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Controlled traffic farming maintains soil physical functionality in sugarcane fields

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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 machinery 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 machinery 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 and visual assessment of soil structure (VESS) were measured. In addition, the soil physical quality index (SPQI) was assessed for the following soil functions: support root growth, 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 traffic farming 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 the treatments. Controlled traffic in sugarcane fields was able to reduce soil physical degradation induced by agricultural machinery traffic, whose mitigation of compaction occurs mainly at row-position. These results suggest that controlled traffic farming may be a strategy to reduce soil physical restrictions for root growth in sugarcane fields.

1. Introduction

Brazil is the major and influential global player in sugarcane production (Hughes et al., 2020), accounting for 40.5% of world production (FAO, 2020). 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 reduction of soil's ability to sustain its essential physical functions (Cherubin et al., 2016; Keller et al., 2022) and causing the reduction of sugarcane yields 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 farming involves either the matching of crop row spacing with 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

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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; da 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; da 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 physical indicators can be integrated into an additive index for evaluating and monitoring the impact of traffic systems on soil physical functionality (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 (de 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 the controlled traffic system over the years creates permanent traffic lanes and minimizes soil compaction in untrafficked zones, preventing soil physical degradation in sugarcane fields.

2. Material and methods

2.1. Study sites and experimental design

The study was carried out in a commercial sugarcane field located in the municipality of Lençóis Paulista, 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 areas within the same textural class were in proximity (~50 m) with similar soil attributes, topographic, and climate conditions (Table 1). The size of each area was 10 ha. 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 the 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 sugarcane planting was carried out manually in the Clayey soil and mechanically in the 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 the Clayey soil, organic fertilizer such as 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 (both soils). The harvester (Model A8810) was characterized by treadmill wheels of 47 cm in width, the track width of 150 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 track width 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 (Table 2). 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 6190 M). The wagons weighed 9.5 Mg, had a track width of 240 cm, 600/50 × 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 (Table 2). 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.

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. Within each soil, a completely randomized design was used, with two treatments and four pseudo-replicates. The use of pseudo-replicates is a procedure commonly used in ecological and agronomic studies when commercial

Table 2
Parameters of Machinery related to controlled traffic farming (CTF) and random traffic farming (RTF).

Machinery parameters	Total Weight (Mg)	Track Width (cm)	Tire Width (cm)	Tire inflation pressure (kPa)	Transport capacity (Mg)
CTF					
Harvester	18.5	150	47		
Wagon	17.5	300	41	300	16
RTF					
Harvester	18.5	150	47		
Wagon	9.5	240	56	280	16
Tractor	14	270	60 - Front	124 - Front	
			72 - Rear	242 - Rear	

farms are evaluated. A total of 96 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 × depth). Considering the two sites, a total of 96 undisturbed and disturbed samples were taken (i.e., 2 traffic systems × 4 pseudo-replicates × 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 min 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 Eq. (1):

$$\mathrm{MWD} = \sum\nolimits_{i=1}^{n} \mathrm{WiXi} \tag{1}$$

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. The soil particle-size analysis was carried out according to Gee and Or (2002).

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 Eq. (2):

$$\mathrm{VESS\ Sq} = \sum\nolimits_{i=1}^{n} \frac{\mathrm{SqiTi}}{\mathrm{TT}} \tag{2}$$

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.

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 (Eq. (3):

$$\mathrm{SPQI} = \sum f(\mathrm{scores})\ W \tag{3}$$

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.

2.4. Statistical analysis

Treatments were compared via analysis of variance applying a linear mixed-effects model (lme function; R package nlme, Pinheiro et al., 2014). In the formulation of the model, traffic control (controlled and random traffic) and row position (row and inter-row) were considered as fixed effect factor, whereas clay content was considered as random effect. The linear mixed-effects model was applied for each soil layer individually or soil type (i.e., Clayey or Sandy clay). Tukey's test was applied for mean comparisons of significant effects using the R package emmeans, which compute estimated marginal means for specified factors or factor combinations in a linear model. Additionally, correlation analysis among soil physical indicators was applied based on Pearson's correlation coefficients. A regression analysis was also performed to explore the relationship between SPQI and earthworm abundance. All statistical procedures were performed using the software R (R Core Team, 2021).

3. Results

3.1. Soil porosity (macro, micro, and total porosity)

In the Clayey soil, MaP was similar in both traffic systems and positions. The MaP varied from 0.08 m^3 m^{-3} to 0.17 m^3 m^{-3} (Fig. 1a) and from 0.05 m^3 m^{-3} to 0.14 m^3 m^{-3} (Fig. 1b) at row and inter-row positions respectively. In addition, traffic system did not change the MiP in which mean values varied from 0.36 m^3 m^{-3} to 0.40 m^3 m^{-3} (Fig. 1c, 1d). Consequently, the TP was similar in both traffic systems at row position (Fig. 1e). However, RTF reduced TP from 0.48 m^3 m^{-3} to 0.40 m^3 m^{-3} in the 0–10 cm layer at the inter-row position (Fig. 1f).

In the Sandy clay soil, RTF reduced MaP (from 0.27 m^3 m^{-3} to 0.20 m^3 m^{-3}) and MiP (from 0.21 m^3 m^{-3} to 0.14 m^3 m^{-3}) in the 0–10 cm layer at the row position (Fig. 2a, 2c). Consequently, the TP was 0.14 m^3 m^{-3} higher under CTF in that soil layer and position (Fig. 2e). At the inter-row position, both CTF and RTF showed similar MaP (Fig. 2b), MiP (Fig. 2d), and TP (Fig. 2f) in the Sandy clay soil.

3.2. Bulk density, soil penetration resistance, mean weight diameter, and VESS

In the Clayey soil, the BD values varied from 1.25 Mg m^{-3} to 1.56 Mg m^{-3}. The higher BD was verified in RTF in relation to CTF in the 0–10 cm layer at the inter-row position (Fig. 3b). In this soil layer and position, BD was higher in RTF (1.56 Mg m^{-3}) than CTF (1.37 Mg m^{-3}) (Fig. 3b). However, in the 10–20 and 20–40 cm layers, both CTF and RTF showed similar BD at both positions. After five years of sugarcane cultivation, machinery traffic impacted SPR only in the 0–10 cm soil layer at the inter-row position (Fig. 3d). In this layer, SPR was lower in CTF (1.46 MPa) than RTF (2.07 MPa). RTF altered the MWD only at the row position in the 0–10 cm soil layer in Clayey soil. In this layer and position, MWD was lower in RTF (1.2 mm) than in CTF (2.1 mm) (Fig. 3e).

