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Effect of cover crops and tillage systems on soil quality and sugarcane yield

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Abstract

The management adopted in the establishment and replanting of sugarcane fields, with conventional tillage followed by fallow, is one of the main causes of soil quality degradation. In this context, the soil quality index (SQI) is an important tool to guide the use of more sustainable practices and management. This study aimed to monitor the effect of different cover crops in association with different tillage systems on sugarcane yield based on key indicators and an SQI developed using the Soil Management Assessment Framework (SMAF). The experiment was carried out on a sugarcane expansion area located in the municipality of Ibitinga, São Paulo, Brazil. The following soil physical and chemical attributes were analyzed: soil bulk density, macroaggregates, available phosphorus and potassium. Soil carbon content was also analyzed and used to calculate the SQI. Productivity over the 4 years of sugarcane cultivation was also analyzed. The use of subsoilers for soil tillage proved efficient in managing compaction by providing lower soil bulk density values in the first years of cultivation (1.59 and 1.63 $g\,cm^{-3}$); however, these effects occurred in the short term with a 10% increase in later years. The use of millet in association with subsoiling showed the best results for soil quality (0.59), reflected in the maintenance of yields at 100 $Mg\,ha^{-1}$ over time. Thus, our study reinforces the importance of using soil conservation systems in sugarcane replanting areas to achieve production longevity.

KEYWORDS
cover crops, millet, no-tillage, subsoiler, sunn hemp, tillage

1 | INTRODUCTION

Soil quality—the "capacity of a soil to function within the limits of an ecosystem to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran & Parkin, 1994)— is a essential component of agronomic and environmental sustainability of an agricultural system. Soil quality assessment is based on the monitoring of soil attributes (indicators) that are dynamic, responding to land use and management practices (Bünemann et al., 2018). However, the detection of these changes depends on long-term studies, since, in short term (1–2 years), these changes are quite subtle and difficult to quantify (Cherubin, Borsonal, et al., 2021; Mikha et al., 2017).

In Brazil, the sugarcane crop cycle is characterized 5–6 years of harvesting until the sugarcane field is replanted; therefore, soils must be studied over long periods to monitor soil quality and, consequently, production (Scarpare et al., 2019). Recently, there has been increasing concern about soil degradation in sugarcane areas (Martíni et al., 2020); such concern stems from the fact that Brazil is being the world's largest producer of this commercial crop, with a total area harvested (2019/20) of around 8.4 million hectares and production of 642.7 million tons (CONAB, 2020).

The traffic of machines and implements during successive harvests over time is the main factor that reduces soil quality, reflected in compaction and thus changes in its attributes, such as increased bulk density and reduced porosity (Cavalcanti et al., 2019; Guimarães Júnnyor et al., 2019; Lima et al., 2015; Silva et al., 2016). In addition to soil degradation caused by mechanized harvesting, soil tillage for cultivation and replanting of sugarcane fields is still the conventional approach, with plows and harrows used to eliminate or bury vegetation cover, which may leave the soil exposed and susceptible to erosion (Telles et al., 2018).

The use of subsoilers is another mechanical intervention in the soil, used to minimize the effects of compaction, which, according to Chamen et al. (2015), have short-term effects and can increase greenhouse gas emissions, in addition to favouring the mineralization of organic matter. According to Guimarães Júnnyor et al. (2019), sugarcane planting and harvesting reduce soil support capacity, increasing the risks of compaction, especially at soil depths up to 0.33 m.

In this context, alternative soil management and tillage systems have been sought to reconcile soil capacity to function in a sustainable manner and, consequently, increase crop productivity. No-till is considered a type of conservation agriculture because it promotes plant biodiversity through crop rotation, control of the machine and implement traffic, in addition to maintaining a permanent soil cover that contributes to its protection and providing numerous benefits, such as increased organic matter, nutrients, water availability, and protection against erosion (Bordonal et al., 2018; Carvalho et al., 2017).

Minimum tillage, as well as no-till, aims to maintain vegetation cover and minimize soil disturbance, in order to reduce soil tillage and cultivation operations. As an example, the use of systemic herbicide that eliminates ratoons in areas under sugarcane replanting, thus avoiding the use of destroyers, as the harrow (Furlaneto et al., 2010).

After sugarcane harvest, the soil remains uncovered for weeks or months until replanting, which spans from September to March, increasing the risk of water and wind erosion (Cherubin, Karlen, Franco, Tormena, et al., 2016). According to Dechen et al. (2015), the higher the percentage of plant cover, the lower the losses of water, organic matter, and essential nutrients, such as P, K, Ca, and Mg, this can result in 70% lower losses in areas with approximately 90% of cover crops. Thus, it is important to highlight the use of cover crops in the off-season or even before sowing, which mainly aims to control soil erosion and loss of nutrients through runoff (Baumhardt & Blanco-canqui, 2014).

