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MARCELA PACOLA OLIVEIRA

SISTEMAS DE PREPARO E QUALIDADE DO SOLO EM CANA-DE-AÇÚCAR

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Aos meus amados pais Roberto e Márcia,

Aos meus irmãos Roberta e Rodrigo,

Que são grandes incentivadores dos meus estudos

Dedico

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“A vida não é apenas sobreviver, é fazer a diferença”

Emerson, K. **Lost in Space**: Infinity's Edge. New York: Little, Brown and Company, 2020

ABSTRACT

The intensification of mechanization in sugarcane cultivation has spurred the development of new technologies to mitigate the effects of soil compaction. Deep strip-till with traffic control has been adopted by the sugar-energy industry as an alternative for improving soil profile. However, few studies have evaluated the effects of deep soil preparation on soil structure and sugarcane yield. The objective of this study was to evaluate the residual effects of liming and soil preparation on soil physical attributes, soil organic matter quality and sugarcane stalk yield after four years of cultivation in a clayey soil. The experiment followed a randomized block design with four treatments and four replicates. The treatments were conventional tillage without liming (CT0), conventional tillage with liming (CT2), modified deep tillage without liming (DT0) and modified deep tillage with liming (DT2). Soil physical attributes, total organic carbon, physical fractionation of organic matter, soil microbial biomass and sugarcane yield were evaluated. Regardless of lime application, deep tillage in the planting band improved the soil porosity to a depth of 0.4 m and decreased the carbon content in the surface layer. Both soil preparation methods improved aggregate stability in the 0.2–0.4 m layer in the absence of liming. Conventional tillage increased the surface soil C content and the mineral-associated C content in deeper layers. Deep tillage with liming increased microorganism activity and decreased compaction throughout the soil profile. Overall, deep tillage with liming improved soil chemical attributes and increased cane yield.

Keywords: *Saccharum spp;* deep strip tillage; traffic control; soil compaction; lime.

RESUMO

Com a intensificação da mecanização das áreas cultivadas com cana-de-açúcar, novas tecnologias para mitigar os efeitos da compactação do solo tem surgido. O preparo profundo canteirizado com controle de tráfego, tem sido adotado pelo setor sucroenergético como alternativa para melhoria do perfil do solo. Entretanto, existem poucos estudos na literatura sobre a eficácia desse sistema na estrutura do solo e produtividade do canavial. Diante disso, objetivou-se avaliar o efeito residual da calagem e sistemas de preparo nos atributos físicos, qualidade da matéria orgânica e produtividade de colmos da cana-de-açúcar após quatro anos de cultivo, em solo com textura argilosa. O delineamento experimental utilizado foi em blocos casualizados, com quatro tratamentos e quatro repetições. Os tratamentos consistiram em: Preparo Convencional sem calcário (CT0), Preparo Convencional com calcário (CT2), Preparo Profundo Modificado sem calcário (DT0) e Preparo Profundo Modificado com calcário (DT2). Foram avaliados os atributos físicos do solo, carbono orgânico total (COT), fracionamento físico da matéria orgânica, biomassa microbiana do solo e produtividade. Observou-se que o preparo profundo independentemente da aplicação do calcário melhorou a porosidade do solo na camada até 0,4 m e diminuiu os teores de carbono na camada superficial. Ambos os preparos sem calagem aumentaram a estabilidade de agregados na camada 0,2-0,4 m. A utilização do preparo convencional aumentou os teores de C em superfície e também os teores de carbono associado a minerais em profundida. O preparo profundo do solo com aplicação de calcário aumentou a atividade dos microrganismos e diminuiu a compactação em todo perfil. O preparo profundo com calagem melhorou os atributos químicos do solo e aumentou a produtividade de colmos.

Palavras-chave: *Saccharum spp;* preparo profundo em faixa; controle de tráfego; compactação do solo; calcário.

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FIGURES LIST

Chapter 1 – Soil tillage systems and forms of lime application on soil attribute enhancements in ratoon sugarcane

TABLES LIST

Chapter 1 - Soil tillage systems and forms of lime application on soil attribute enhancements in ratoon sugarcane

Chapter 2 - Soil management and liming in sugarcane fields improve soil quality and stalk yield

SUMMARY

GENERAL INTRODUCTION

Sugarcane is a semiperennial crop that is harvested annually. Brazil accounts for approximately 30% of global sugarcane production, and it is estimated that approximately 8.24 million hectares are destined for sugar-alcohol activity. The 2020/2021 harvest in Brazil yielded 654.52 million tons, more than half of which was produced in the state of São Paulo (354.28 million tons) (FAOStat 2018; CONAB 2022).

A major problem in sugarcane cultivation is soil compaction by mechanized operations from soil preparation to harvesting, which generate intense, heavy traffic on the soil (ESTEBAN et al., 2019). The machines used to harvest sugarcane cut one row at a time, resulting in heavy traffic in a given area that tends to be greatest near or directly on the planting row. As the size and weight of the agricultural machines involved in these tasks continue to grow, this problem is further aggravated and hinders crop emergence and growth (BOCHTIS et al., 2010; ESTEBAN et al., 2019).

Research has shown that the negative effects of mechanical intervention depend on soil characteristics such as texture, water content, organic matter, soil mobilization/depth of preparation and type of implement used and can include changes in density and soil microporosity (VISCHI - FILHO et al., 2017), macroporosity and total porosity (LANA et al., 2017), and soil resistance to root penetration (DE LIMA et al., 2017). It is essential to develop practices that minimize damage to soil structure to avoid impairing water and nutrient absorption and sugarcane yield (SOUZA et al., 2014).

One of the most effective strategies to reduce soil compaction is controlled traffic agriculture, which concentrates all of the tire load in a permanent traffic zone (ESTEBAN et al., 2019). Controlled traffic agriculture increases the volume of uncompacted soil for crop development (Galambošová et al., 2017). Guidance systems based on the Global Positioning System (GPS) allow soil preparation and furrowing to be planned and carried out only in predefined locations. This technology prevents ratoon damage due to machine traffic (SOUZA et al., 2014), in addition to providing fuel and energy savings compared with conventional tillage (MARTINS et al., 2021).

Deep tillage in strips was developed to promote the development and maintenance of the most favorable soil structure for root development and infiltration and water storage in a delimited “bed” site. This tillage system mobilizes the soil in a localized way using implements that simultaneously perform deep subsoiling, break clods, apply and incorporate amendments and windrow the straw (MARASCA et al., 2015; SCARPARE et al., 2019a). The effects of soil preparation on the physical structure of soil and yield depend on complex mechanisms that are sensitive to equipment type(s), traffic intensity, soil moisture conditions at the time of preparation, and management of plant residues, among other factors (KUMAR; SAINI; BHATNAGAR, 2012; MARASCA et al., 2015; SCARPARE et al., 2019a).

Furthermore, in mechanized harvesting systems, straw is left on the soil surface. Straw maintenance and decomposition directly affect the quantity, quality and lability of soil organic matter (SOM) and favor increases in total organic carbon (TOC) content in the surface layers (LOSS et al., 2011). TOC and SOM are very sensitive to disturbances caused by soil management (CORREIA; ALLEONI, 2011). Some components of SOM are indicators of its quality, such as labile carbon, light-fraction carbon and particulate organic matter carbon (POC) resulting from different particle size fractions (TORRES et al., 2015). Physical fractioning of SOM enables the quantification of not only POC but also mineral-associated organic carbon (MOC), which is useful for identifying changes arising from soil management practices (CAMBARDELLA; ELLIOT, 1992; TORRES et al., 2015).

Other indicators of soil quality include the microbiological properties of the soil, such as microbial biomass and metabolic activity (SANTONI et al., 2022). Microorganisms play a key role in maintaining soil quality by performing many essential functions, such as nutrient cycling, SOM renewal, nutrient mobilization and immobilization and soil structure maintenance (SANTONI et al., 2022; XUE; YAO; HUANG, 2006). Any change in the soil can directly affect soil microbial activity and abundance, leading to changes in biochemical processes, plant growth and development and soil fertility (DA SILVA et al., 2012; MUNIER-LAMY; BORDE, 2000).

For sugarcane cultivation, soil preparation is not limited to operations that impact the physical structure of the soil but also includes management of soil chemical properties to provide an ideal environment for sugarcane development.

Liming is particularly relevant, as it neutralizes toxic Al^{3+}, provides Ca^{2+} and Mg^{2+}, increases pH and improves soil physical and chemical attributes, resulting in better yields (ROSSETTO et al., 2004; SCARPARE et al., 2019a; ZANDONÁ et al., 2015). Liming also physically (MUNNER; OADES, 1989) and chemically (PAUL; CLARK, 1989) protects SOM from decomposition.

Liming recommendations for sugarcane were developed for use in conventional tillage systems. Research has not fully addressed the impact of new soil preparation practices on acidity correction. Raij (2008) evaluated the application of lime to sugarcane and concluded that the official recommendations for liming by Spironello et al. (1997) are underestimates for current cropping systems.

The present research hypothesized that deep tillage and concentrated lime application improve soil physical attributes, organic matter quality and microbial activity and provide favorable conditions for root development, thereby increasing stalk yield. In addition, the residual effect of liming under deep tillage is expected to correct soil acidity at greater depths than under conventional tillage, which promotes a correction gradient. Therefore, the objective of this work was to evaluate sugarcane performance and soil physical attributes, organic matter quality, microbial activity and C stocks as a function of conventional or deep tillage with and without liming.

CHAPTER 1

Soil tillage systems and forms of lime application on soil attribute enhancements in ratoon sugarcane

Abstract

Combining deep tillage (DT) with lime application at greater depths may improve sugarcane yield. The objective of this study was to evaluate the impact of conventional tillage (CT) and DT systems and liming on sugarcane productivity and soil physical attributes. The experiment was conducted in a clayey-textured Rhodic Hapludox soil cultivated with sugarcane for two growing seasons (first and third ratoons) using a randomized block design with four treatments and four repetitions. The treatments consisted of DT without liming (DT0), DT with liming (DT2), CT without liming (CT0), and CT with liming (CT2). In addition to sugarcane stalk and sugar yields, macroporosity (MA), microporosity (MI), total soil porosity (TP), weighted average diameter (WAD), aggregate stability index (ASI), soil penetration resistance (SPR), pH, potential acidity (H+Al), total soil organic carbon (SOC), particulate organic carbon (POC), mineral-associated organic carbon (MOC), calcium (Ca) and magnesium (Mg) were analyzed. Until the first ratoon, DT0 management alleviated soil compaction, but surprisingly, after the fourth ratoon, soil compaction was lowest in DT2. Unexpectedly, soil aggregation was similar between DT and CT. In general, DT, regardless of lime application, reduced SOC and POC in the soil surface layer. However, the combination of liming with DT (DT2) provided better soil fertility, leading to increased sucrose concentrations and stalk yields.

Keywords: *Saccharum spp*, furrower, physical soil, lime, deep strip-tillage, localized tillage

[1] This chapter was submitted in the Use soil management follows the formatting rules of the same.

1.1 Introduction

Brazil accounts for approximately 1/3 of global sugarcane production. An estimated 8.2 million ha in Brazil are dedicated to sugar-alcohol activity, with production of 654.52 million tons in the 2020/2021 season. The state of São Paulo is responsible for more than half of the country's production (Conab 2022; FAOStat 2018). However, this yield is below the productive potential of the crop, which according to Monteiro and Sentelhas (2014) can reach up to 200 Mg ha^{-1}. As it is a semi-perennial crop, it remains in the field for a long period of time, which results in a progressive loss of productivity, since the structural quality of the soil is reduced due to the intense traffic of machines.

Soil physical attributes typically change during the sugarcane cultivation period, and these changes may impact crop development and yield (Cherubin et al. 2017). The cost of preparing the soil for sugarcane field implantation is equivalent to approximately 1/4 of the crop yield (Martins et al. 2021). Hence, the choice of soil preparation systems has a substantial impact on sugarcane yield, longevity, and maximum economic return (Blanco-Canqui et al. 2017).

The total area to be planted is typically subjected to conventional soil preparation (plowing and harrowing) and scarification to improve root development and crop yield (Campos et al. 2022a). However, in the long term, this preparation accentuates soil degradation, changes soil attributes, causes erosion and compaction, alters water flow, and increases CO_2 emissions and production costs due to the greater energy input required for full-area scarification (Filho et al. 2017; Marasca et al. 2015; Martins et al. 2021; Tim Chamen et al. 2015).

An emerging alternative for sugarcane cultivation is controlled traffic, a new soil mechanization management technique that minimizes the adverse effects of conventional mechanization by separating traffic areas from crops and limiting the passage lines of tires (Roque et al. 2010). Controlled traffic reduces soil compaction close to the cultivation zone (Barbosa et al. 2020; Lovera et al. 2021; Scarpare et al. 2019). As a result, sugarcane roots can develop in deeper layers than under conventional tillage. Under controlled traffic, only strips of soil are toiled for furrowing and planting sugarcane (Farhate et al. 2022; Rossetto et al. 2008; Scarpare et al. 2016).

However, the impact of controlled traffic practices on water and nutrient use, root development and biomass production are unknown. It is thought that controlled traffic will mitigate the negative impact of soil organic matter (SOM) mineralization stimulated by excessive soil turning and pH elevation (Campos et al., 2022; Scarpare et al., 2019; Shukla et al., 2021). Moreover, improving the physical and chemical characteristics of the soil may increase soil C stocks due to long-term increases in phytomass and root production. In addition, limestone application is expected to increase the chemical and physical protection of SOM by favoring cationic bridges and the formation of organomineral complexes that hinder SOM decomposition (Muneer and Oades 1989; Paul 2015).

In most Brazilian states, the standard practice is to harvest the raw plant without burning. Limestone recommendations were developed for conventional preparation systems and harvesting of burnt sugarcane, and research on the impact of innovative systems for preparing and harvesting sugarcane on limestone application is lacking. Raij (2008) concluded that the official recommendations for liming of sugarcane given by Spironello et al. (1996) are underestimates for the current sugarcane cultivation system.

Overall, there is little evidence to support the benefits of this innovative management practice for promoting improvements in physical and chemical soil conditions over the long term. We hypothesized that the deep-bands tillage system i) increases phytomass and sugarcane yield by improving soil physical properties and ii) decompacts soil more efficiently than conventional management. We aimed with this work to evaluate the influence of conventional and deep soil tillage systems, combined or not with liming, on the chemical and physical properties of the soil, and on the stalks and sugar yields throughout the sugarcane cycle. In this paper we present and discuss the effect of two tillage practices on sugarcane crop establishment, improvement soil profile structural conditions and reduction of environmental impacts

1.2 Materials and methods

1.2.1 Location and characteristics of the experimental area

The study was conducted on a sugarcane plantation after the second and fourth mechanized harvests (first and third ratoons, 2016/2017 and 2018/2019 harvests, respectively). The experiment was established in August 2015 in partnership with Zilor Sugar Mill Group in the municipality of Macatuba, SP (22º 29' 20" Sd 48º 47' 06" W), using the variety CTC20. The soil in the experimental area is classified as a clayey-textured

Rhodic Hapludox (USDA - Soil Survey Staff 2014). The predominant climate in the region is classified according to Alvares et al. (2013) as Cwa, with an average annual temperature of 21°C, minimum temperature of 4°C (June to August) and maximum temperature of 38°C (November to February). The highest volume of precipitation occurs between the months of September and March, with January being the rainiest (Cunha and Martins 2009). The monthly meteorological data for maximum, average and minimum temperatures and precipitation during the period of the experiment are presented in Figure S1.