In the Sandy clay soil, the BD values varied from 1.38 Mg m^{-3} to 1.83 Mg m^{-3} (Fig. 4a, 4b). The difference between traffic systems in BD was significant only at the row position in the 0–10 cm soil layer, in which BD value was higher in RTF (1.74 Mg m^{-3}) when compared to CTF (1.38 Mg m^{-3}) (Fig. 4a). On the other hand, BD was similar in both traffic systems in the 10–20 and 20–40 cm layers at the row position and in all soil layers at the inter-row position (Fig. 4b).

In the Sandy clay soil, SPR was lower than 2.0 MPa under CTF at the row position in all soil layers (Fig. 4c). In addition, RTF increased the SPR in all soil layers at the row position (Fig. 4c). Although both traffic 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 the Sandy clay soil, no significant effects were found in both positions and soil layers (Fig. 4e, 4f). The MWD values range from 0.6 mm to 1.4 mm in this soil.

In the Clayey soil, the data indicated that VESS was similar in both treatments with mean values below the critical level of 3.0 in all layers and both positions (Fig. 5a, 5b). However, in the Sandy clay soil, RTF increased the VESS sq in the 10–25, and 0–25 cm (overall) soil layers at the row position (Fig. 5c) and in the 0–10 and 0–25 cm soil layers at the inter-row position (Fig. 5d). In this soil, values of VESS sq were near 2.0 under CTF, meanwhile, VESS sq were either near or higher than the critical value of 3.0 under RTF in the 0–10 cm, 10–25 cm, and 0–25 cm soil layers (Fig. 5c, 5d).

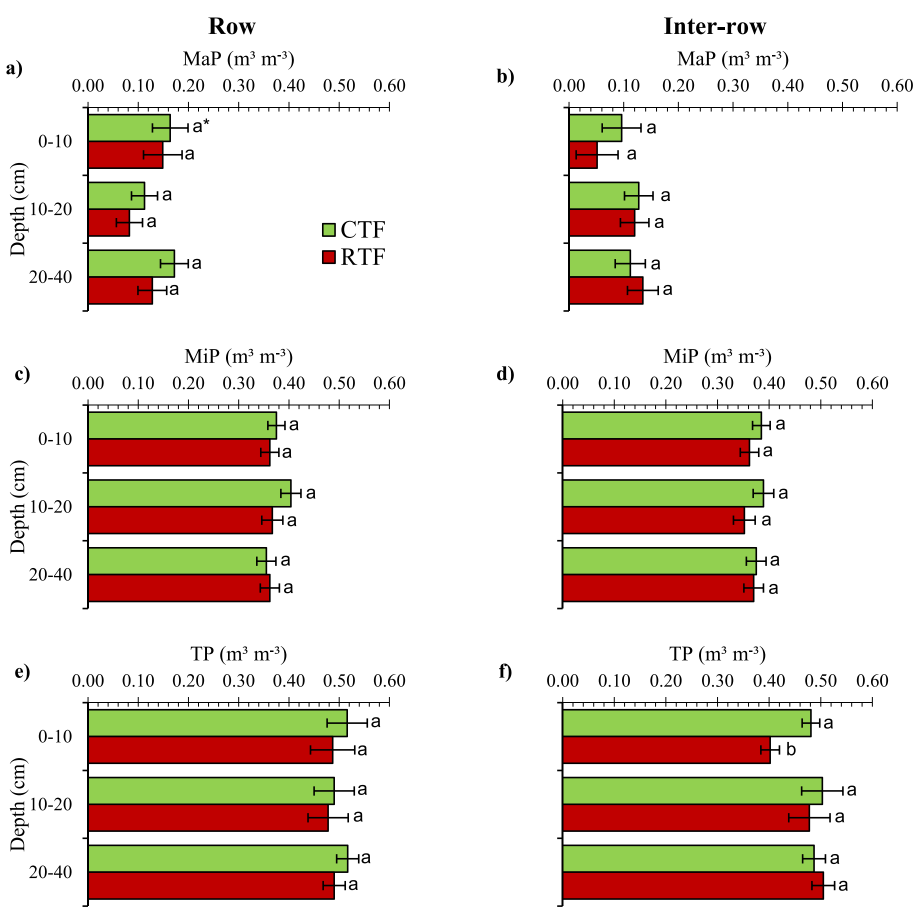

Fig. 1. Average values of macroporosity (MaP), microporosity (MiP), and total porosity (TP) from 0–10, 10–20, and 20–40 cm layers at the row (a, c, and e) and inter-row (b, d, and f) positions at Clayey soil managed under controlled traffic farming (CTF) and random traffic farming (RTF). Within the same layer, the horizontal bars denote the estimated marginal means (least-squares means) using the R package emmeans with a confidence level of 0.95. *Mean values within each position in the same layer followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$).