Soil quality indicates the state of an agricultural system under based on a set of physical, chemical, and biological attributes. The most used physical soil quality indicators bulk density, total porosity, aggregate stability, and soil resistance to penetration (Simões et al., 2018). According to Bünemann et al. (2018), total organic matter, organic carbon and pH are also common indicators, followed by available phosphorus and some water storage indicators.

To monitor soil quality and dynamics, indices have been developed based on these soil indicators, enabling integrated assessment and monitoring of the impacts of land use and management over time (Cherubin, Karlen, Cerri, Franco, et al., 2016). The Soil Management Assessment Framework (SMAF) (Andrews et al., 2004), which while developed in for North American soil has been widely employed and is one of the several approaches and tools used to assess soil quality. The SMAF spreadsheet indicators that reflect changes in the physical, chemical and biological functions of the soil, and changes promoted by different management systems can be observed (Cherubin et al., 2015). Cherubin, Karlen, Franco, Cerri, et al. (2016) tested the potential of SMAF by evaluating the impacts on the quality of an Oxisol, under different management practices, showing that this technique was sensitive to detect changes in soil indicators.

Other authors have also corroborated the suitability of this tool to detect or even quantify the effects of different practices and tillage on soil quality in different crops (Cherubin, Karlen, Cerri, Franco, et al., 2016; Cherubin, Karlen, Franco, Tormena, et al., 2016; Luz et al., 2019; Nunes et al., 2020), demonstrating that SMAF can be an easily accessible and understandable alternative for farmers and agricultural land managers, enabling more sustainable and economic decision-making.

SMAF has been a very useful tool to assess soil quality in sugarcane areas in Brazil (Cherubin, Carvalho, et al., 2021; Cherubin, Karlen, Franco, Cerri, et al., 2016; Lisboa et al., 2019; Luz et al., 2019; Ruiz et al., 2020), but none of these studies evaluated the effectiveness of the tool in detecting the effects of different tillage systems and cover crops.

Considering the above, this study aimed to use a soil quality index, developed with the SMAF tool, to temporally monitor the effect of different cover crops associated with tillage systems on an area under sugarcane productivity over 4 years. To this end, we tested the hypothesis that the use of sunn hemp (legume) as a cover crop, associated with minimum tillage, improves or maintains soil quality and increases crop yield compared to conventional tillage.

2 | MATERIALS AND METHODS

2.1 | Study area description and history

The study was conducted under field conditions in an experimental area belonging to Santa Fé Mill, already implemented since 2014, in the municipality of Ibitinga, São Paulo, Brazil, located at 21°45′ South latitude and 48°49′ West longitude and with an average altitude of 455 meters above sea level. This area had not been cultivated for 11 years, being used only for pasture.

In November 2014, before the experiment, a pedological survey was carried out, in which the soil was classified as Utisols Udults, with sandy loam texture for the 0.0–0.20 m layer and sandy clay loam for the deeper layers (Farhate et al., 2020).

When the area was still pasture, before the land use change (LUC), the analysis of soil physical and chemical attributes and carbon stock was performed, so as to compare changes that occurred in the experimental area after planting sugarcane. After area characterization, the land use change was initiated: in which the soil was tilled by applying dolomitic limestone for pH correction and using a plow followed harrow leveller. Later, the following cover crops were sowed: peanut (*Arachis hypogaea L.*), sunn hemp (*Crotalaria juncea*), millet (*Pennisetum glaucum L.*), and sorghum (*Sorghum bicolor L.*). Upon reaching maximum flowering, plants were sampled for dry biomass analysis. The results for area characterization (Table S1), land use change processes, and dry biomass analysis of cover crops (Table S2) are presented in Farhate et al. (2022).

In April 2015, the sugarcane variety CTC 4 was planted with different soil preparations—no-tillage (NT), minimum tillage with subsoil at 0.40 m (MT), and minimum tillage with subsoil at 0.70 m (Deep subsoiling) (MT/DS). Fertilization used NPK 10-51-00 of 300 kg ha^{-1}; in June 2016, 400 kg ha^{-1} of NPK 00-25-15 was used.

Considering the practical nature of the treatments, the experiment was designed in strips with three replications each (blocks), consisting of four cover crops (A) in the horizontal strips and the three tillage systems (B) in the vertical strips. Each plot was composed of six rows of sugarcane, spaced 1.5 m apart and 30 m long, totaling 300 m^2 per plot. Strip experiments are a variation of split-plot experiments, where factors A and B are arranged in strips, as if they were the main plots (Figure 1). In this experiment, there is no independent randomization of factor levels, and the two factors are allocated into the main plots.