For the initial characterization of soil chemical (Raij et al. 2001) (Table 1), physical and granulometric attributes (EMBRAPA 1997)(Table 2), 12 samples were randomly collected from each experimental area with a Dutch-type auger at soil depths of 0–0.2 m, 0.2–0.4 m, 0.4–0.6 m, and 0.8–1.0 m. At these same depths, undeformed samples were collected using Kopecky's steel ring from the crop row for soil physical characterization (Table 2).

1.2.2 Experimental design and treatments

The experimental design was a randomized block design with four treatments and four repetitions, giving a total of 16 experimental plots. The treatments were DT2–deep tillage with limestone; DT0–deep tillage without limestone; CT2–conventional tillage with limestone; and CT0–conventional tillage without limestone (Figure 1). Each experimental plot had an area of 240 m² and contained 10 20-m-long rows with alternating spacing of 1.50 × 0.90 m between rows. Lime application followed the results of the analysis of the soil characteristics in the area according to the recommendation of Spironello et al. (1996). The lime rate was based on previous experiments that revealed that yields are highest when twice the recommended rate is applied. Dolomitic lime with a composition of 300 g kg^{-1} CaO, 170 g kg^{-1} MgO, relative total neutralization power (TNP) of 95%, and neutralization power (PN) of 107% was used.

Conventional tillage comprised tillage with a plowing harrow, subsoiling and plowing harrow again over the total area, which was followed in CT2 by the application of 10 Mg ha^{-1} of lime over the total area. Deep tillage was performed as modified deep tillage using equipment with a rotary hoe that worked up to 0.4 m and a subsoiling rod that worked up to a depth of 0.8 m. In DT2, liming was performed only in the tillage strips (50% of the area); ¾ (7.5 Mg ha^{-1}) of the dose was distributed on the soil surface and subsequently incorporated with the rotary hoe and subsoiler. The remaining dose (2.5 Mg ha^{-1}) was applied via tines located behind the subsoiler shaft of the equipment. In both tillage systems, controlled traffic was used; the traffic zones were separated by controlling the passage of machines in a permanent line around the plant growth zones by GPS.

1.2.3 Soil physical analysis

Soil physical analysis was performed after the second and fourth harvests in September 2017 and November 2019, respectively. A mini backhoe was used to open trenches with a width of 1.2 m, length of 1.0 m and depth of 1.0 m; one wall exposed the crop row, while the other exposed the traffic zone. A total of 16 trenches were opened. In each wall of the trench, undeformed samples were collected using Kopecky's steel ring from the crop row (not trafficked by machines) and the inter row (area trafficked by machines) at soil depths of 0.0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–1.0 m. The macroporosity (MA), microporosity (MI) and total porosity (TP) were determined following the Embrapa (1997) procedures. Monoliths (0.2 m high x 0.1 m wide) were also collected at the same soil depths for aggregate stability analysis. The aggregate stability (ASI) and weighted average diameter (WAD) were determined using wet soil according to Kemper and Chepil (1965) with a vertical oscillation device (Yoder 1936).

The same samples used to determine the chemical attributes of the soil were used to determine total organic carbon (SOC), particulate organic carbon (POC) and mineral-associated organic carbon (MOC). Granulometric fractionation was adapted from Cambardella and Elliot (1992). SOC was measured by an elemental analyzer (LECO-TruSpec1 CHN, Leco Corp., St. Joseph, MI, USA). MOC was calculated as the difference between SOC and POC.

SPR was determined after the sugarcane harvest using an impact penetrometer model IAA/Planasucal (Stolf et al. 2014) with a cone area of 1.29 cm^2, angle opening of 30° and stem length of 0.7 m. Readings were taken in the form of a 1.2-m perpendicular transept graded every 0.2 m to a depth of 0.8 m. In all, 9 points at 0.15-m intervals were evaluated; the first point was located in the center of the crop row, and the last point was in the traffic zone. The first three points was averaged to obtain SPR value for the crop row. The data are presented in Megapascals (MPa) according to the equation proposed by (Stolf et al. 2014).

The analysis of physical fractionation of organic matter was performed using the adapted methodology of Cambardella and Elliot (1992).

1.2.4 Soil chemical analysis

Soil was sampled for fertility analysis after the second and fourth harvests (first ratoon, October 2017, and third ratoon, October 2019). Soil was removed from five sampling points per plot with the aid of a probe-type auger at depths of 0.0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8 and 0.8–1.0 m. The samples were air-dried, crushed, passed through a 2-mm sieve and placed in properly sealed and identified plastic bags. pH ($CaCl_2$), potential acidity (H+Al), calcium (Ca) and magnesium (Mg) concentrations were determined according to the methodology proposed by Raij et al. (2001).

1.2.5 Stalk and sugar yields

Stalk and sugar yields (Mg ha^{-1}) were determined before harvesting (October 2017 and September 2019 for first and third ratoons, respectively). The stalk yield was determined by collecting two 4-m lengths of stalks from adjacent rows in each plot; the stalks were topped, defoliated, and weighed on a portable digital scale. The clean stalks were sent for processing in the laboratory, and the total recoverable sugar (TRS; kg of sugar per Mg of stems) was measured according to Fernandes (2011). Sugar yield (Mg ha^{-1}) was obtained by multiplying the stalk yield values (Mg ha^{-1}) by the TRS (kg Mg^{-1}), and divided by 1000.

1.2.6 Statistical analysis

Data were subjected to analysis of variance (ANOVA). The means of the soil physical and chemical attributes were compared separately by depth and sugarcane production parameters in each season of the year by the LSD test at 10% probability.

1.3 Results

1.3.1 Soil physical properties and SOM quality

After four sugarcane cycles, tillage management impacted soil porosity attributes (Figure 2). In general, the modified deep tillage (DT) increased ($p<0.1$) soil macroporosity in both years (Figure 2 A and B), mainly at a soil depth of 0.2–0.4 m. Regardless of liming, DT increased macroporosity by approximately 50% in 2019 compared with 2017 (0.10 cm^{-3}), while CT increased macroporosity by nearly twofold in 2019 compared with 2017 (0.03 cm^{-3}). In 2017, microporosity at the soil surface (0–0.2 m) was lowest in DT0.

The effects of lime application and soil preparation management on aggregation varied depending on soil depth (Figure 3). In both years, WAD decreased with increasing depth. In the soil surface layer (0.0–0.2 m), DT2 decreased WAD ($p<0.1$) by 34% in 2017 compared with DT0 (3.81 m^3 m^{-3}), and CT2 decreased WAD by 40% in 2019 compared with CT0 (3.22 m^3 m^{-3}). WAD in the deepest layer (0.8–1.0 m) was lowest in CT2 in 2017 and DT2 in 2019 (Figure 3 A and B).

In general, soil aggregation as measured by ASI decreased over the crop cycles. Soil aggregation was highest in DT0 ($p<0.1$) in 2017, with values of greater than 90% in the topmost layer ($p<0.1$), while in 2019, ASI values were highest in the 0.2–0.4 and 0.8–1.0 m layers in CT0 (Figure 3 C and D).

As shown in Table 1, before experiment establishment in 2017, SPR was lowest in DT0, mainly in the upper layers (up to 0.4 m). Interestingly, in 2019, DT2 resulted in SPR values less than 2 MPa across the entire soil profile (Figure 4), in contrast to the other treatments ($p<0.1$).

SOC was highest ($p<0.1$) in the soil surface layer (0.0–0.2 m) in both years (Figure 5 A and B). In general, SOC was approximately 36% higher in CT0 than in DT0 in 2017. In 2019, SOC in the 0.0–0.2 m soil layer was 17% higher under DT (12.4 g kg^{-1}) than under CT, regardless of liming. Similar to the trend of SOC, POC was highest at a soil depth of 0.0–0.2 m in 2017 and was 90% higher in CT2 than in DT0 (0.84 g kg^{-1}). In 2019, CT, regardless of the addition of limestone, increased POC by approximately 25% compared with DT (1.47 g kg^{-1}) (Figure 5 C and D). As expected, POC decreased in the deeper soil layers; at a soil depth of 0.4–0.6 m, POC was highest in DT0 and CT0, while at a soil depth of 0.8–1.0 m, POC was the same in all treatments. In general, in both years, MOC was higher ($p<0.1$) under CT than under DT at soil depths of 0.0–0.2 and 0.2–0.4 m, regardless of liming (Figure 5 E and F). At soil depths of 0.4–0.6 and 0.6–0.8 m, MOC was highest in CT0 ($p<0.1$) in both years.

1.3.2 Soil chemical properties

In 2017, the soil pH ranged from 4.5 in the treatments without liming to 5.6 in the treatments with liming. In 2019, the soil pH ranged from 4.1 (high acidity) in DT to 6.0 (low acidity) in CT2 at soil depths ≤0.4 m (Figure 6 A and B). In general, DT improved soil acidity throughout the sugarcane cycle. The potential acidity (H+Al) decreased with increasing pH (Figure 6 C and D). Similar to the trend of pH values, Ca and Mg contents were highest ($p<0.1$) in DT2 at depths ≤0.4 m (Figure 6 E, F, G and H) and decreased in deeper layers.

1.3.3 Stalk and sugar yields

For first ratoon (2017), TRS and stalk and sugar yields were higher under liming application ($p<0.1$) (Figure 7). For third ratoon (2019), these variables were highest in DT2 (Figure 7 A and B). When the two harvests were combined, stalk and sugar yields and TRS increased ($p<0.1$) by 47%, 63% and 6%, respectively, under DT2 compared with CT0, which had the lowest yields.

1.4 Discussions

1.4.1 Soil physical properties

Soil preparation is an important agricultural practice that impacts soil properties (primarily soil physics) and crop development (Sharma et al. 2011). Compared with CT, DT improved macroporosity over the years (Figure 2 A and B). This increase was related to the disruption of the soil layer surface by the rotary hoe, which reached a working depth of 0.4 m during bed formation, increasing soil porosity and reducing soil bulk density (Barbosa et al. 2019; Farhate et al. 2022) and SPR (Cherubin et al. 2016; Marasca et al. 2015; Shukla et al. 2021). Although the treatments did not affect TP (Figure 2A and B), studies suggest that high TP is common in clayey soils and mainly reflects micropores, whereas the volume of macropores is usually deficient, which causes problems with water infiltration, gas exchange and reduced root growth (Cintra et al. 1983).

Mechanized harvesting leaves sugarcane straw on the soil surface, which is expected to enhance soil macrofauna over the years and improve soil physical quality (Barbosa et al. 2019b, 2021; Castioni et al. 2018; Tenelli et al. 2019). Indices such as MWD and WAD are used to evaluate aggregate stability, with higher values indicating better stability (Yan et al. 2020). The highest WAD indices obtained in our work in limestone treatments suggest that soil improved soil structure, increased resistance to erosion and physical protection to increase the fixation of organic carbon (Gao et al. 2019; Hu et al. 2021).

DT0 reduced soil aggregation at greater depths in both years due to the decrease in SOC in the soil surface layers (Regelink et al. 2015; Rigon et al. 2021). Lime application had a detrimental effect on soil aggregation under DT, possibly because the soil preparation led to greater pulverization. In addition, liming may promote an increase in the net negative charge, which will influence the dispersive forces of soil colloids and affect the structural stability of the soil (Roth and Pavan 1991; Seta and Karathanasis 1996). Persson et al. (1995) reported that SOC losses after liming can be attributed to increased rates of mineralization and increased transport at underlying horizons. Liu et al. (2014) found that intensive soil preparation practices decreased soil aggregation indices, with destruction of macroaggregates > 1 mm. Our study suggests that DT increased SOC mineralization as a result of deep soil disturbance (Cavalcanti et al. 2019; Góes et al. 2005; Weiler et al. 2019).

Soil organic matter is one of the main indicators of agroecosystem sustainability, particularly under tropical conditions (Gao et al. 2017), but is extremely susceptible to land use and management (Kunde et al. 2018). Mechanized harvesting adds large quantities of crop residues (sugarcane straw) to the soil surface, which along with the root system contribute to SOC stock enhancement (Carvalho et al. 2017). Hence, the decrease in SOC under DT is important. According to Rangel and Silva (2007), SOC stocks can increase in systems with less soil disturbance. The increase in POC under CT also helps explain the enhancement of soil physical properties. The POC fraction is more susceptible to soil disturbance than SOC and is used as an indicator of conservation management (Castioni et al. 2018; Gmach et al. 2019). The increase in POC might have been a result of enhanced crop rooting (Franzluebbers and Stuedemann 2002).

The pressure that the tires of sugarcane machinery apply to the soil surface is a real issue (Marasca et al. 2015). Maintaining sugarcane straw on the surface is essential for preserving soil physical quality (Castioni et al. 2018), dissipating loads, and avoiding increases in soil density and SPR (Barbosa et al. 2019; Gao et al. 2017; Satiro et al. 2017). Our results suggest that the most efficient management for soil decompaction was DT2, despite the lack of an effect on soil density (Table SUPL A), thus confirming our second hypothesis. The positive impact of DT2 was likely due to the rotary hoe mechanism associated with the deep subsoiler, which breaks the soil structure and reduces physical limitations to crop development by increasing soil macroporosity and consequently minimizing SPR (Guimarães 2019). Compaction in deeper layers is particularly problematic, as highlighted by Tim Chamen et al. (2015) and Tullberg et al. (2007), due to the difficulty of recovering the soil structure by natural or mechanical processes.

Lime application, particularly at greater depths, might promote favorable conditions for sugarcane root development (Campos et al. 2022a). An SPR value of 2 MPa is considered the critical limit (Lima et al. 2015; Serafim et al. 2012), but this limit may vary depending on soil type, management and cultivated species. Barbosa et al. (2018) established a value of 2.5 MPa as a limiting factor for root development in a clayey oxisol cultivated with sugarcane. Hence, the SPR values in our study are below the critical limits in the literature, which suggests that DT can reduce root restriction due to soil compaction after four years of cultivation. These SPR values may reflect the beneficial effect of liming on SOC content. In addition, increased pH stimulates microbial activity and greater stabilization of soil aggregates (Franco et al. 2020; Martíni et al. 2021).

1.4.2 Soil fertility

As expected, liming also improved soil fertility attributes. In both years, the enhancements in soil fertility were pronounced throughout the soil profile, confirming the correction of soil acidity by liming in deeper layers (Campos et al. 2022a, b). Because lime particles have low solubility, the lime reaction occurs close to the application site (Campos et al. 2022a; Vargas et al. 2019).

