traffic farming on soil physical indicators and soil physical functionality in sugarcane fields. Agricultural controlled traffic prevented the soil physical degradation at the sugarcane row position and did not induce additional degradation of soil physical quality at the sugarcane inter-row position compared to random traffic. Therefore, controlled traffic may be a strategy to reduce soil physical restrictions for root growth, supporting structural stability and soil functions related to the flow of water and gases in both Clayey and Sandy clay soils.

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Supplementary Materials

Table S1. Descriptive statistical parameters of soil organic carbon (SOC) and soil moisture used to calculate the soil physical quality index (SPQI) at 0-40 cm soil depth at row and inter-row positions at Clayey soil and Sandy Clay soil managed under controlled traffic farming (CTF) and random traffic farming (RTF). Standard deviation (SD), coefficient of variation (CV).

Variable	Row		Inter-row	
	CTF	RTF	CTF	RTF
	Clayey soil			
SOC (g kg^{-1})				
Maximum	19.91	17.87	19.91	17.87
Minimum	17.38	14.64	17.38	14.64
Mean	18.30	16.08	18.30	16.08
SD	1.18	1.39	1.18	1.39
CV (%)	6.47	8.65	6.47	8.65
Moisture (%)				

Maximum	21.05	19.82	21.05	19.82
Minimum	19.73	18.30	19.73	18.30
Mean	20.30	19.02	20.30	19.02
SD	0.55	0.62	0.55	0.62
CV (%)	2.75	3.31	2.75	3.31
	Sandy clay soil			
SOC (g kg^{-1})				
Maximum	12.70	11.93	12.70	11.93
Minimum	8.64	9.95	8.64	9.95
Mean	9.83	10.85	9.83	10.85
SD	1.92	1.00	1.92	1.00
CV (%)	19.53	9.23	19.53	9.23
Moisture (%)				
Maximum	22.97	17.93	15.37	14.00
Minimum	17.00	12.57	18.07	19.03
Mean	21.28	15.13	16.42	16.47
SD	2.86	2.60	1.23	2.39
CV (%)	13.46	17.19	7.54	14.51

6. FINAL REMARKS

The sugarcane cultivation effects on soil physical quality and related soil functions were assessed in this thesis. The hypotheses were that i) sugarcane expansion under conventional tillage on pasture areas degrades soil structure and reduces its related functions and ii) the adoption of reduced tillage and traffic-free seedbed zones instead of conventional tillage improves soil structure and consequently the related soil functions and services. According to chapter two, long-term land-use change from native vegetation to extensive pasture induced the degradation of soil physical quality and soil water dynamics. However, the results surprisingly showed that even conventional tillage, used during conversion from pasture to sugarcane, did not cause additional degradation on soil structure and soil water dynamics. This finding refuted the first hypothesis (Figure 1). Chapter two also highlighted that sustainable management practices to enhance soil physical quality and water dynamics in sugarcane fields are needed to prevent limiting conditions to plant growth and synergically contribute to delivering other nature's contribution to people. Those highlights were according to the second hypothesis which was confirmed in the following chapters.

In the third chapter, the adoption of reduced tillage practices did not negatively impact the soil physical quality assessed. The least limiting water range (LLWR), air permeability, and air-filled porosity remained unaltered in relation to conventional tillage practice in both Clayey and Sandy Loam soils. These results reinforce that conventional tillage could be replaced by reduced tillage to improve soil water availability and air fluxes in sugarcane fields. However, the soil benefits provided by reduced tillage are conditioned by the adoption of traffic-free seedbed zones. It increased LLWR, air permeability, and pore continuity in Sandy Loam soil as well as air permeability and pore continuity in Clayey soil. In chapter four, conventional tillage and reduced tillage resulted in similar soil structure conditions and functioning, regardless of the soil structure assessment scales after the fourth cycle of sugarcane ratoon. Therefore, conventional tillage did not bring additional benefits in alleviating soil compaction compared to reduced tillage over the sugarcane cycle. In agreement with results for water availability and air fluxes, the adoption of reduced tillage alone was not able to improve soil structure. The preservation and/or recovery of soil structure was conditioned by the additional adoption of traffic-free seedbed zones. In addition, chapter four showed that a diversity of assessment scales is an advisable strategy to assess the soil structure quality due to the unique features of each scale. For instance, one assessment scale proved to be more suitable for specific soil function. Therefore, the union of a diversity of techniques is recomeded to evaluate the soil physical functionality.