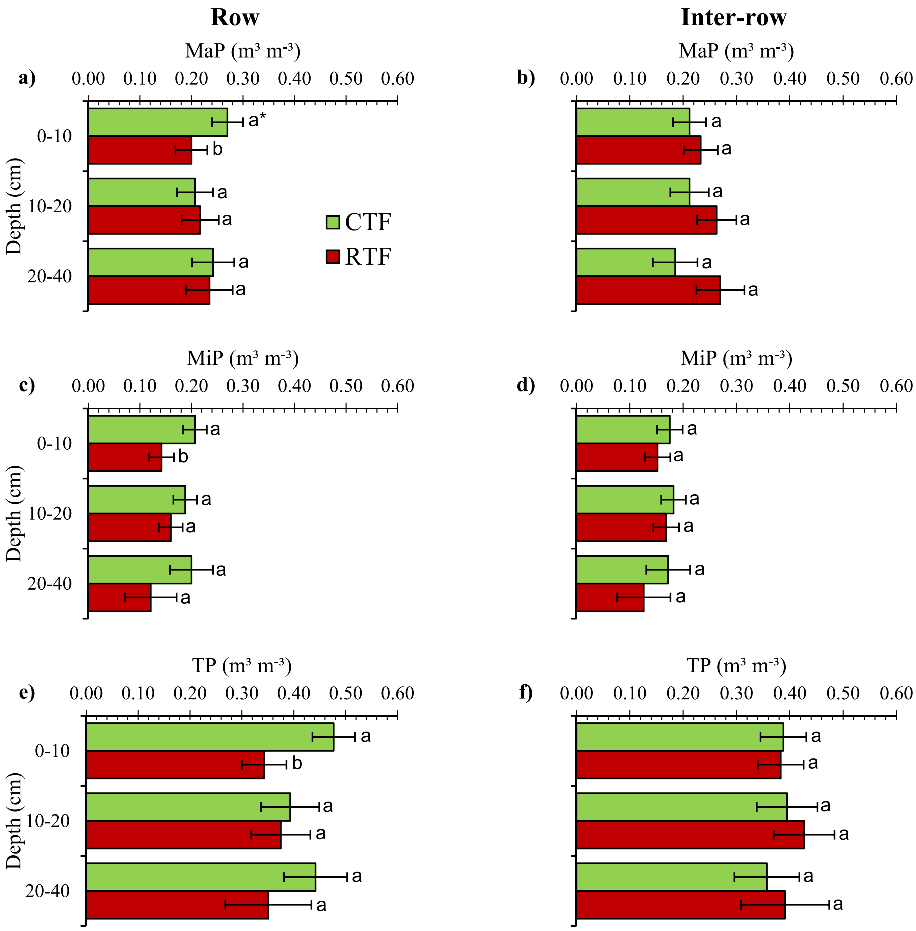

Fig. 2. Average values of macroporosity (MaP), microporosity (MiP), and total porosity (TP) from 0–10, 10–20, and 20–40 cm layers at the row (a, c, and e) and inter-row (b, d, and f) positions at Sandy clay soil managed under controlled traffic farming (CTF) and random traffic farming (RTF). Within the same layer, the horizontal bars denote the estimated marginal means (least-squares means) using the R package emmeans with a confidence level of 0.95. *Mean values within each position in the same layer followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$).

3.3. Pearson's correlations among soil physical indicators

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 3). There was a negative correlation between MWD and BD (-0.31), MWD and SPR (-0.28), MWD and VESS (-0.37) in the Clayey soil. However, there was a significant correlation only between MWD and SPR (-0.29) in the Sandy clay soil (Table 3).

3.4. Soil physical functionality and SPQI

The overall scores of each soil physical function and SPQI for both soils are presented in Fig. 6. In the Clayey soil, f(i), f(ii), and f(iv) soil functions showed similar scores under CTF and RTF (Fig. 6a). However, the f(iii) soil function showed higher score under CTF which resulted in higher SPQI at the row position. SPQI was 0.84 under CTF and 0.73 under RTF. Besides higher score in the f(iii) soil function under CTF, SPQI was similar between treatments ranged from 0.70 to 0.74 at the inter-row position in the Clayey soil (Fig. 6c). In the Sandy clay soil, RTF reduced f(i) and f(iii) soil functions (21% and 22%, respectively) which resulted in a SPQI = 0.63 at the row position. This value was 12% lower than the value found in CTF (0.75) (Fig. 6d). Although CTF showed a higher score in the f(i) soil function and RTF showed a higher score in the f(iv) soil function, there was no difference between farming systems in SPQI at the inter-row position in the Sandy clay soil. At this position, SPQI was 0.65 in both farming systems (Fig. 6d).

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 the 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).

4. Discussion

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 the Sandy clay soil, the effect of CTF adoption was more evident at the row position, whereas in the Clayey soil, RTF decreased soil physical quality at the inter-row position. In the 0–10 cm layer, CTF showed lower BD and VESS Sq at the row position in the Sandy clay soil and higher MWD in the Clayey soil. 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 system. Regarding the row spacing of 150 cm, a 70 cm lane is intended for transit and the remaining 80 cm lane is designed for the traffic-free seedbed zones under CTF. In this sense, if the traffic is directed to the center of the interrow, more space is allocated for root growth. Therefore, in the 0–10 cm soil layer, there is a higher root concentration (Lovera et al., 2021) and biological activity, which can change the soil structure (da Luz et al., 2022) and consequently improve soil physical functionality (Colombi and Keller, 2019). In addition, annual cycles 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). However,