The residual effect of liming on soil fertility observed in our study is important because sugarcane productivity gradually decreases over years of cultivation. In addition, sugarcane requires high amounts of nitrogen fertilizer and extracts large amounts of nutrients (Campos et al. 2022b; Crusciol et al. 2017; Otto et al. 2021). These requirements are associated with the exudation of organic acids by the roots, which may cause soil reacidification. Hence, high doses of lime, which has low reactivity, could be an alternative to reduce the costs associated with liming operations (Campos et al. 2022a; Hinsinger et al. 2003).

Ca^{2+} and Mg^{2+} concentrations were highest in DT2, which reflects the high dose of lime as well as the form of application and distribution, specifically, near the crop row (Campos et al. 2022a). The displacement of fine lime particles downward from the application site is a function of precipitation/leaching of Ca^{2+} and Mg^{2+} bound to organic acids from SOM decomposition and inorganic (carbonate, nitrate and sulfate) binders (Antonangelo et al. 2017; Shukla et al. 2021). Furthermore, physical displacement of lime particles can occur through the soil biopores created by root growth and decomposition Auler et al. (2017) since the root system of sugarcane is renewed at each harvest, which can facilitate the entry of organic material throughout the soil profile (Ball-Coelho et al. 1992; Campos et al. 2022a).

Lime doses of 1 to 6 Mg ha^{-1} have been reported to increase soil pH, SOC, exchangeable Ca^{2+}, Mg^{2+} and base saturation and decrease subsurface aluminum saturation (up to 0.6 m) (Crusciol et al. 2016; Vieira Fontoura et al. 2019). In addition, the increase in soil pH due to liming reduces the concentrations of Fe, Cu, Mn and Zn in the soil profile

(Auler et al. 2019; Bossolani et al. 2021b, 2022). Despite this, a possible reduction in the levels of micronutrient studies in our studies were not sufficient to limit sugar yields.

Sugarcane has a high demand for Ca and Mg (Wang et al. 2021). In weathered soil with high acidity, root development at greater soil depths can be limited, even when adequate limestone is deposited under the surface. Thus, the mode of distribution of soil amendments is an essential consideration (Bossolani et al. 2021a; Costa and Crusciol 2016). DT2 improved the distribution of Ca^{2+} and Mg^{2+} along the entire soil profile, creating an environment suitable for root development (Campos et al. 2022a). The positive impact of the lime application treatments reflects the importance of Ca in the formation of the cell wall and of Mg in the physiological processes of sucrose synthesis and distribution (de Bang et al. 2021; Garcia et al. 2020; Kleczkowski and Igamberdiev 2021).

1.4.3 Stalk and sugar yields

The higher stalk yield under DT and sugar yield in DT2 can be explained by improvements in soil physical properties compared with CT management, confirming our first hypothesis. The application of lime is cost-effective for sugarcane, as it increases stalk yield and, most importantly, allows several years of harvesting (Basto et al. 2010), which positively impacts the availability concentrations of macro- and micronutrients. In addition, our results show that even though sugarcane is considered tolerant of soil acidity (Rossetto et al. 2004), high doses of lime can improve yields, especially in soils with high acidity and low levels of Ca and Mg.

DT management provided higher porosity, aeration and water distribution along the entire soil profile, allowing better root development (Barbosa et al. 2020; Farhate et al. 2022; Lovera et al. 2021; Marasca et al. 2015). In addition, the increase in sucrose in DT2 can be explained by the improvement of Ca and Mg contents by liming, as previously discussed. Considering that the DT system is a relatively new and expensive form of management, further studies evaluating soil physical, chemical and biological attributes in different production environments are recommended.

1.5 Conclusions

Deep tillage management with liming provided the best soil conservation effect in the sugarcane fields. Until the first ratoon, DT0 relieved soil compaction. Surprisingly, after the fourth ratoon, the soil in DT2 was uncompacted. Unexpectedly, soil aggregation was similar between DT and CT. In general, DT, regardless of lime application, reduced SOC and POC in the superficial soil layer. The addition of liming in DT2 enhanced soil fertility, which resulted in improved sucrose concentrations and stalk yields. Our results are important to improve sugarcane management with integrated approaches focused on reducing environmental impacts. More research to assess the agronomic and economic feasibility of no-tillage systems in sugarcane strips should be carried out so that all aspects that make up the production system are clearly explained and the technology validated.

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Conflicts of Interest

The authors declare no competing interests

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Table 1 - Chemical attributes of the soil before the implementation of the experiment in a Red Nitosoil, 2015, Macatuba, SP, Brazil.

Depth	pH	M.O	P_{resina}	S	Al^{3+}	H+Al	K	Ca	Mg
(m)	$CaCl_2$	(g dm^{-3})	(mg dm^{-3})		------------ (mmolc dm^{-3}) -----------				
0.0-0.2	4.4	23	12	21	5	52	2.0	19	9
0.2-0.4	4.0	15	7	47	10	59	0.8	10	5
0.4-0.6	4.0	12	4	36	13	59	0.3	6	3
0.6-0.8	3.9	10	3	50	11	66	0.2	7	3
0.8-1.0	4.0	10	4	45	13	59	0.7	6	2
Depth	SB	CTC	V%	m	Fe	Cu	Mg	Zn	B
(m)	-(mmolc dm^{-3})-			%	--------------- (mg dm^{-3}) ------------				
0.0-0.2	31	82	37	14	23	3.0	9.7	1.1	0.20
0.2-0.4	16	75	21	38	15	3.3	4.3	0.5	0.18
0.4-0.6	10	69	14	57	8	2.2	3.0	0.1	0.12
0.6-0.8	10	76	13	52	7	1.8	1.2	0.1	0.06
0.8-1.0	9	68	13	59	7	1.8	2.0	0.1	0.08

Table 2 - Physical attributes of the soil before the implementation of the experiment in a Rhodic Hapludox, 2015, Macatuba, SP, Brazil.

Depth	Attributes				Porosity			SPR
	WAD	WMD	ASI	Sd	TP	MA	MI	
(m)	---- mm ----		(%)	(g cm^{-3})	----- (cm^3 cm^{-3}) -----			(MPa)
0.0-0.2	4.17	3.38	97.54	2.34	0.41	0.02	0.40	2.41
0.2-0.4	3.19	1.70	94.99	2.16	0.44	0.03	0.42	2.96
0.4-0.6	2.70	1.86	90.28	2.05	0.47	0.05	0.42	2.63
0.6-0.8	2.07	1.23	55.50	1.95	0.47	0.06	0.41	2.37
0.8-1.0	2.39	1.26	85.85	-	-	-	-	-

WAD = weighted average diameter; WMD = weighted mean diameter; ASI = aggregate stability index; TP = total porosity; MA = macroporosity; MI = microporosity; Sd = soil density; SPR = soil penetration resistance

Figure 1 - Conceptual diagram showing soil tillage treatments with and without lime

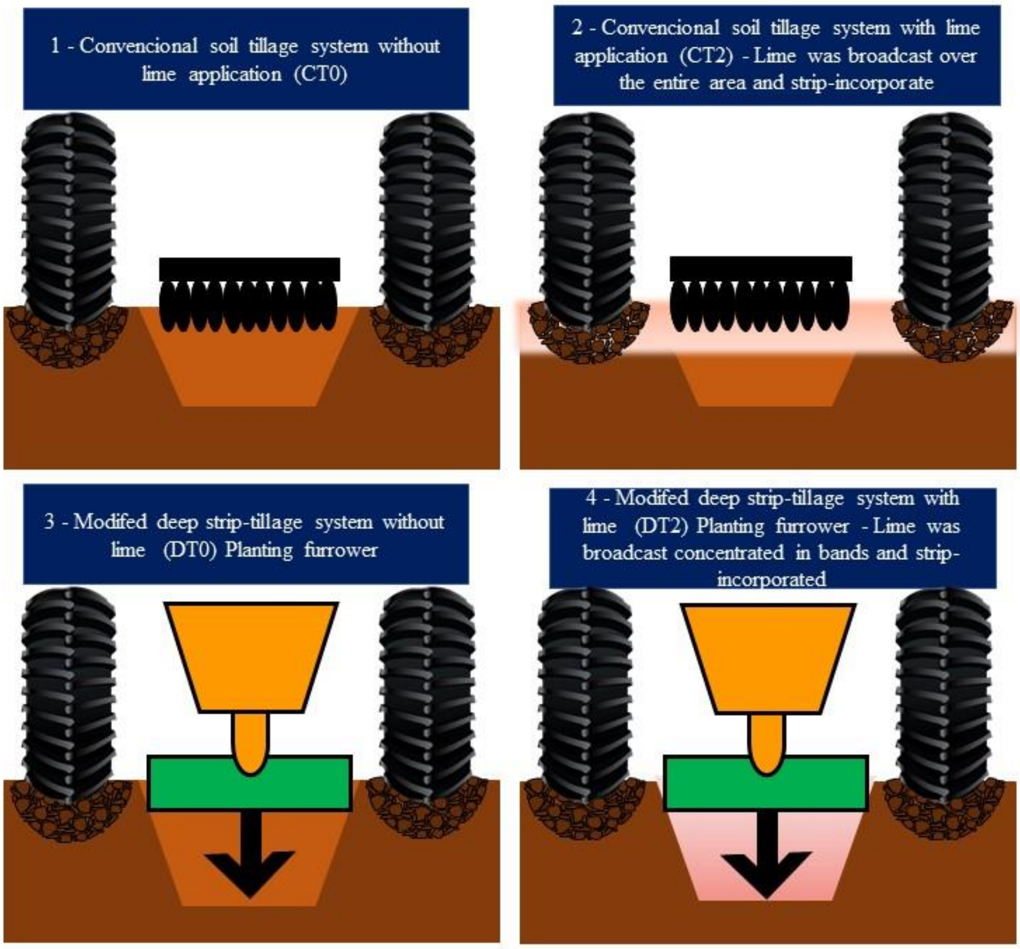


Figure 2 - Total porosity (TP)**,** microporosity (MI), macroporosity (MA) at depths of 0.0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8 and 0.8-1.00 m, after the second (A) and fourth harvest (B) in function of the type of soil tillage, in the presence or absence of limestone application, Macatuba, SP. DT2= Modified Deep Tillage with limestone, DT0= Modified Deep Tillage without limestone, CT2= Conventional Tillage with limestone, CT0= Conventional Tillage without limestone. Different letters represent significative difference between the treatments within each growing parameter (LSD, $p \leq 0.1$).

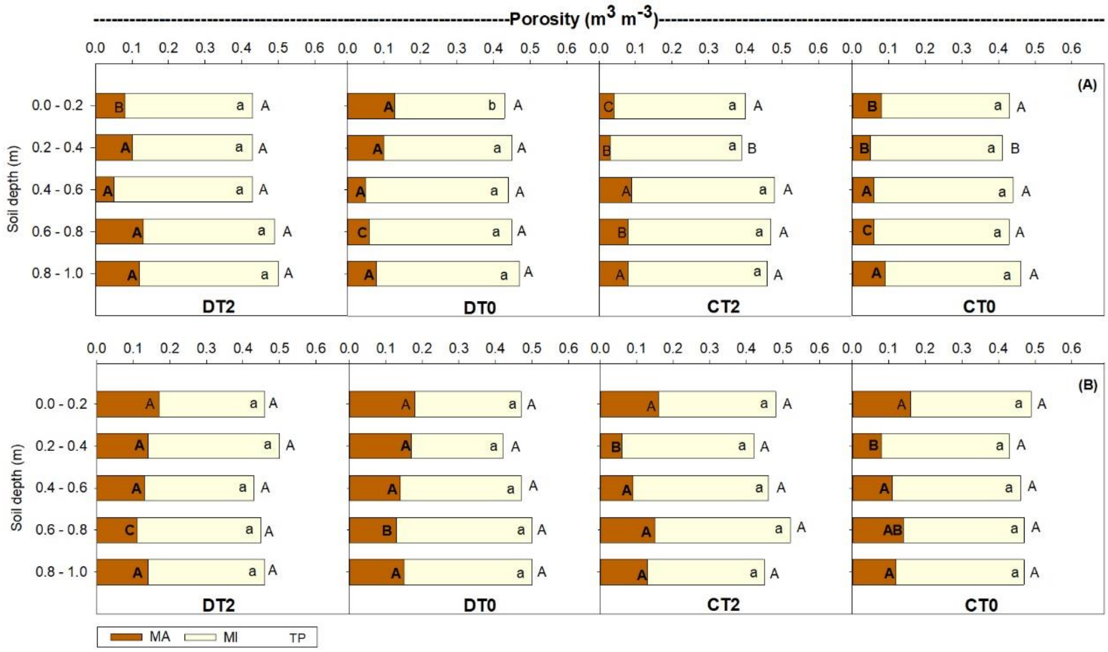


Figure 3 - Weighted mean diameter (WAD) and aggregate stability index (ASI), at of 0.0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8 and 0.8-1.00 m soil depths according to the soil preparation, and lime application or absence, Macatuba, SP. DT2= Modified Deep Tillage with limestone, DT0= Modified Deep Tillage without limestone, CT2= Conventional Tillage with limestone, CT0= Conventional Tillage without limestone. Different letters represent significative difference between the treatments within each depth (LSD, p ≤ 0.1).