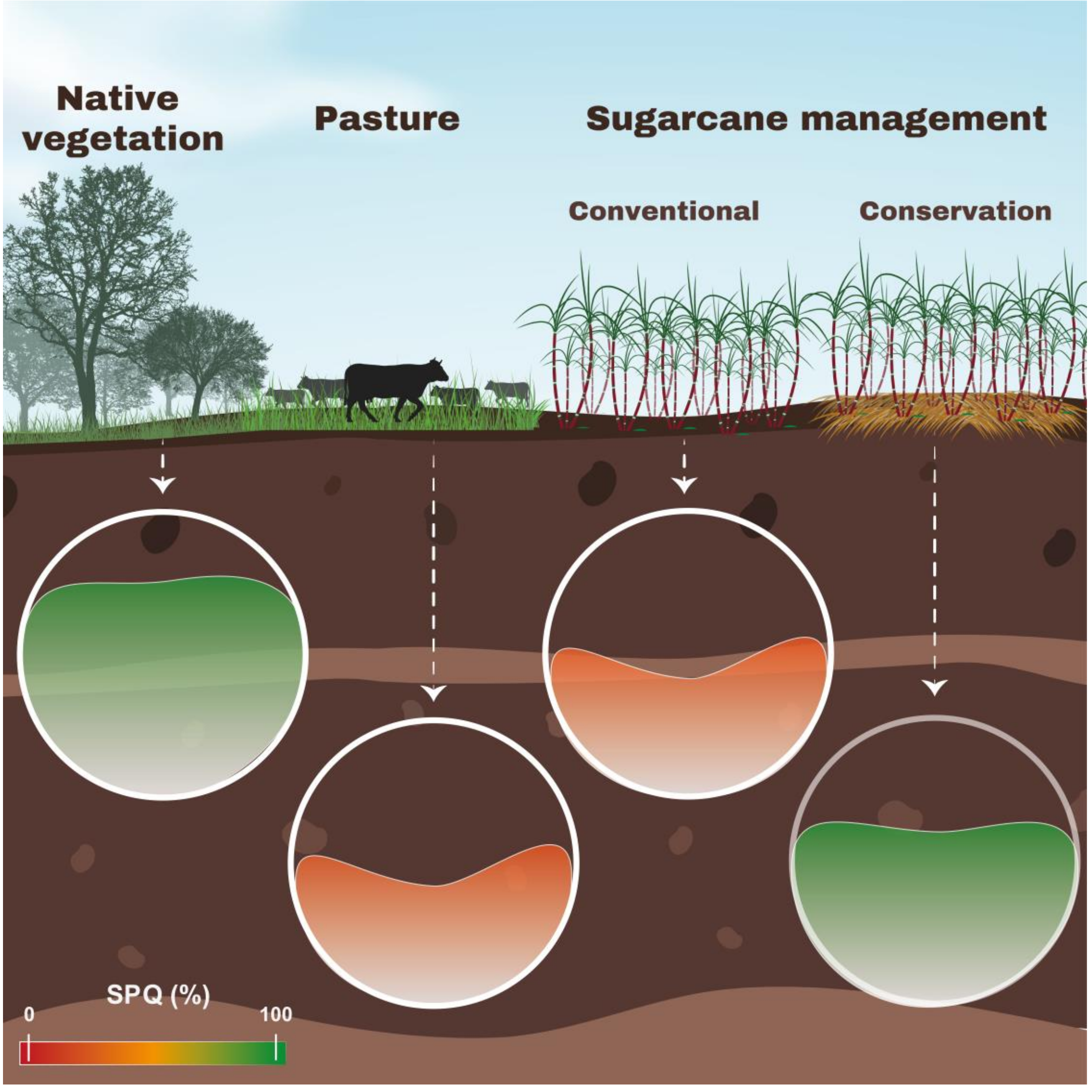

Figure 1. Soil physical quality (SPQ) responses to land-use change and different management practices in sugarcane cultivation. The circle fill and color represent the magnitude of SPQ. Conversion from pasture to sugarcane did not cause additional degradation in SPQ, refuting the first hypothesis. The adoption of conservation management practices such as reduced tillage and traffic-free seedbed zones in sugarcane cultivation enhanced SPQ. Native vegetation represents a natural condition and the best SPQ. Red and green colors represent poor and good SPQ respectively.

In the fifth chapter, the impact of controlled traffic practices on soil physical indicators and soil physical functionality in sugarcane fields was measured. Agricultural controlled traffic prevented the soil physical degradation at the seedbed position and did not induce additional degradation of soil physical quality at the sugarcane inter-row position compared to random traffic in both Clayey and Sandy clay soils. Therefore, the adoption of reduced tillage and traffic-free seedbed zones instead of conventional tillage improved soil structure and the related soil functions (Figure 1). In addition, the discussion of chapters four and five highlighted that reduced tillage and controlled traffic practices support the biological activity. This biological activeness is imperative to improve the soil structure and consequently soil functions related to physical stability and support, carbon storage, and fluxes of water and air.

Besides the impacts on soil structure and related soil functions, reduced tillage and controlled traffic can provide other benefits such as lower production costs, lower environmental impacts, sugarcane yield stability during the production cycle, and the potential to increase the production cycle from five to six or more years. However, this study did not assess aspects related to soil fertility and fertilizer applications. In tropical soils, specifically in the sugarcane-producing region, there are soils with poor natural fertility. In some cases, it is necessary to plow the soil to apply lime and fertilizers in deep soil layers making no-tillage or reduced tillage a challenge. In this case, reduced tillage may be indicated for eutrophic instead of dystrophic soils and/or soils with their nutrient concentration above the critical levels. In addition, tillage is usually recommended for some pest and weed control. Therefore, future studies are encouraged to assess other soil functions such as primary productivity, carbon storage and regulation, cycling and provision of nutrients, and provision of a habitat for biodiversity under different sugarcane management practices. For example, the trade-offs and synergies between soil water regulation and primary productivity should be further studied to understand the relationship among soil structure, related soil functions, and sugarcane yield under different tillage and machinery practices.

Finally, this study supports that the adoption of reduced tillage and traffic-free seedbed zones are two of the most important pillars for reducing soil compaction. These management practices maintain soil physical quality in sugarcane fields and consequently can contribute positively to provide nature's contribution to people.