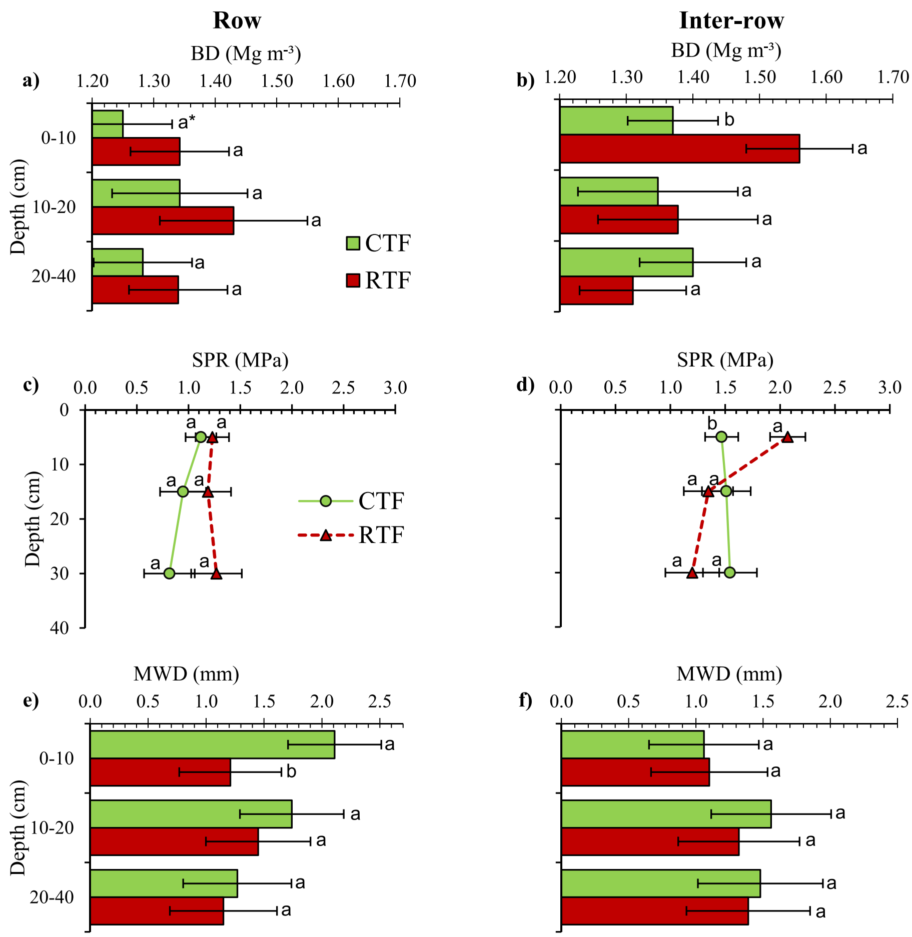

Fig. 3. Average values of bulk density (BD), soil penetration resistance (SPR), and mean weight diameter (MWD) from 0–10, 10–20, and 20–40 cm layers at the row (a, c, and e) and inter-row (b, d, and f) positions at Clayey soil managed under controlled traffic farming (CTF) and random traffic farming (RTF). Within the same layer, the horizontal bars denote the estimated marginal means (least-squares means) using the R package emmeans with a confidence level of 0.95. *Mean values within each position in the same layer followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$).

similar BD and soil porosity between treatments in the 10–20 and 20–40 cm soil layers can be associated with tillage practices adopted before the establishment of different traffic system in the areas (da Luz et al., 2022).

The soil porosity in the two types of soils is affected differently by the traffic systems. It can be explained by the soil texture composition. According to a study led by de Lima et al. (2022), TP and MaP depend on the soil compactness degree and texture. The magnitude of those changes is associated with particle size range. In their study, TP and MaP decreased with increasing compaction, mainly for soils with silt + clay content lower than ~500 g kg^{-1}. However, TP and MaP reduction in response to compaction was substantially lowered for further increase in silt + clay content (>500 g kg^{-1}) due to more significant soil aggregation in clayey soils. Therefore, the effect of CTF on soil porosity at the row position was higher in the Sandy clay soil (Fig. 2). In addition, values of BD (e.g., higher than 1.7 Mg m^{-3}) (Fig. 4a, 4b), SPR (e.g., higher than 2.0 MPa) (Fig. 4c, 4d), 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 positions in the Sandy clay soil. In a similar textured sandy clay soil, Braunack and McGarry (2006) also found greater BD and SPR under random traffic compared to controlled traffic.

The result of MWD in 0–10 cm soil layer (Fig. 3e) indicated a better soil structure under controlled traffic at the row position in the Clayey soil. This finding is due to the reduced mechanical disturbance (de Andrade 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., 2022). The higher MWD is also associated with other soil physical indicators, e.g., lower BD and SPR (Table 3) in the Clayey soil. Those results are according to a previous study in which controlled traffic increased root biomass by about 17.9% and enabled sugarcane yield gains of 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 to the fact that the compressive stresses applied to the soil extend vertically and horizontally. This may cause soil compaction at the inter-row position when traffic control in mechanical operations is adopted. We highlight that CTF 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 the Clayey and Sandy clay soil, respectively. However, we encourage further long-term studies evaluating the impacts of controlled traffic on root growth at the inter-row position.

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

Soil structure at the rows was better under CTF system. In the Clayey soil, this occurs due to the difference found in the f(iii) soil function (Fig. 6a). In the Sandy clay soil, it was found a higher difference in f(i) and f(iii) soil functions (Fig. 6b). In a study led by de Souza et al. (2014), the controlled traffic system based on the adjustment of the tractor-trailer track width and the use of an autopilot preserved the soil physical quality (e.g. increased water availability and soil porosity) at the plant rows and resulted in greater compaction at the inter-row position. 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 machinery traffic at the inter-row position by controlled traffic provided high trafficability areas as well as places with better soil physical conditions at the crop row