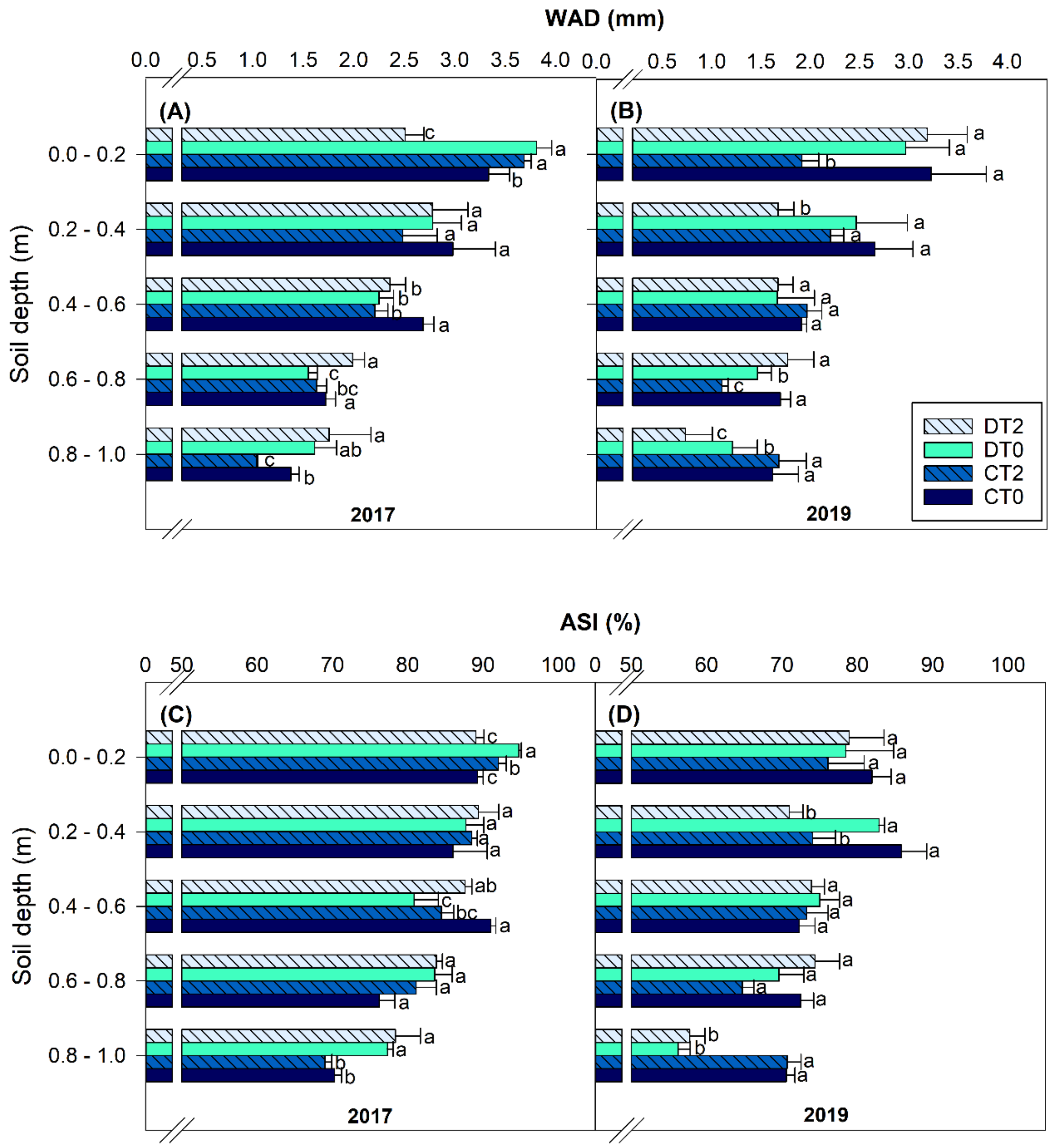


Figure 4 - Evaluation of soil resistance to penetration (SPR) as a function of tillage systems in the presence or not of lime. Horizontal bars indicate the least significant difference of LSD test ($p < 0.1$) for each depth

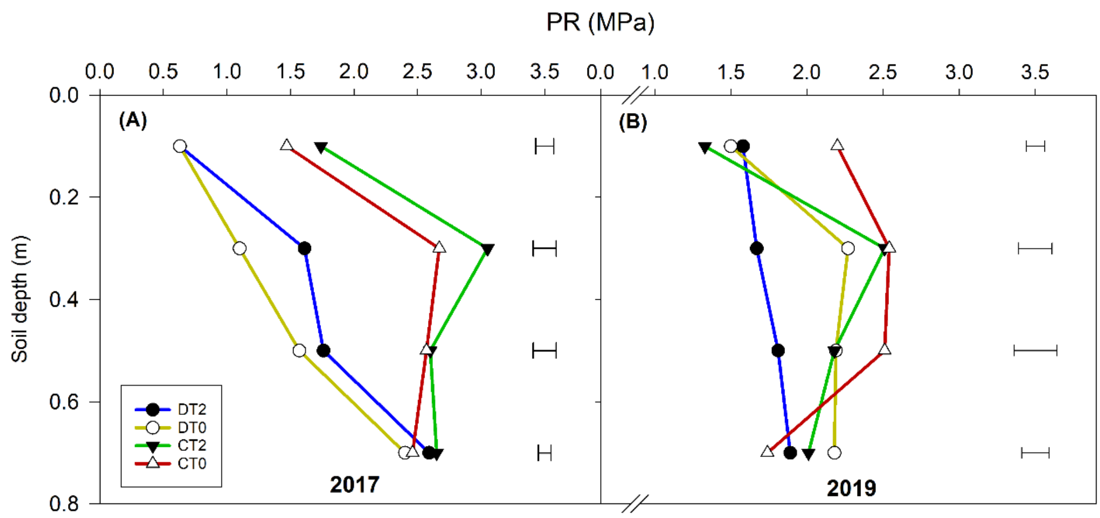


Figure 5 - Soil organic carbon (SOC), particulate organic carbon (POC) and mineral-associated organic carbon (MOC) at the soil profile under different soil tillage systems and liming, Macatuba, SP. Different letters represent significative difference between the treatments within each depth (LSD, $p \leq 0.1$).

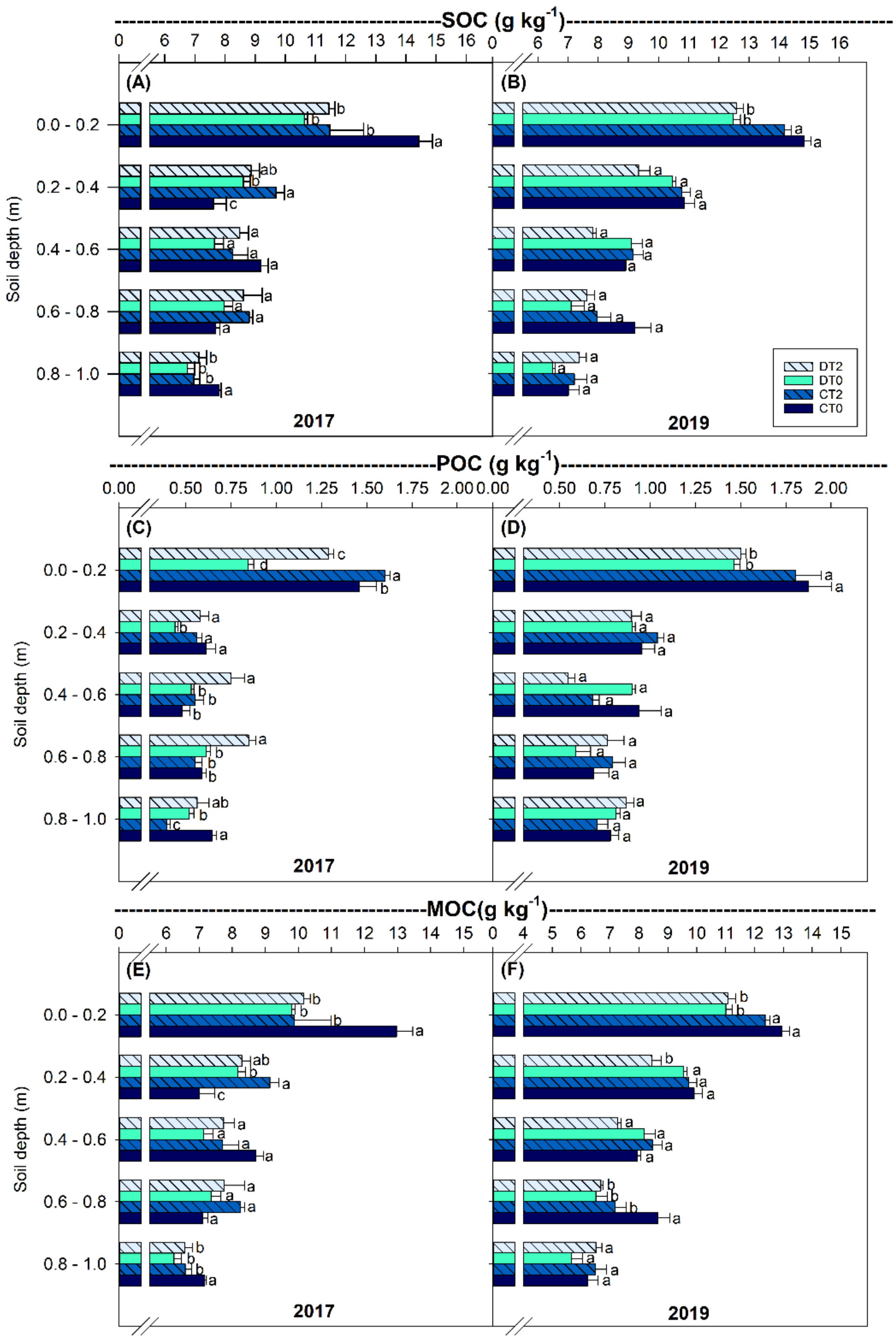


Figure 6 - Soil acidity (pH), potential acidity (H+Al), calcium (Ca) and magnesium (Mg) in layers 0.0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0 m depth. Horizontal bars indicate the least significant difference of LSD test ($p < 0.1$) for each depth

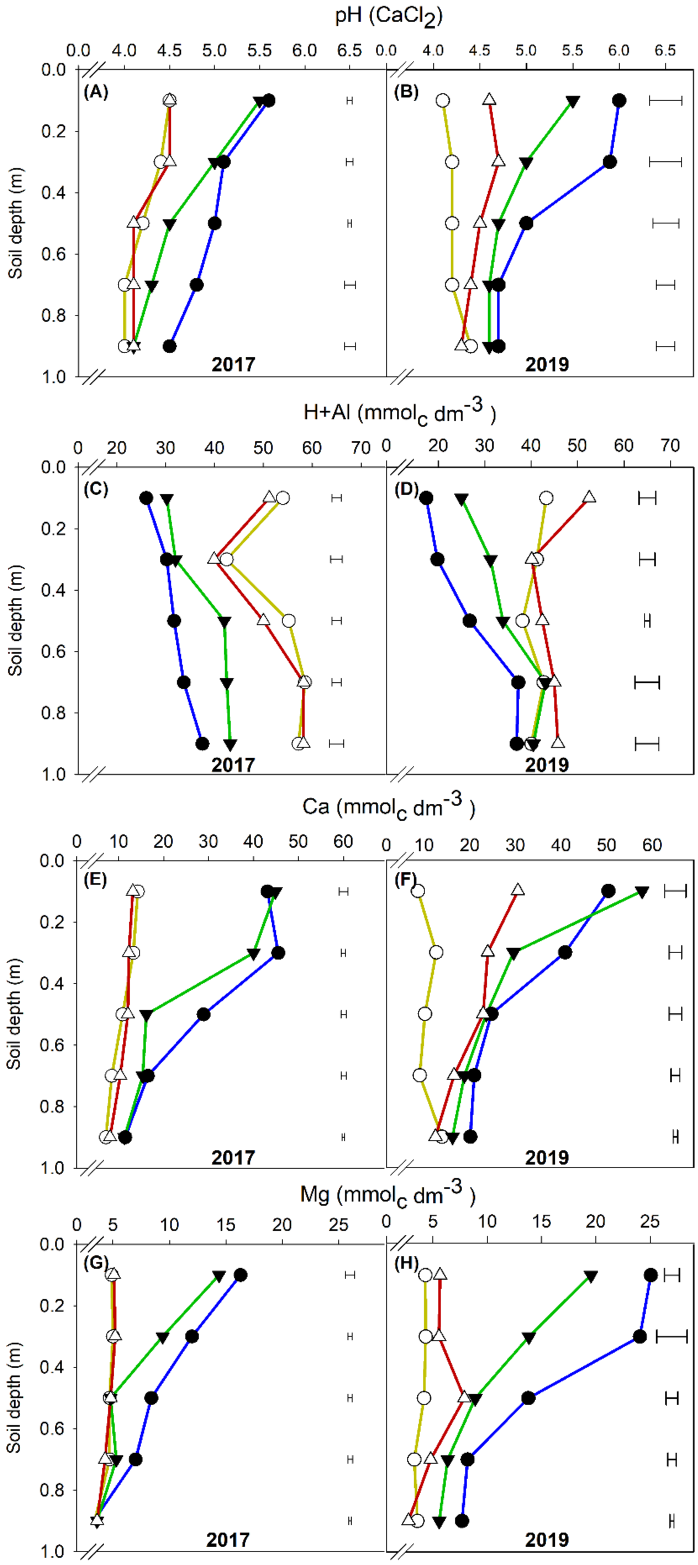


Figure 7 - Stalk yield (tons of stalk per hectare), sugar yield and Total Recoverable Sugar (TRS) of the second and fourth ratoon as a function of tillage systems. Different letters represent significative difference between the treatments.

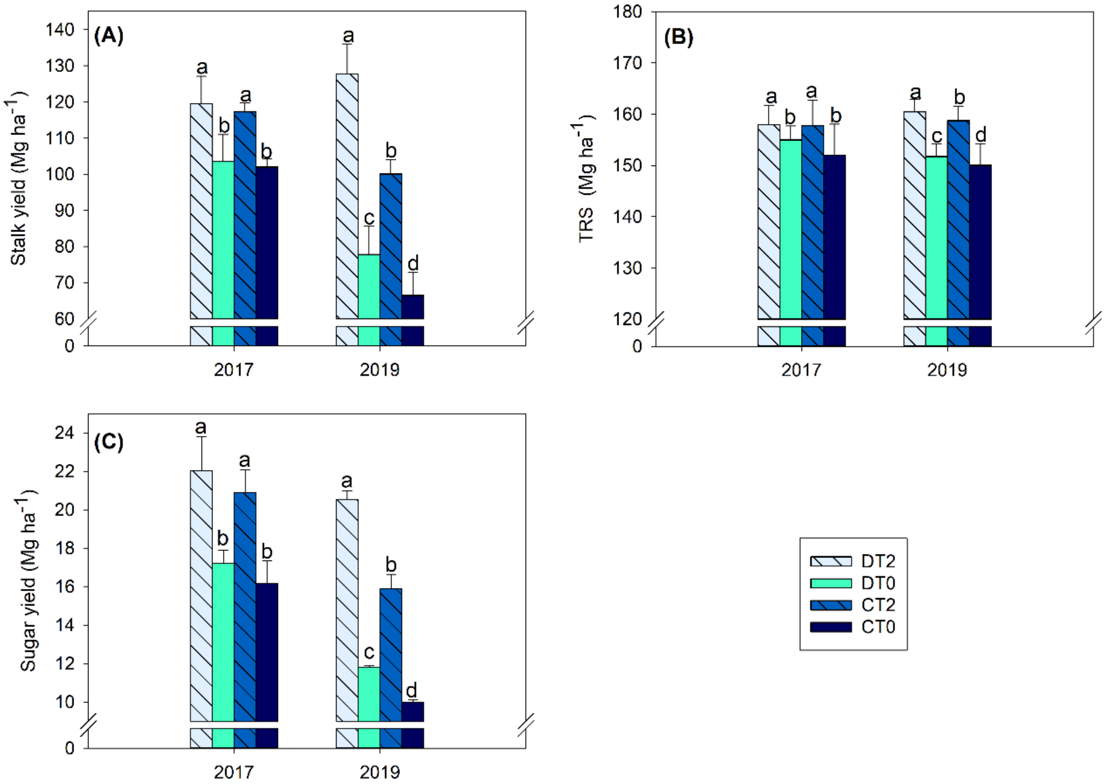
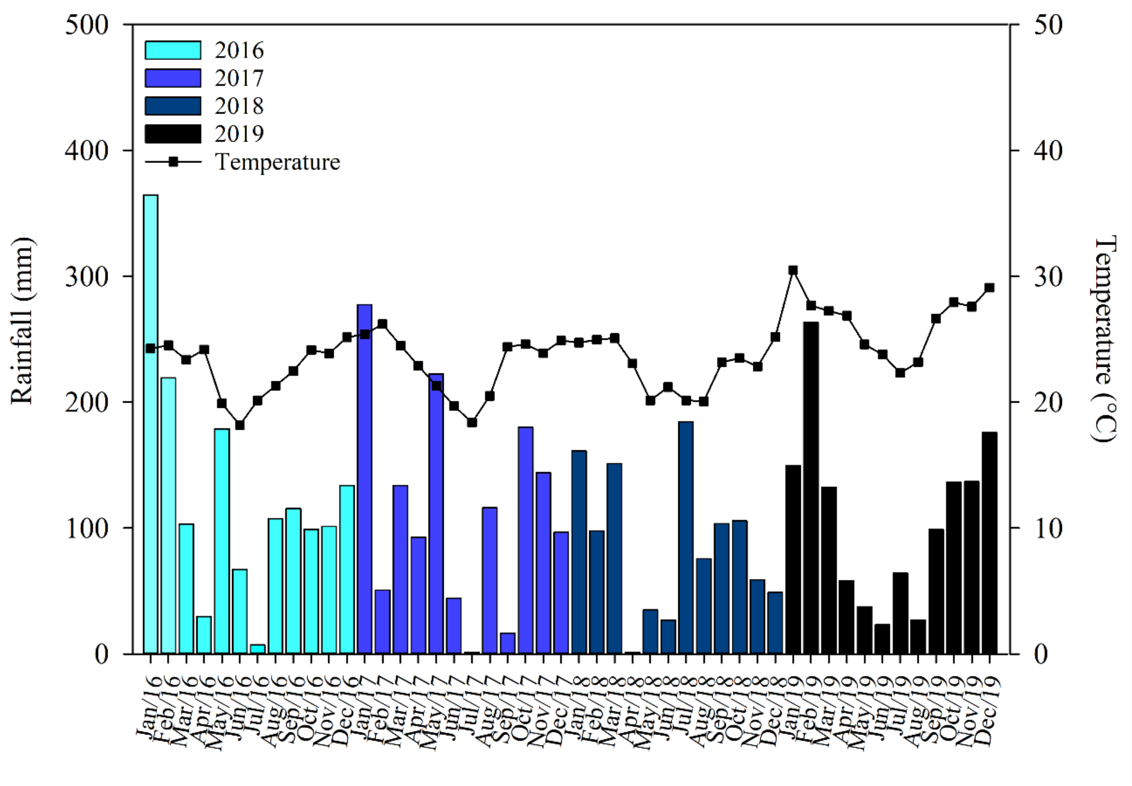