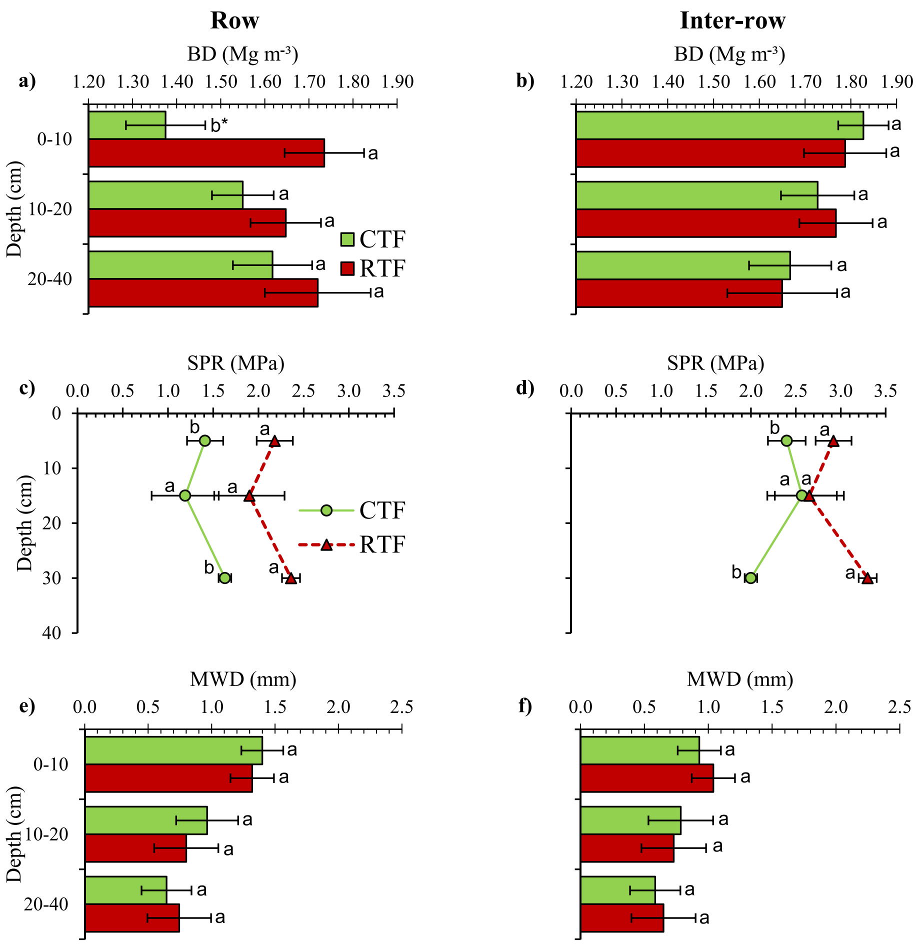

Fig. 4. Average values of bulk density (BD), soil penetration resistance (SPR), and mean weight diameter (MWD) from 0–10, 10–20, and 20–40 cm layers at the row (a, c, and e) and inter-row (b, d, and f) positions at Sandy clay soil managed under controlled traffic farming (CTF) and random traffic farming (RTF). Within the same layer, the horizontal bars denote the estimated marginal means (least-squares means) using the R package emmeans with a confidence level of 0.95. *Mean values within each position in the same layer followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$).

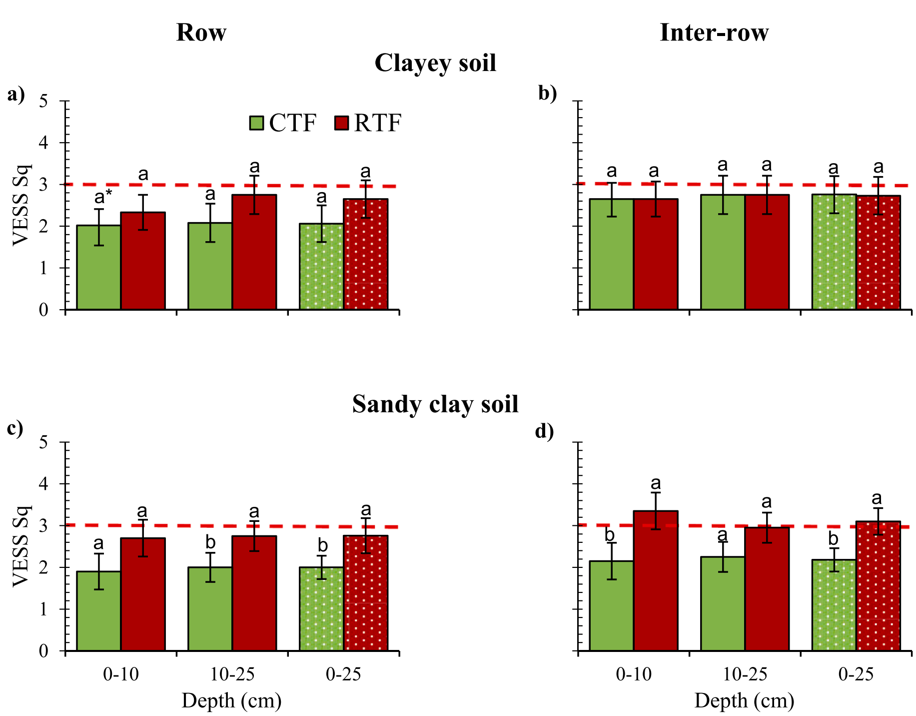

Fig. 5. Average values of VESS scores from 0 to 10, 10–25, and 0–25 cm (overall) layers at the row (a, c) and inter-row (b, d) positions at Clayey soil (a, b) and Sandy clay soil (c, d) managed under controlled traffic farming (CTF) and random traffic farming (RTF). Dashed lines indicate the threshold of soil structure quality (VESS Sq = 3). Within the same layer, the horizontal bars denote the estimated marginal means (least-squares means) using the R package emmeans with a confidence level of 0.95. *Mean values within each position in the same layer followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$).

Table 3
Pearson's correlations coefficients and probability of error among soil physical indicators in Clayey and Sandy clay soils managed under controlled traffic farming (CTF) and random traffic farming (RTF).

		BD*	SPR	MWD	VESS
		Clayey soil			
BD	**Sandy clay soil**	1	**0.69**[b] <0001	-0.31 0.033	0.35 0.045
SPR		**0.58** <0001	1	-0.28 0.046	0.39 0.028
MWD		-0.24 0.09	-0.29 0.044	1	-0.37 0.039
VESS		**0.46** 0.007	**0.49** 0.004	-0.16 0.364	1

*Abbreviations: BD – bulk density, SPR – soil penetration resistance, 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, MWD), n = 32 (VESS).