Figure S2 - Average temperature and rainfall (mm) during the third and fourth year of sugarcane cultivation, corresponding to the period from January 2016 to December 2019, in Macatuba, SP, Brazil.



CHAPTER 2

Soil management and liming in sugarcane fields improve soil quality and stalk yield

Abstract

We hypothesized that deep soil preparation and the residual effects of localized lime application improve soil quality and increase sugarcane yield. The objective of this study was to evaluate the influence of conventional and deep tillage on soil carbon stocks, soil microbial activity, soil physicochemical attributes, and sugarcane yield after four cropping cycles. The experiment was conducted from 2016 to 2019 in a clay Hapludox, and the second and fourth ratoons were evaluated. A randomized block design with four preparation systems and four repetitions was used. The treatments consisted of conventional tillage without liming (CT0), conventional tillage with liming (CT2), deep strip tillage without liming (DT0) and deep strip tillage with liming (DT2). In addition to sugar and stalk yields, the following soil physical attributes were evaluated: macro (MA) and microporosity (MI), weighted average diameter (WAD), aggregate stability index (ASI), density (SD) and resistance to penetration (PR). The analyzed soil chemical attributes were pH, potential acidity (H+Al), calcium (Ca^{2+}) and magnesium (Mg^{2+}). Soil carbon and microbial activity were assessed by determining soil organic carbon (SOC), microbial biomass (Cmic), the metabolic quotient (qCO2), the microbial quotient (qMic), microbial respiration (Resp) and dehydrogenase enzyme activity (DHA). The results showed that DT2 improved soil quality by enhancing fertility, increasing aggregate stability, and alleviating soil compaction. In addition, DT2 increased microbial activity but decreased SOC content. Finally, DT2 resulted in increased stalk and sugar yields.

[1] This chapter was submitted in the Applied soil ecology follows the formatting rules of the same.

Key words: *Saccharum officinarum*, deep tillage, lime, soil physical characteristics, soil fertility, microbial activity.

2.1 Introduction

Despite aging sugarcane fields, a low renewal rate, low investment, outdated technology, and average yields of less than 80 Mg ha^{-1}, Brazil has the highest sugarcane production in the world (CONAB, 2022). However, the shift from crop residue burning to mechanized planting and raw sugarcane harvesting has increased soil physical degradation by increasing soil compaction, which also impairs sugarcane root growth (Guimarães Júnnyor et al., 2019; Shukla et al., 2021). To avoid further degradation of soil cultivated with sugarcane, management systems designed to increase soil organic matter (SOM) are highly recommended (Segnini et al., 2013). Maintaining crop residues on the soil surface improves SOM lability and stimulates increases in soil organic carbon (SOC) in the topsoil layers (Xu et al., 2019). Long-term studies have confirmed that limiting soil disturbance and maintaining crop residues on the soil surface increase SOC content (da Costa et al., 2021; Rigon et al., 2020; Rigon and Calonego, 2020), consistent with soil conservation principles. The ability of soil management practices to enhance agricultural sustainability (Carvalho et al., 2017; Crusciol et al., 2017), mitigate soil degradation (Marasca et al., 2015; Scarpare et al., 2019), and increase sugarcane yield and profitability (Campos et al., 2022b) has been widely studied. However, no-tillage practices are rarely applied in sugarcane cultivation in Brazil (Cherubin et al., 2018), and conventional tillage is the most common management practice for sugarcane establishment (de Campos et al., 2022).

Precision agriculture and guidance systems based on global positioning systems allow the soil to be selectively prepared and furrowed for sugarcane in predefined locations (Campos et al., 2022b; De Moraes et al., 2019; Sanches et al., 2021). In addition, new equipment for furrow planting that allows in-depth root exploration has been developed. These technologies are expected to improve the chemical properties of tropical weathered soil by enabling soil corrective application specifically in the planting row (concentrated correction) to increase soil pH, Ca^{2+} and Mg^{2+} and neutralize Al^{3+} (Crusciol et al., 2017; Zandoná et al., 2015). In addition, splitting crop rows between machine traffic reduces the impact of wheel traffic (Scarpare et al., 2019) on the physical structure of the soil.

Lime application hinders the decomposition of organic matter by protecting it both physically (Munner and Oades, 1989) and chemically (Paul and Clark, 1989). However, in highly weathered soils, liming facilitates clay particle dispersion and aggregate breakdown, which could lead to short-term SOC depletion due to increased soil microbial activity (Albuquerque et al., 2000; Paradelo et al., 2015). On the other hand, the correction of soil acidity by liming also favors plant growth, leading to a greater contribution of C via plant residues from the shoots and roots (Bossolani et al., 2022). Few long-term studies have evaluated the effects of soil acidity and soil management on SOM dynamics and soil quality by integrating physical, chemical, and biological soil properties.

We hypothesized that deep tillage with concentrated lime application has complementary residual effects compared with conventional tillage, including i) increased SOC due to higher sugarcane biomass and soil microbial biomass and activity, mainly on the soil surface; ii) reduced soil compaction; and iii) increased sugarcane yield. The aim of this study was to evaluate the effects of conventional and deep strip tillage with lime application on soil quality by assessing soil carbon stocks, soil microbial biomass, soil physicochemical attributes and sugarcane yield in the second and fourth ratoons.

2.2 Materials and methods

2.2.1 Site description, experimental design, and treatments

The experiment began in 2015 and continued until August 2019, a period encompassing four crop cycles (plant cane and three subsequent ratoons), in a commercial area of Macatuba (22º 29 ′ S and 48º 47' W) in São Paulo State, Brazil. The climate of the region is classified as Cwa tropical according to the Köppen climate classification, with high humidity and hot summers. Fig. S1 presents the average monthly temperatures and rainfall from January 2017 to December 2019. The soil is classified as a clayey-textured Rhodic Hapludox (Ditzler et al., 2017), and the chemical and textural characteristics are presented in Tables 1 and 2.

The experimental design was randomized blocks with four treatments and four replications. The treatments were as follows: CT0 (conventional tillage without lime); CT2 (conventional tillage with lime); DT0 (deep tillage without lime) and DT2 (deep tillage with lime) (Fig. 1). The plot size was 240 m^2, with ten 20-m-long rows. The CT system used in this study is the standard in Brazil for sugarcane cultivation. CT consisted of tillage with a harrow, subsoiling and harrowing again in the total area, while DT comprised tillage with a rotary hoe and a subsoiler rod only in the crop cultivation band.

The lime dose was calculated based on the results of the soil analysis (Table 1) and the recommendations of Spironello et al. (1996), which call for a base saturation of 60% for sugarcane. Lime was applied at twice the recommended dose based on the results of previous experiments testing 4 lime doses (no liming, recommended dose, twice the recommended dose and three times the recommended dose), which showed that productivity was highest at twice the recommended dose.

In CT, lime was applied in the total area before the first soil-turning operation. Then, subsoiling was carried out with four rods spaced 1.5 m apart with a working depth of 0.40 m. In DT, lime was applied only in the preparation band (half of the area); ¾ of the dose was applied to the soil surface and incorporated with a rotary hoe and subsoiler rod, and ¼ of the dose was applied in bands behind the subsoiler rod with outlets at depths of 0.4 m and 0.8 m. The dose at the lowest depth was corrected for the smaller volume, since it was applied in bands.

Immediately after liming, sugarcane variety CTC20 was planted mechanically using controlled traffic technology at 18 viable buds per m^2, a depth of 0.3 to 0.4 m, and a spacing of 1.50 x 0.90 m. During planting, 500 kg ha^{-1} of 06-28-24 NKP fertilizer and 40 kg ha^{-1} of S in tablet form were applied at the bottom of the planting furrow. Sixty days after planting, 200 kg ha^{-1} of fertilizer containing micronutrients (10% Zn, 1.8% B, 0.12% Mo, 0.6% Cu and 1.2% Mn) was applied. In the subsequent crops (ratoons), 650 kg ha^{-1} of 18-07-28 NPK fertilizer plus 40 kg ha^{-1} of S in tablet form were applied as topdressing. Other standard management practices were carried out according to the needs of the crop.

2.2.2 Soil physical and chemical analyses

Immediately after harvesting the second and fourth ratoons, trenches with a width of 1.0 m and depth of 1.2 m were opened, and undisturbed soil samples were collected at a depth of 0.0–0.2 m using volumetric rings with a height of 0.05 m and a diameter of 0.048 m. The apparent density of the soil (Bd) was calculated from the relationship between the dry mass and the sample volume, and the total porosity of the soil was calculated from the difference in mass between saturated and dry samples. The soil macroporosity (MA) was calculated from the difference between the water content of the saturated sample and the mass of the sample at equilibrium at a pressure of -0.006 MPa. The soil microporosity (MI) was calculated as the difference between the total porosity and macroporosity (Smith et al., 1991).

To analyze soil aggregate stability, spatulas were used to extract three soil monoliths (0.1 m long × 0.15 m wide, 0.05 m thick) per plot from the center of the 0–0.2 m layer in the same trench used to collect the volumetric rings. After air drying, the soil samples were passed through a set of superimposed sieves in which the upper and lower sieves had meshes of 8 and 4 mm, respectively. Aggregate stability was evaluated using 25 g of the soil that passed through the 8-mm mesh and was retained on the 4-mm mesh. The weighted average diameter (WAD) was calculated according to the methodology of Kemper and Chepil (2015).

Soil chemical analyses were performed using standard methods for Brazilian tropical soils (Raij et al., 2001). Five individual soil subsamples were collected from each plot at a depth of 0.0–0.2 m with the aid of a galvanized steel probe auger (69 mm in diameter) and pooled to form a single sample for each plot. The soil pH was measured in 0.01 M $CaCl_2$ according to Raij et al. (2001). Exchangeable cations (Ca^{2+} and Mg^{2+}) were extracted using cation exchange resins and determined by atomic absorption spectrometry (Shimadzu AA-7000; Raij et al., 2001). Total acidity at pH 7.0 (H+Al) was estimated by the Shoemaker-McLean-Pratt buffer method (Shoemaker et al., 1961).

2.2.3 Physical fractionation of soil organic matter

The samples used to analyze soil chemical attributes were also used to determine SOC by granulometric fractionation (Cambardella and Elliot, 1992) The samples were air dried, crushed, passed through a 2-mm mesh sieve and ground in a porcelain mortar. SOC was measured by an elemental analyzer (LECO-TruSpec1 CHN, Leco Corp., St. Joseph, MI, USA). This method is based on the principle that combustion at an elevated temperature (950°C) in the presence of oxygen gas inflow will convert all carbon in the sample to CO_2.

2.2.4 Microbial analysis

Soil was sampled from a depth of 0–0.1 m to determine microbial biomass C (Cmic) by the fumigation-incubation method of Jenkinson (1976) with modifications. The soil dehydrogenase enzyme activity (DHA) was estimated according to Van Os and Van Ginkel (2001). The results were fit to a standard curve and expressed as the content of triphenyl formazan (TTF - g g^{-1}). The metabolic quotient (qCO_2), expressed in mg C-CO_2 g^{-1} CBMS h^{-1}, was calculated as the ratio of C-CO_2 released in the microbial respiration analysis to the carbon content in the soil microbial biomass (Anderson and Domsch, 1993). The microbial quotient (qMic), expressed as a percentage, was calculated as the ratio of the carbon content in the soil microbial biomass to the total organic carbon content (Anderson and Domsch, 1993).

2.2.5 Stalks and sugar yield

Before harvest (second ratoon in October 2017 and fourth ratoon in September 2019), stalk and sugar yields (Mg ha^{-1}) were determined by collecting the plants in the central 4 m of two rows. In the laboratory, cleaned stalks were used to determine total recoverable sugar [TRS; kg of sugar per Mg of stalks (Fernandes, 2003)]. Sugar yield (Mg ha^{-1}) was calculated by multiplying the stalk yield (Mg ha^{-1}) by the TRS (kg Mg^{-1}) and dividing by 1000.

2.2.5 Statistical analysis

The homogeneity and normality of the data were tested prior to analysis of variance. The means of the soil physical and chemical attributes and sugarcane yield parameters in each year were compared by the LSD test ($p \leq 0.1$). Redundancy analysis (RDA) with the Monte Carlo permutation test (999 permutations) was performed to determine whether the microbial biomass and productivity responses of the sugarcane were correlated with soil properties to identify the most important soil factor(s) shaping the responses.

2.3 Results

2.3.1 Soil physical properties

The soil management treatments significantly ($p<0.1$) affected all soil physical attributes except soil bulk density (Bd) in one or both growing seasons (2017 and 2019; Fig. 2). In 2017, soil macroporosity (MA) was highest in DT0, with a corresponding decrease in microporosity (MI), but in 2019, neither MA nor MI differed significantly between the treatments (Fig. 2-A and B). Soil aggregation, as measured by the weighted average diameter (WAD), was approximately 35% lower in DT2 than in DT0 in 2017 ($p<0.1$) (Fig. 2-C). Compared with the average of all other treatments, WAD was approximately 38.5% lower in CT2 in 2019. The aggregate stability index (ASI) was highest in DT0 in 2017 ($p<0.1$) and did not significantly differ among the treatments in 2019 (Fig. 2-D). Finally, PR was higher in the CT treatments than the DT treatments in 2017, regardless of liming. In 2019, PR was approximately 50% higher in CT0 than in DT0 (Fig. 2-F).

2.3.2 Soil chemical attributes

As expected, the liming treatments (CT2 and DT2) improved soil fertility (Fig. 3). Interestingly, even after four years of lime application (2019), deep tillage (DT2) had the greatest positive impact on soil acidity (Fig. 3-A) and potential acidity (Fig. 3-B). In addition, the liming treatments increased Ca^{2+} and Mg^{2+} levels compared with the corresponding treatments without liming (Fig. 3-C, D). The impact of localized application (DT2) was most pronounced for Mg^{2+}, particularly in 2019. In both ratoons evaluated, Ca^{2+} was highest in CT2. In addition, DT2 and CT2 reduced H+Al levels in 2017 and 2019 compared with DT0 and CT0, respectively (Fig. 3-B).

2.3.3 Soil organic carbon and microbial biomass analysis

In general, soil organic carbon (SOC) and microbial biomass (Cmic) increased between 2017 and 2019, particularly in the liming treatments. In 2017, SOC in CT0 was approximately 30% higher than the average SOC in DT0 and DT2 (Fig. 4-A). In 2019, SOC remained highest in the CT treatments, where the average SOC content was approximately 17% higher than the average for the DT treatments.

CT0 resulted in the highest Cmic in 2017 and 2019 and the highest microbial quotient (qMIC) in 2019 (Fig. 4-B). In 2017, qMIC did not differ between CT0 and CT2 (Fig. 4-C). But it increased considerably in DT2 treatment within the evaluated period.

DT2 presented the highest values of qCO2 and RESP in the two years of evaluation (Fig. 4-D and E). It is also emphasized that DT0 presented the lowest values in these attributes in 2019.

Dehydrogenase activity (DHA) was clearly much higher in 2017 than in 2019 (Fig. 4-F). Overall, there was an average reduction of 60% in DHA between the two assessments, but the treatments that received limestone showed higher values in 2019.

2.3.4 Stalk and sugar yields

Soil management and liming application significantly ($p<0.1$) affected the sugarcane yield parameters in both years (Fig. 5). Specifically, in 2017, lime application significantly ($p<0.1$) increased stalk yield by 15%, sugar yield by 28% and TRS by 3% (Fig. 5-A, B, and C, respectively). In 2019, isolated effects of soil management and lime application on these variables were observed, but stalk yield, sugar yield and TRS were highest in DT2.

2.3.5 Redundancy analysis of environmental and biological factors

Redundancy analysis (RDA) showed that 96% of the soil factors were explained (sum of X and Y axes) by the total variation in soil microbial activity (Fig. 6-A). The treatments segregated into three groups: group 1 was DT2, group 2 was DT0, and group 3 was CT2 and CT0. Monte Carlo permutation analysis indicated that PR ($F = 55.15$; $p \leq 0.001$), SOC ($F = 2.98$; $p \leq 0.100$), and MI ($F = 5.05$; $p \leq 0.061$) were the soil factors that positively impacted qCO_2 and qMIC in the CT treatments, regardless of lime application, while pH ($F = 15.60$; $p \leq 0.016$) and Ca^{2+} ($F = 7.19$; $p \leq 0.022$) were the factors responsible for increasing RESP in DT2.

Soil microbial activity was responsible for 70% of the sugarcane yield variation (Fig. 6-B). The treatments segregated into two groups: group 1 comprised the treatments without liming (CT0 and DT0), and group 2 corresponded to the treatments with liming (CT2 and DT2). RESP ($F=10.06$; $p\leq0.009$), qCO_2 ($F=3.44$; $p\leq0.087$) and Cmic ($F=3.56$; $p\leq0.073$) strongly influenced stalk and sugar yields and TRS in CT2 and DT2.

The third RDA revealed that the soil attributes were responsible for 99% of the variation in sugarcane yield (Fig. 6-C). The treatments segregated into two groups, with CT0 and DT0 as group 1 and CT2 and DT2 as group 2. Significant correlations between sugarcane parameters and soil attributes were observed. In the liming treatments (CT2 and DT2), sugarcane yield was most strongly influenced by Mg^{2+} ($F=2.60$; $p \leq 0.097$), pH ($F=2.34$; $p \leq 0.100$), Bd ($F=2.97$; $p \leq 0.100$) and MI ($F=4.09$; $p \leq 0.037$). In the treatments without liming (CT0 and DT0), H+Al ($F=111.82$; $p \leq 0.001$) and WAD ($F=5.45$; $p \leq 0.021$) were the main soil attributes responsible for reducing sugarcane parameters.

2.4 DISCUSSION

2.4.1 Soil physical attributes

The effects of deep tillage observed in 2017, especially on soil macroporosity, indicated short-term improvements in soil porosity (Fig. 3). Over successive crop cycles, heavy machine traffic can result in soil particle disaggregation and soil compaction, and deep tilling can disrupt these changes in soil structure (Aguilera Esteban et al., 2019; Esteban et al., 2020; Oliveira et al., 2022). These results are consistent with the effects of DT on soil compaction and physical quality reported in the literature (Botta et al., 2022; Marasca et al., 2015). However, the effects of mechanical methods on soil physical conditions are reportedly temporary, especially in annual cropping systems (Calonego et al., 2017; Tuzzin de Moraes et al., 2016).

Consistent with our second hypothesis, soil management with DT efficiently alleviated soil compaction in the soil surface layers (Fig. 2-F) and maintained PR below the critical limit of 2 MPa (Cherubin et al., 2016), even after the third ratoon cycle. MA also increased (Fig. 2-A). These results are in agreement with those of de Oliveira et al. (2019), who observed beneficial impacts of DT on soil quality in plant cane and first ratoon. According to Otto et al. (2011), improving soil physical attributes is essential for the initial establishment and root development of sugarcane. Thus, DT appears to be a promising soil management option to ensure adequate soil physical quality for sugarcane cultivation.

The enhancements in WAD and ASI in DT0 (Fig. 2-A and B) could be associated with increased root growth in addition to changes in physical and biological processes, which together can promote soil aggregate formation and stabilization (Graf and Frei, 2013; Hu et al., 2021; Le Bissonnais et al., 2018). Aggregate size impacts soil structure, nutrient availability, and soil biological activity and therefore is closely related to soil quality (Yan et al., 2020).

2.4.2 Soil chemical attributes

In general, DT2 alleviated soil acidity and improved the soil chemical properties in the surface layers compared with the initial soil fertility (Table 1). The correction of soil acidity in DT2 indicates that neutralization occurred close to the lime application site (Campos et al., 2022a, 2022b). Furthermore, the lime concentration applied in DT2 was nearly twice the applied dose in CT2, and higher doses can lead to lower lime reactivity (Bossolani et al., 2020; Rheinheimer et al., 2018; Tiritan et al., 2016).

Ca^{2+} and Mg^{2+} concentrations increased in DT2. Lime application is an important strategy to improve soil fertility, particularly in weathered soils in tropical regions with dry seasons (Bossolani et al., 2021b, 2021c; Rigon et al., 2021). Combining a balanced soil pH with adequate Mg^{2+} availability may help crops withstand water deficit periods without marked decreases in yield (Bossolani et al., 2021b). Ca^{2+} plays a fundamental role in membrane formation and cell wall structure (Meriño-Gergichevich et al., 2010); thus, low soil Ca^{2+} concentrations directly interfere with sugarcane leaf and root development (Campos et al., 2022a; Li et al., 2019b; Meriño-Gergichevich et al., 2010).

Due to sugarcane's high nutrient demands, residual effects of liming are essential, especially for managing nitrogen fertilization (Cantarella and Rossetto, 2014; Otto et al., 2019). Agricultural mismanagement will result in a progressive decline in soil fertility that will be further potentiated by successive cuttings throughout the sugarcane crop cycle, increasing the need to renew the sugarcane field (Crusciol et al., 2017; Otto et al., 2021).

2.4.3 Soil organic carbon and microbial biomass analysis

The increase in SOC was smaller in the DT treatments than in the CT treatments due to the greater soil disturbance and higher rate of SOM mineralization in the former (Castioni et al., 2018; Gmach et al., 2019). The rate of SOM mineralization depends not only on the tillage system and soil management but also on soil texture and mineralogy (Kusumawati et al., 2019; Mouhamad et al., 2015). The interactions of clay minerals with Fe and Al sesquioxides in tropical soils significantly influence C protection (Six et al., 2002). The soil disturbance associated with lime application may have stimulated losses of organic matter, and there was insufficient time to input new biomass and increase the labile and active soil C pools (Ferrari Neto et al., 2021). High clay content may indicate a substantial level of association of SOM with soil minerals (Carmo et al., 2012). According to Carmo et al. (2012), soils with higher clay content have a greater capacity for SOM conservation and stabilization.

Contrary to our first hypothesis, SOC was lowest under DT. This result suggests that the impact of intense tillage systems, such as DT that spray the soil surface by rotary hoe, increases SOM mineralization in clayey soils (Kögel-Knabner and Amelung, 2021). Further longitudinal assessments of SOC content are needed to understand the potential effects of soil management on the C distribution in deeper soil layers. We hypothesize that transitory C pool restoration is balanced at the soil surface and that decreases in SOC content are offset by increased C inputs from crop residues in the long term (Costa et al., 2021). The trend in SOC content mainly reflects the large amount of crop residues available at the soil surface and the stimulation of microbial activity resulting from lime application (Inagaki et al., 2017). The increase in the metabolic coefficient (qCO2) observed in the DT treatments may also partially explain the lower evolution of SOC in the two years, as there was a greater loss of C in these treatments due to microbial activity. This effect may be more pronounced by soil disturbance, liming and with a consequent increase in O2 in the system, but it may favor some groups within the succession and microbial community (Karhu et al., 2014).

The different segregations of the treatments in the RDAs indicate strong impacts of soil fertility and physical attributes on soil microbial activity and cascading effects on SOM decomposition processes, nutrient availability, biological sustainability and ecosystem yield (Bossolani et al., 2022; Ferreira et al., 2007; Souza et al., 2012).

Soil microbial biomass is an active component of soil organic C that is sensitive to soil changes and therefore is often used as an indicator of soil quality (Cardoso et al., 2013; Nunes et al., 2020). Microbial biomass is greatest inside soil macroaggregates, which protect SOM from oxidation and generate an ideal chemical and physical environment for soil microorganisms (Oliveira et al., 2014; Garcia et al., 2020). The decreases in microbial biomass carbon levels in the DT0 treatment may also be the result of impact of soil disturbance on macroaggregate formation and stabilization, without the protective effect of liming.

The limited Cmic under DT0 soil management may also be due to greater soil disturbance. The action of the rotatory hoe and surface soil pulverization influence microbial populations and result in oscillations in substrate, temperature, soil moisture and aeration (Morugán-Coronado et al., 2022). qMic is often related to soil quality/degradation (Islam and Weil, 2000) and indicates the amount of soil carbon that is immobilized by microbial biomass (Carneiro et al., 2009). According to Sun et al. (2016), reduced tillage increases the microbial population and activity in the top 0.05 m of soil, and these changes are directly related to increased microbial metabolic capacity. According to Anderson and Domsch (1978) qMic values of 2 to 5% are considered suitable for soil sustainability, but were not observed in any of the treatments in this study (Fig. 4). The observed qMic values covered a wide range (0.27 to 1.6%), most likely due to the differences in soil management practices. Physical soil disturbance causes macroaggregate breakdown and exposes the carbon protected inside macroaggregates from microbial processes (Cambardella and Elliot, 1992).

Interestingly, DT2 increased qCO_2, indicating a decrease in the efficiency of organic compound utilization, with greater release of C in the form of CO_2 and incorporation of less C into microbial tissues (Kuzyakov, 2010). In addition, qCO_2 was highest in this treatment, as soil microorganisms under stress consume more oxidizable carbon for maintenance (Partelli et al., 2012). Liming clearly interferes with soil microbial activity, increases the rates of labile organic matter mineralization and soil respiration, and causes greater consumption of SOM pools by microorganisms (Bossolani et al., 2021a; Holland et al., 2018). It is known that soil practices with the introduction of nutrients can reduce its diversity and also favor some groups such as copiotrophs that can more actively consume the more labile organic matter (Kim et al., 2021) this may have happened in the treatments that received the liming.

Dehydrogenase activity is highly sensitive to changes in land use, and several studies have used dehydrogenase activity to assess the effects of different soil management practices on the soil biota (Latkovic et al., 2020; Melero et al., 2009; Shukla et al., 2020). DHA was higher under CT than under DT, indicating higher respiratory potential, that is, more intense SOM decomposition, under the former (Järvan et al., 2014; Latkovic et al., 2020). DHA evaluation may also represent the greater presence of active microorganisms that respond within hours to soil C input. In contrast, the lack of response shows a greater predominance of dormant microorganisms (Blagodatskaya and Kuzyakov, 2013). It can be confirmed by the reduction of DHA in 2019, which reduced active microorganisms in the soil. This may be a reflection of the lower availability of C in the soil and also unfavorable conditions in the physical attributes of the soil.

2.4.4 Crop yield

Our study confirmed that DT soil management has a positive impact on sugarcane yield, when combined with concentrated lime (Fig. 5). Liming was associated with increases in the concentrations of sucrose and TRS, indicating improved soil fertility and residual effects of liming on Mg^{2+} availability, which is directly related to sucrose biosynthesis and transport (Bossolani et al., 2018; Campos et al., 2022a; Fageria and Nascente, 2014; Tiritan et al., 2016). The RDAs confirmed the positive associations of soil fertility parameters (Mg^{2+} and pH) and microbial activity (RESP and qCO_2) with sugarcane stalk yield that were previously reported by Campos et al. (2022b, 2022a) for experiments conducted in the same geographic area.

2.4.5 Conclusions

Our study makes an important contribution to understanding the long-term changes in the soil surface and sugarcane performance under different tillage systems. Compared with conventional tillage, deep tillage of soil strips pulverized the surface soil, resulting in greater qCO_2, and greater disaggregation of the soil structure. Regardless of the cultivation systems used, it was found that in the long term there is a reduction in the enzymatic activity of the soil, more pronounced where liming was not applied. The results confirmed our hypothesis that DT decreases soil compaction in the long term. Liming improved soil fertility in both tillage systems, but its residuais effects were greater under DT. DT in association with liming resulted in increased sugar and stalk yields throughout the crop cycle. This study demonstrates that DT with localized lime application is an alternative for improving soil quality and minimizing the environmental impact of sugarcane cultivation.