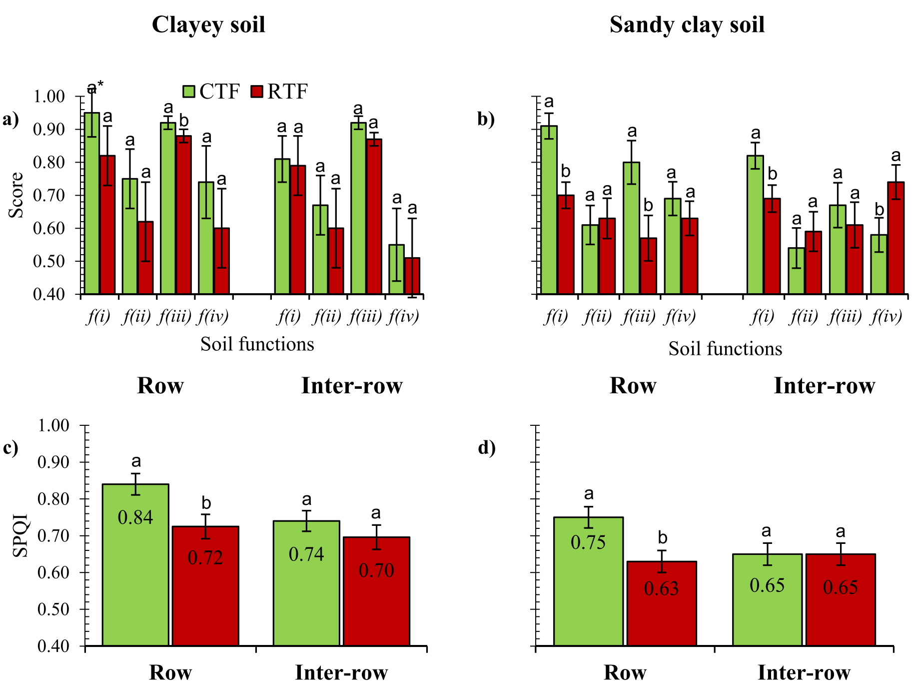

Fig. 6. Scores of soil functions (f(i) - support root growth, f(ii) - ability to resist erosion and physical degradation, f(iii) - supply water for plants and edaphic fauna, and f(iv) - allow gases exchange between soil and atmosphere) and soil physical quality index (SPQI) at 0–40 cm soil depth at the row and inter-row positions at Clayey soil (a, c) and Sandy Clay soil (b, d) managed under controlled traffic farming (CTF) and random traffic farming (RTF). Within each soil function the horizontal bars denote the estimated marginal means (least-squares means) using the R package emmeans with a confidence level of 0.95. *Mean values within each position in the same soil function followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$).

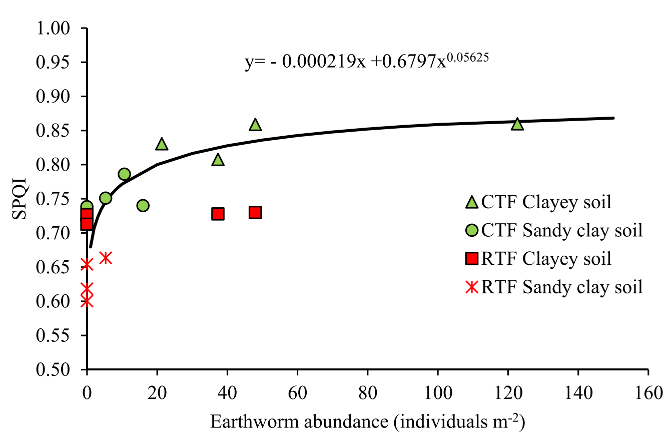

Fig. 7. Relationship between soil physical quality index (SPQI) and abundance of earthworm in Clayey and Sandy clay soils managed under controlled traffic farming (CTF) and random traffic farming (RTF). The curve was fitted with dataset from CTF.

position. Consequently, CTF can increase root growth (Esteban et al., 2019) and sugarcane yield (Barbosa et al., 2021).

RTF caused a reduction by 12% in SPQI at row position in both Clayey (Fig. 6c) and Sandy clay (Fig. 6d) soils. Therefore, the adoption of traffic-free seedbed zones created a more stable and functional soil structure, reducing soil compaction at row-position. In addition, the higher score in the f(iii) soil function under CTF system improved the abundance of earthworms. In Fig. 7, the relationship between SPQI and the abundance of earthworms indicated that CTF benefited earthworm abundance and consequently soil physical quality. This finding highlights that CTF system benefited the f(iii) soil function (Fig. 6a, 6b), as well as earthworms abundance, which should be of crucial importance in decreasing the sugarcane yield gap (Dias and Sentelhas, 2018) 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 increase soil physical quality and earthworm abundance (Fig. 7).

The benefits of CTF on soil physical quality in sugarcane fields would increase with time (Braunack and McGarry, 2006; Latsch and Anken, 2019) mainly at the row position. However, the soil conditions at the inter-row position could be improved by the adoption of additional practices, such as reduced or no-tillage (Tweddle et al., 2021; da Luz et al., 2022), cover crops cultivation on sugarcane renewal (Farhate et al., 2022), and control of soil moisture for machinery traffic. In addition, the use of traffic control techniques primarily involves designing an efficient planting project, including parallelism between traffic lines, maintaining areas with no traffic as premise, and using autopilot. Two additional machinery adjustments are recommended. The first one is adapting the machinery set to solve the excess load on the axle by using low pressure on high-flotation tires. The second one is increasing the number of axles of the trailers without increasing the load capacity (Guimarães Júnnyor et al., 2019). These strategies combined with CTF system can improve soil structure creating an environment more resistant to physical degradation (Guimarães Júnnyor et al., 2022). To sum up, traffic-free seedbed zones (Barbosa et al., 2021) decrease the risk of soil re-compaction related to conventional management (Colombi and Keller, 2019). It is one of the essential pillars to improve soil physical 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. Conclusion

Controlled traffic farming 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 regardless of soil texture. Therefore, controlled traffic may be a strategy to reduce soil physical restrictions, support root growth, and supply water for plants and edaphic fauna in sugarcane areas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2023.116427.

References

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services - A global review. Geoderma 262, 101–111. https://doi.org/10.1016/j.geoderma.2015.08.009.

Anderson, J.M., Ingram, J.S.I., 1993. Tropical Soil Biology and Fertility: A Handbook of Methods, 2nd ed. CAB International, Wallingford.

Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agric. Ecosyst. Environ. 90, 25–45. https://doi.org/10.1016/S0167-8809(01)00174-8.

Angst, G., Mueller, C.W., Prater, I., Angst, Š., Frouz, J., Jílková, V., Peterse, F., Nierop, K.G.J., 2019. Earthworms act as biochemical reactors to convert labile plant compounds into stabilized soil microbial necromass. Comun. Biol. 2 (1) https://doi.org/10.1038/s42003-019-0684-z.

Barbosa, L.C., Magalhães, P.S.G., Bordonal, R.O., Cherubin, M.R., Castioni, G.A.F., Tenelli, S., Franco, H.C.J., Carvalho, J.L.N., 2019. Soil physical quality associated with tillage practices during sugarcane planting in south-central Brazil. Soil Tillage Res. 195, 104383 https://doi.org/10.1016/j.still.2019.104383.

Barbosa, L.C., Magalhães, P.S.G., Bordonal, R.O., Cherubin, M.R., Castioni, G.A., Rossi Neto, J., Franco, H.C.J., Carvalho, J.L.N., 2021. Untrafficked furrowed seedbed sustains soil physical quality in sugarcane mechanized fields. Eur. J. Soil Sci. 72 (5), 2150–2164. https://doi.org/10.1111/ejss.13107.