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Conflicts of Interest

The authors have no competing interests to declare.

Table 1 - Chemical attributes of the soil before implementation of the experiment in a Rhodic Hapludox, 2015, Macatuba, SP, Brazil.

Depth	pH	M.O	P_{resin}	S	Al^{3+}	H+Al	K	Ca	Mg
(m)	$CaCl_2$	(g dm^{-3})	(mg dm^{-3})		------------ (mmolc dm^{-3}) -----------				
0.0-0.2	4.4	23	12	21	5	52	2.0	19	9
0.2-0.4	4.0	15	7	47	10	59	0.8	10	5
Depth	SB	CTC	V%	m	Fe	Cu	Mg	Zn	B
(m)	-(mmolc dm^{-3})-			%	--------------- (mg dm^{-3}) ------------				
0.0-0.2	31	82	37	14	23	3.0	9.7	1.1	0.20
0.2-0.4	16	75	21	38	15	3.3	4.3	0.5	0.18

Table 2 - Physical attributes of the soil before implementation of the experiment in a Rhodic Hapludox, 2015, Macatuba, SP, Brazil.

Depth	Attributes				Porosity			PR
	WAD	WMD	ASI	Ds	TP	MA	MI	
(m)	---- mm ----		(%)	(g cm^{-3})	----- (cm^3 cm^{-3}) -----			(MPa)
0.0-0.2	4.17	3.38	97.54	2.34	0.41	0.02	0.40	2.41
0.2-0.4	3.19	1.70	94.99	2.16	0.44	0.03	0.42	2.96

QAD = weighted average diameter; ASI = aggregate stability index; TP = total porosity; MA = macroporosity; MI = microporosity; Sd = soil density; WMD = weighted mean diameter

Figure 1 - Illustration of the tillage systems: conventional tillage system (CT) and modified strip tillage system (DT) with and without lime application.

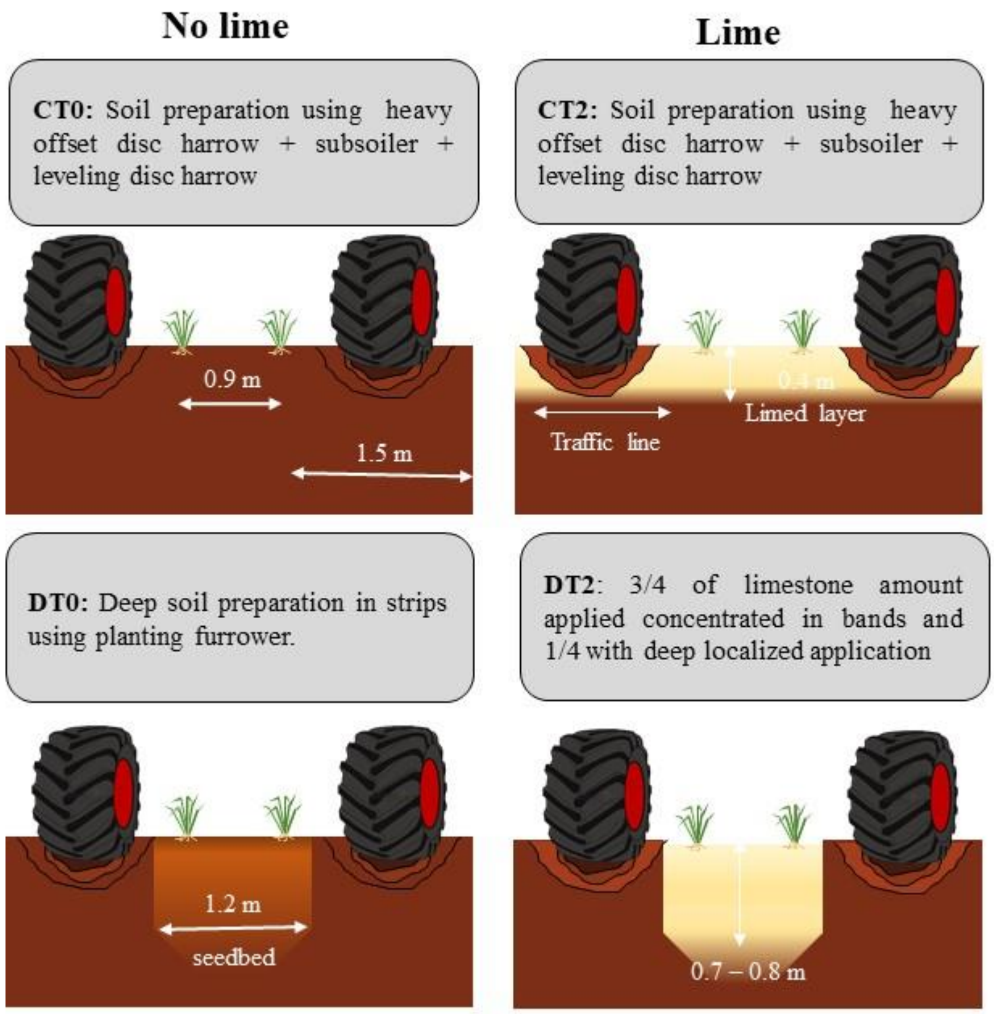


Figure 2 – Weighted mean diameter (WAD), aggregate stability index (ASI), macroporosity (MA), microporosity (MI), bulk density (Bd) and soil resistance to penetration (PR) under different soil tillage systems and liming. Different lowercase letters indicate significant differences in the 2017 cycle, and different uppercase letters indicate significant differences in the 2020 cycle by the LSD test ($p \leq 0.1$).

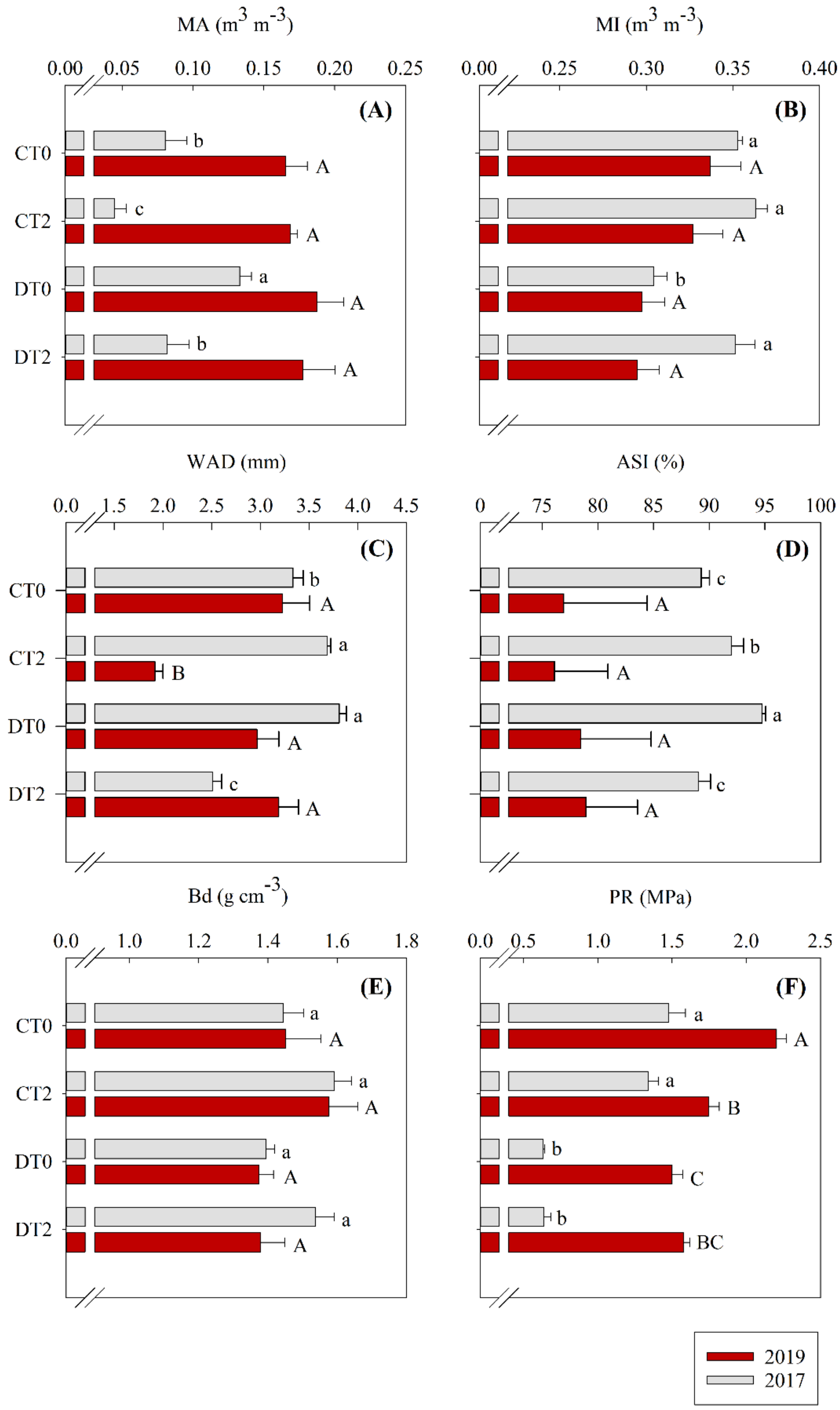


Figure 3 – Soil acidity (pH), potential acidity (H+Al), calcium (Ca) and magnesium (Mg) under different soil tillage systems and liming. Different lowercase letters indicate significant differences in the 2017 cycle, and different uppercase letters indicate significant differences in the 2020 cycle by the LSD test ($p \leq 0.1$).

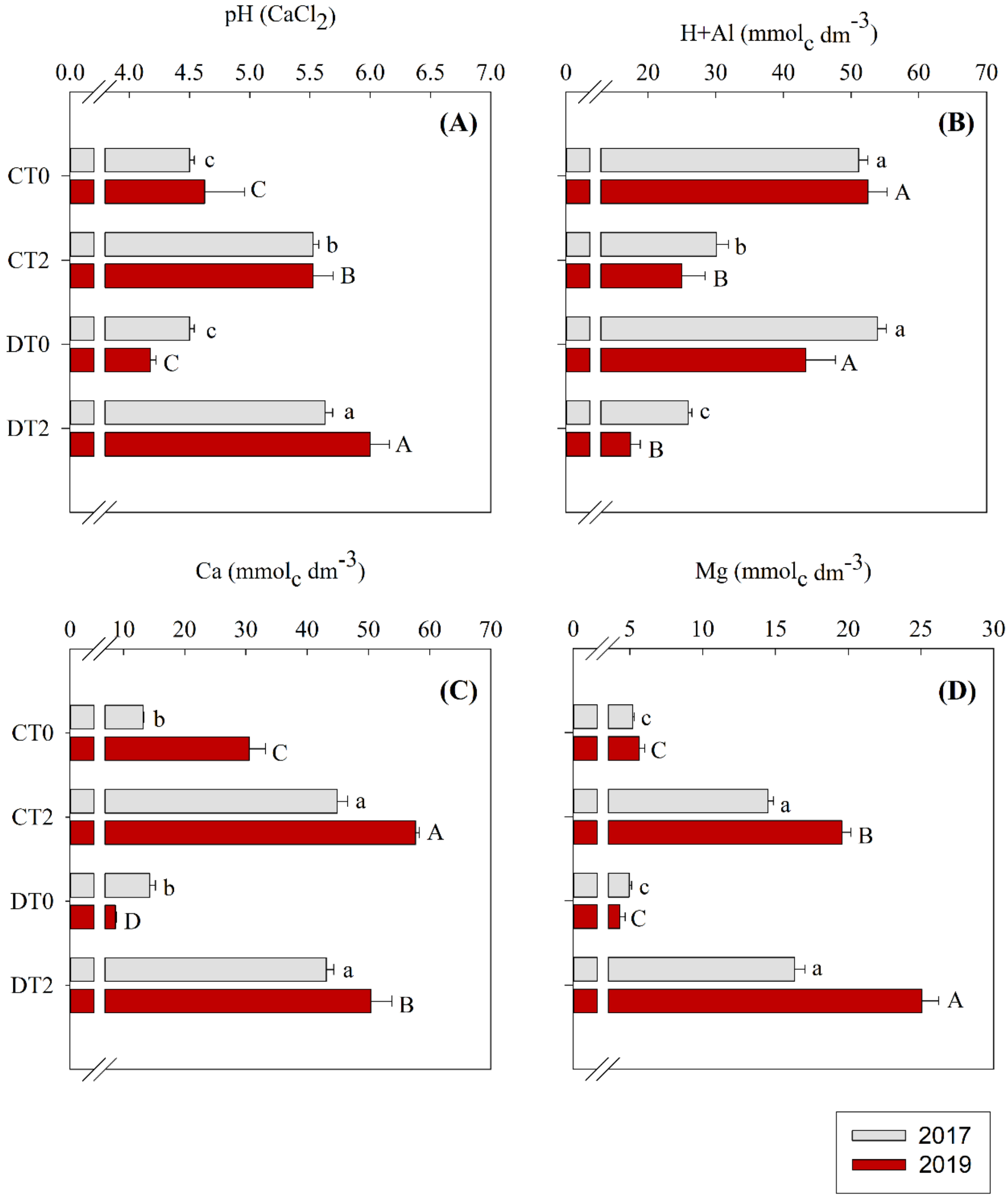


Figure 4 - Soil organic carbon (SOC), microbial biomass carbon (Cmic), microbial quotient (qMIC), metabolic quotient (qCO_2), soil basal respiration (Resp) and soil dehydrogenase activity (DHA). Different lowercase letters indicate significant differences in the 2017 cycle, and different uppercase letters indicate significant differences in the 2020 cycle by the LSD test ($p \leq 0.1$).