Bernardo, R., Lourenzani, W.L., Satolo, E.G., Caldas, M.M., 2019. Analysis of the agricultural productivity of the sugarcane crop in regions of new agricultural expansions of sugarcane. Gest. e Prod. 26 https://doi.org/10.1590/0104-530X3554-19.

Braunack, M.V., McGarry, D., 2006. Traffic control and tillage strategies for harvesting and planting of sugarcane (Saccharum officinarum) in Australia. Soil Tillage Res. 89, 86–102. https://doi.org/10.1016/j.still.2005.07.002.

Braunack, M.V., Arvidsson, J., Ha, I., 2006. Effect of harvest traffic position on soil conditions and sugarcane (Saccharum officinarum) response to environmental conditions in Queensland. Australia 89, 103–121. https://doi.org/10.1016/j.still.2005.07.003.

Castioni, G.A., Cherubin, M.R., Menandro, L.M.S., Sanches, G.M., Bordonal, R.d.O., Barbosa, L.C., Franco, H.C.J., Carvalho, J.L.N., 2018. Soil physical quality response to sugarcane straw removal in Brazil: A multi-approach assessment. Soil Tillage Res. 184, 301–309.

Cavalcanti, R.Q., Rolim, M.M., de Lima, R.P., Tavares, U.E., Pedrosa, E.M.R., Cherubin, M.R., 2020. Soil physical changes induced by sugarcane cultivation in the Atlantic Forest biome, northeastern Brazil. Geoderma 370, 114353. https://doi.org/10.1016/j.geoderma.2020.114353.

Cherubin, M.R., Karlen, D.L., Franco, A.L.C., Tormena, C.A., Cerri, C.E.P., Davies, C.A., Cerri, C.C., 2016. Soil physical quality response to sugarcane expansion in Brazil. Geoderma 267, 156–168. https://doi.org/10.1016/j.geoderma.2016.01.004.

Cherubin, M.R., Franco, A.L.C., Guimarães, R.M.L., Tormena, C.A., Cerri, C.E.P., Karlen, D.L., Cerri, C.C., 2017. Assessing soil structural quality under Brazilian sugarcane expansion areas using Visual Evaluation of Soil Structure (VESS). Soil Tillage Res. 173, 64–74. https://doi.org/10.1016/j.still.2016.05.004.

Colombi, T., Keller, T., 2019. Developing strategies to recover crop productivity after soil compaction—A plant eco-physiological perspective. Soil Tillage Res. 191, 156–161. https://doi.org/10.1016/j.still.2019.04.008.

da Luz, F.B., Carvalho, M.L., de Borba, D.A., Schiebelbein, B.E., de Lima, R.P., Cherubin, M.R., 2020. Linking soil water changes to soil physical quality in sugarcane expansion areas in Brazil. Water (Switzerland) 12, 1–18. https://doi.org/10.3390/w12113156.

da Luz, F.B., Carvalho, M.L., Castioni, G.A.F., de Oliveira Bordonal, R., Cooper, M., Carvalho, J.L.N., Cherubin, M.R., 2022. Soil structure changes induced by tillage and reduction of machinery traffic on sugarcane – A diversity of assessment scales. Soil Tillage Res. 223, 105469.

de Andrade Bonetti, J., Anghinoni, I., de Moraes, M.T., Fink, J.R., 2017. Resilience of soils with different texture, mineralogy and organic matter under long-term conservation systems. Soil Tillage Res. 174, 104–112.

de Lima, R.P., Rolim, M.M., Toledo, M.P.S., Tormena, C.A., da Silva, A.R., e Silva, I.A.C., Pedrosa, E.M.R., 2022. Texture and degree of compactness effect on the pore size distribution in weathered tropical soils. Soil Tillage Res. 215, 105215.

de Sousa, A.C.M., Farhate, C.V.V., de Souza, Z.M., Torres, J.L.R., da Silva, R.B., 2019. Soil load-bearing capacity and development of root system in area under sugarcane with traffic control in Brazil. Sugar Tech 21, 153–161. https://doi.org/10.1007/s12355-018-0636-9.

de Souza, G.S., de Souza, Z.M., da Silva, R.B., Barbosa, R.S., Araújo, F.S., 2014. Effects of traffic control on the soil physical quality and the cultivation of sugarcane. Rev. Bras. Ciência do Solo 38, 135–146. https://doi.org/10.1590/s0100-06832014000100013.

Dias, H.B., Sentelhas, P.C., 2018. Sugarcane yield gap analysis in Brazil – A multi-model approach for determining magnitudes and causes. Sci. Total Environ. 637–638, 1127–1136. https://doi.org/10.1016/j.scitotenv.2018.05.017.

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50, 627–633. https://doi.org/10.2136/sssaj1986.03615995005000030017x.

Esteban, D.A.A., de Souza, Z.M., Tormena, C.A., Lovera, L.H., de Souza Lima, E., de Oliveira, I.N., de Paula Ribeiro, N., 2019. Soil compaction, root system and productivity of sugarcane under different row spacing and controlled traffic at harvest. Soil Tillage Res. 187, 60–71. https://doi.org/10.1016/j.still.2018.11.015.

Esteban, D.A.A., de Souza, Z.M., da Silva, R.B., de Souza Lima, E., Lovera, L.H., de Oliveira, I.N., 2020. Impact of permanent traffic lanes on the soil physical and mechanical properties in mechanized sugarcane fields with the use of automatic steering. Geoderma 362, 114097. https://doi.org/10.1016/j.geoderma.2019.114097.

FAO, 2020. FAOSTAT Statistical Database.

Farhate, C.V.V., de Souza, Z.M., Cherubin, M.R., Lovera, L.H., de Oliveira, I.N., da Guimarães Júnnyor, W., S., La Scala Junior, N., 2022. Soil physical change and sugarcane stalk yield induced by cover crop and soil tillage. Rev. Bras. Cienc. do Solo 46, 1–24. https://doi.org/10.36783/18069657rbcs20210123.

Gee, G.W., Or, D., 2002. Particle size analysis, in: Methods of Soil Analysis: Part 4 Physical Methods, 5.4. Soil Science Society of America, Madison, pp. 255–293. https://doi.org/10.2136/sssabookser5.4.c12.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J.H., Topp Clarke G. (Eds.), Methods of Soil Analysis: Part 4 Physical Methods, 5.4. https://doi.org/10.2136/sssabookser5.4.c9.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of soil structure. Soil Use Manag. 27, 395–403. https://doi.org/10.1111/j.1475-2743.2011.00354.x.