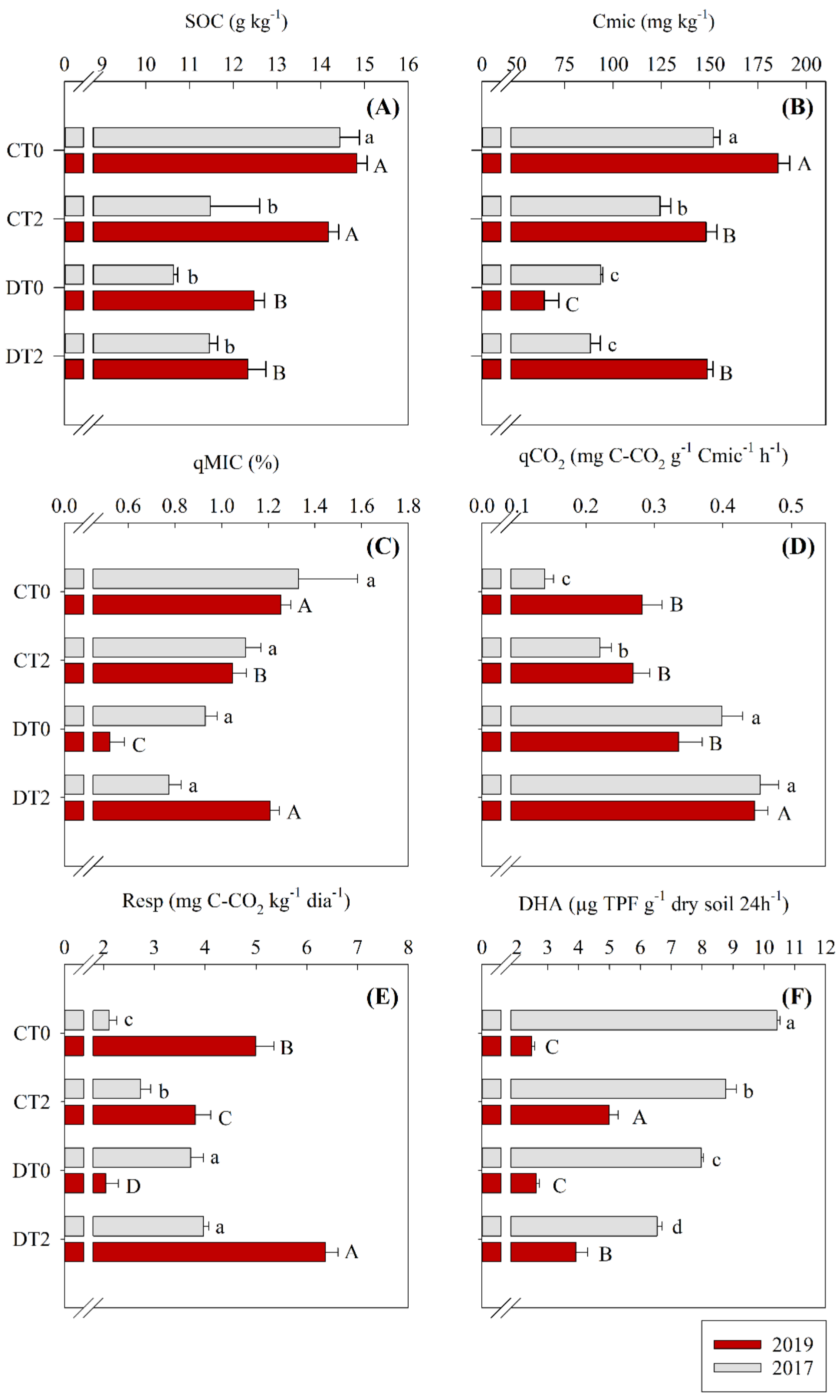


Figure 5 - Stalk yield (tons of stalks per hectare), sugar yield and total recoverable sugar (TRS) as a function of tillage systems. Different lowercase letters indicate significant differences in the 2017 cycle, and different uppercase letters indicate significant differences in the 2020 cycle by the LSD test ($p \leq 0.1$).

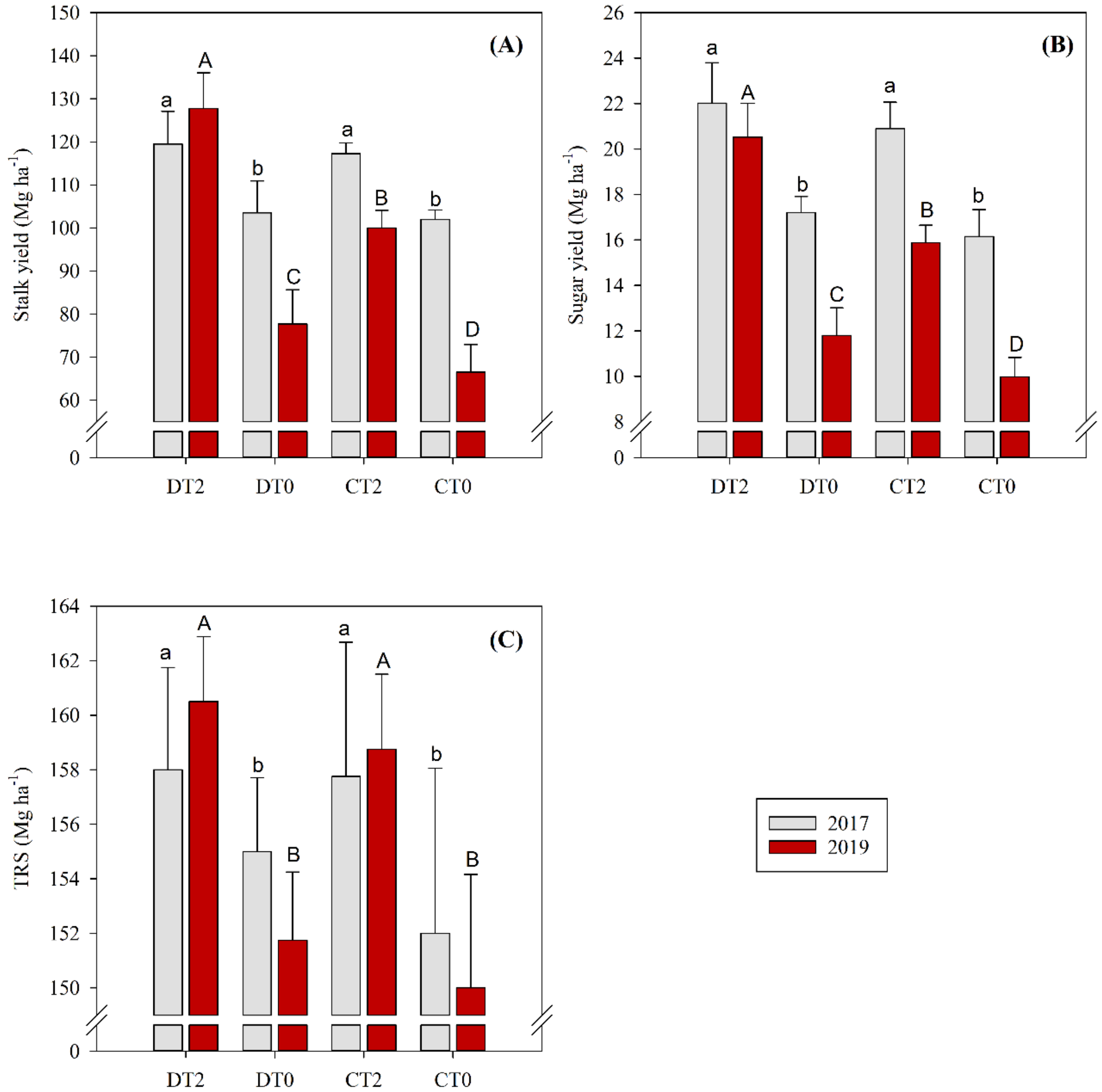


Figure 6 – Redundancy analysis (RDAs) of (A) soil properties and microbial biomass activity, (B) soil properties and sugarcane yield, and (C) microbial biomass activity and sugarcane yield. The arrows indicate correlations between factors. The significance of these correlations was evaluated by a Monte Carlo permutation test (999 permutations) and is indicated by red color ($p \leq 0.05$). The dashed lines indicate significant clusters.

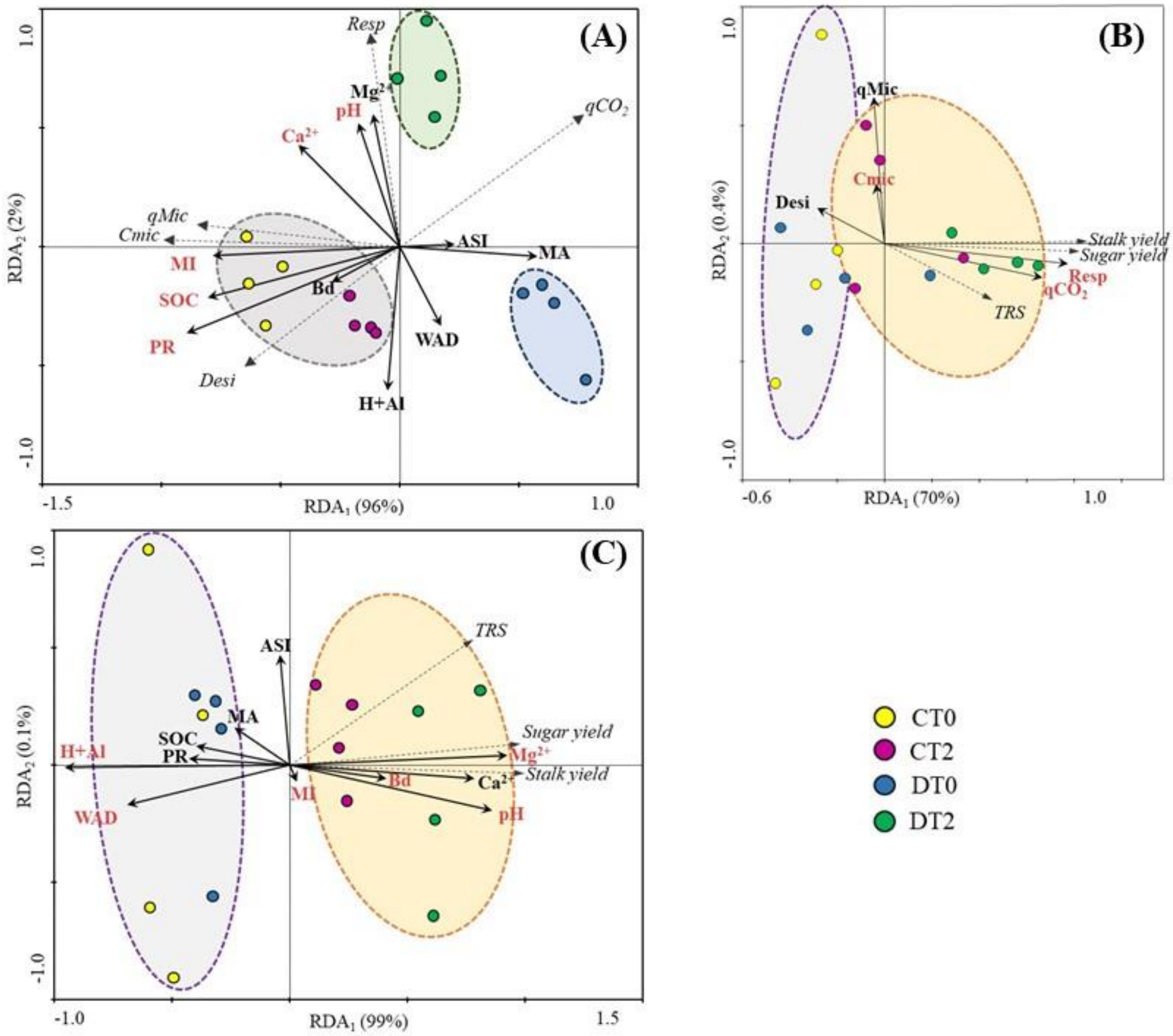
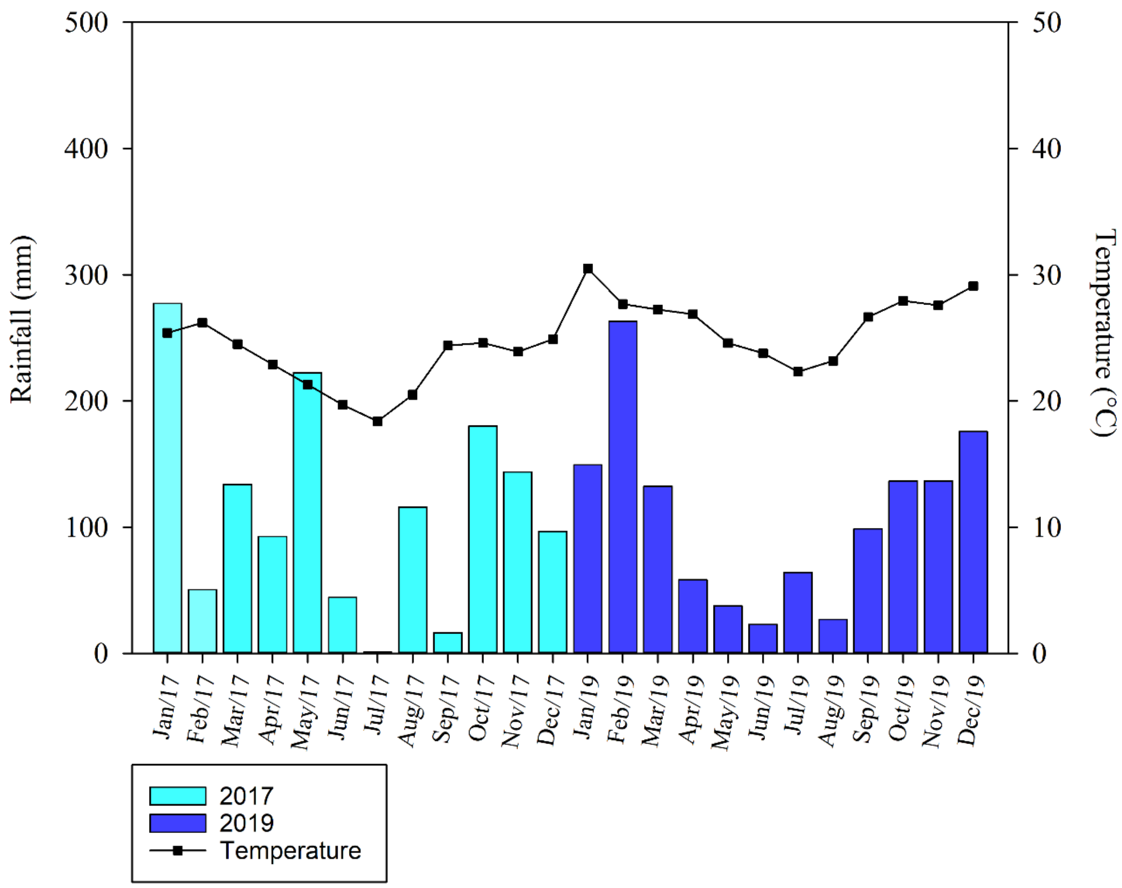


Figure S1 - Average temperature and rainfall (mm) during the third and fourth years of sugarcane cultivation, corresponding to the period from January 2017 to December 2019, in Macatuba, SP, Brazil.



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FINAL CONSIDERATIONS

The present study provides a better understanding of the long-term effects of combining conventional or deep tillage with liming on different soil parameters. Localized lime application under deep tillage improved fertility parameters to a depth of 1 m. Furthermore, this treatment alleviated soil compaction in the long-term but decreased the soil organic carbon content on the surface. In general, the physical parameters of the soil varied depending on the tillage system and lime application, and the best results were obtained under deep tillage. Deep tillage also increased soil microbial activity and, in turn, nutrient mineralization for sugarcane crop uptake. Liming increased stalk and sugar yields, and these effects were greater under localized lime application. These results support the promising potential of this new soil management system, but further studies of different locations, soil textural classes and other system aspects are needed for full validation.

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