Guimarães Júnnyor, W.d.S., Diserens, E., De Maria, I.C., Araujo-Junior, C.F., Farhate, C.V.V., de Souza, Z.M., 2019. Prediction of soil stresses and compaction due to agricultural machines in sugarcane cultivation systems with and without crop rotation. Sci. Total Environ. 681, 424–434. https://doi.org/10.1016/j.scitotenv.2019.05.009.

Guimarães Júnnyor, W.d.S., De Maria, I.C., Araujo-Junior, C.F., Diserens, E., Severiano, E.d.C., Farhate, C.V.V., Souza, Z.M.d., 2022. Conservation systems change soil resistance to compaction caused by mechanised harvesting. Ind. Crops Prod. 177, 114532. https://doi.org/10.1016/j.indcrop.2022.114532.

Hughes, N., Mutran, V.M., Tomei, J., de Oliveira Ribeiro, C., Oller do Nascimento, C.A., 2020. Strength in diversity? Past dynamics and future drivers affecting demand for sugar, ethanol, biogas and bioelectricity from Brazil's sugarcane sector. Biomass and Bioenergy 141, 105676. https://doi.org/10.1016/j.biombioe.2020.105676.

Jimenez, K.J., Rolim, M.M., de Lima, R.P., Cavalcanti, R.Q., Silva, Ê.F.F., Pedrosa, E.M.R., 2021. Soil Physical Indicators of a Sugarcane Field Subjected to Successive Mechanised Harvests. Sugar Technol. 23, 811–818. https://doi.org/10.1007/s12355-020-00916-w.

Keller, T., Lamandé, M., Naderi-Boldaji, M., de Lima, R.P., 2022. Soil compaction due to agricultural field traffic: An overview of current knowledge and techniques for compaction quantification and mapping. In Saljnikov, E., Mueller, L., Lavrishchev, A., Eulenstein, F. (Eds.), Advances in Understanding Soil Degradation. Springer International Publishing, Cham, pp. 287–312. https://doi.org/10.1007/978-3-030-85682-3_13.

Latsch, A., Anken, T., 2019. Soil and crop responses to a "light" version of Controlled Traffic Farming in Switzerland. Soil Tillage Res. 194, 104310 https://doi.org/10.1016/j.still.2019.104310.

Lovera, L.H., de Souza, Z.M., Esteban, D.A.A., de Oliveira, I.N., Farhate, C.V.V., de Lima, E., S., Panosso, A.R., 2021. Sugarcane root system: Variation over three cycles under different soil tillage systems and cover crops. Soil Tillage Res. 208, 104866 https://doi.org/10.1016/j.still.2020.104866.

McHugh, A.D., Tullberg, J.N., Freebairn, D.M., 2009. Controlled traffic farming restores soil structure. Soil Tillage Res. 104, 164–172. https://doi.org/10.1016/j.still.2008.10.010.

McPhee, J.E., Antille, D.L., Tullberg, J.N., Doyle, R.B., Boersma, M., 2020. Managing soil compaction – A choice of low-mass autonomous vehicles or controlled traffic? Biosyst. Eng. 195, 227–241. https://doi.org/10.1016/j.biosystemseng.2020.05.006.

Mouazen, A.M., Palmqvist, M., 2015. Development of a framework for the evaluation of the environmental benefits of controlled traffic farming. Sustain. 7, 8684–8708. https://doi.org/10.3390/su7078684.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., 2014. Nlme: linear and nonlinear mixed effects models. R Packag. Version 3 1–117.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.-J., 2018. Soil structure as an indicator of soil functions: A review. Geoderma 314, 122–137.

Souza, G.S., Souza, Z.M., Cooper, M., Tormena, C.A., 2015. Controlled traffic and soil physical quality of an oxisol under sugarcane cultivation. Sci. Agric. 72, 270–277. https://doi.org/10.1590/0103-9016-2014-0078.

Team, R.C., 2021. A Language and Environment for Statistical Computing [internet].

Tweddle, P.B., Lyne, P.W.L., van Antwerpen, R., Lagerwall, G.L., 2021. A review and synthesis of sugarcane losses attributed to infield traffic, 1st ed, Advances in Agronomy. Elsevier Inc. https://doi.org/10.1016/bs.agron.2020.10.002.

van Raij, B., Cantarella, H., Quaggio, J.A., Furlani, A.M.C., 1997. Recomendação de adubação e calagem para o estado de São Paulo, 2nd ed. Campinas.

Vogel, H.-J., Balseiro-Romero, M., Kravchenko, A., Otten, W., Pot, V., Schlüter, S., Weller, U., Baveye, P.C., 2022. A holistic perspective on soil architecture is needed as a key to soil functions. Eur. J. Soil Sci. 73 (1) https://doi.org/10.1111/ejss.13152.

Vogel, H.J., Bartke, S., Daedlow, K., Helming, K., Kögel-Knabner, I., Lang, B., Rabot, E., Russell, D., Stößel, B., Weller, U., Wiesmeier, M., Wollschläger, U., 2018. A systemic approach for modeling soil functions. Soil 4, 83–92. https://doi.org/10.5194/soil-4-83-2018.

Ward, M., McDonnell, K., Metzger, K., Forristal, P.D., 2021. The effect of machine traffic zones associated with field headlands on soil structure in a survey of 41 tilled fields in a temperate maritime climate. Soil Tillage Res. 210, 104938 https://doi.org/10.1016/j.still.2021.104938.

List of Abbreviations

Abbreviation: **Definition**
CTF: controlled traffic farming
RTF: random traffic farming
BD: bulk density
MiP: microporosity
MaP: macroporosity
TP: total porosity
SPR: soil resistance to penetration
MWD: mean weight diameter
VESS: Visual Evaluation of Soil Structure
SPQI: soil physical quality index
f(i): soil function related to support root growth
f(ii): soil function related to ability to resist erosion and physical degradation
f(iii): soil function related to supply water for plants and edaphic fauna
f(iv): soil function related to allow gases exchange between soil and atmosphere