The use of this experimental design is mainly related to the approach of installing and/or conducting experiments, which generally hold physical limitations (i.e., precipitation, temperature) resulting in such arrangement of factors (Dos Anjos, 2004). Considering these limitations, in this experiment it is necessary to investigate the effects of different cover crops (A) and different soil tillage (B) (soil use levels), there is a reduction in degree of freedom and residue of A and B. This occurs because the levels are not randomized within the plots as in a split-plot experiment only. Therefore, this type of experiment did not allow for any other arrangement (Table 1).

2.2 | Soil sampling and assessment of indicators and sugarcane yield

At the end of the production cycles of the sugarcane plant (2015/16), the first (2016/17), second (2017/18), and third (2018/19) cycle of the ratoon sugarcane, disturbed and undisturbed soil samples were collected at depths of 0.00–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.70 m,

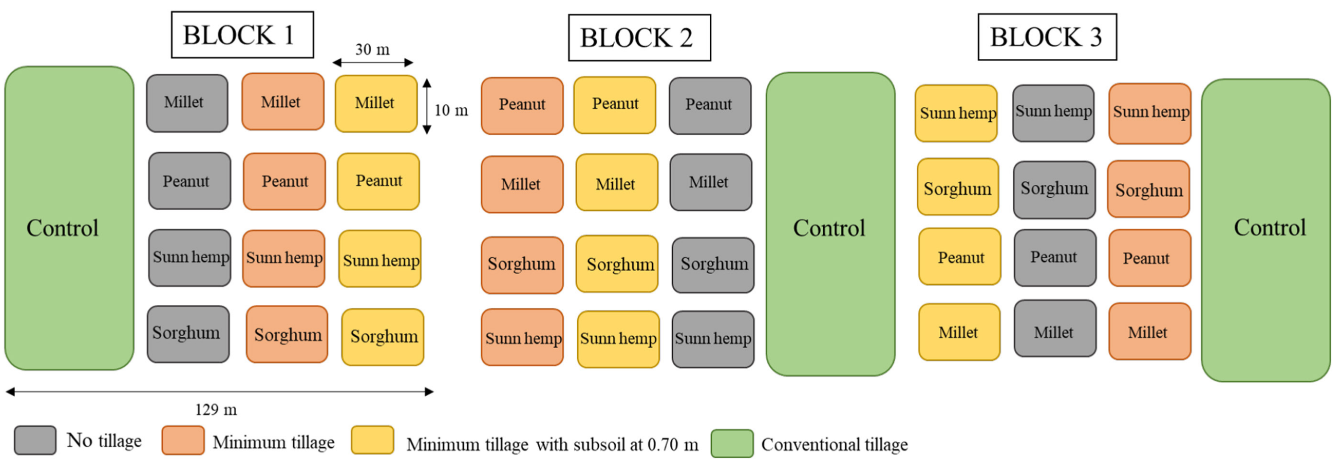

FIGURE 1 Graphical representation of the experimental design installed in the field. The design represents the strip design with three replications (blocks), in which the four cover crops (A) were implemented in the horizontal strips and the three tillage systems (B) in the vertical strips.

TABLE 1 Analysis of variance scheme with the variations considered and their respective degrees of freedom.

Cause of variation	Degrees of freedom
Blocks	2
Cover crop (A)	3
Residue (a)	6
Soil tillage (B)	2
Residue (b)	4
Interaction A×B	6
Residue (c)	12
Total	35

considering the planting row and inter-row. One sample was collected for each repetition (block) to determine the changes occurred in the physical, chemical, and total carbon attributes, as a function of the different soil tillage systems. For data analysis, the depths were combined into horizons: horizon A (0.00–0.20 layer), horizon AB (0.20–0.30 layer), and horizon Bt (0.30–0.70 layer), and the row and inter-row values were integrated into a single weighted average value, in which 27% of the data variability was attributed to the planting row and 73% to the inter-row.

In the laboratory, the following indicators were determined: (i) physical: soil bulk density was estimated in laboratory according to Teixeira et al. (2017) by calculating the relationship between the mass of soil dried in an oven at 105°C and the sample volume, and water stable aggregation for determination of macroaggregates, following Kemper and Chepil (1965); (ii) chemical: P, K, and pH ($CaCl_2$ 0.01 mol L^{-1}) by Van Raij et al. (2001); and (iii) total carbon according to Nelson and Sommers (1996). By obtaining data on bulk density and organic carbon for the studied horizons, the carbon stock can be calculated using Equation 1:

$$E = BD \times C \times e \quad (1)$$

where BD = bulk density (g cm^{-3}); C = carbon content (g 100 g^{-1}); and e = layer (cm).

Crop yield was assessed by counting the number of tillers contained in 10 linear meters and weighing approximately 20 plants in each plot. The cutting was performed at the height of the apical bud and at the defoliation of the harvested plants; this material was then weighed, and the results expressed in megagrams of sugarcane per hectare.

2.3 | Soil quality assessment

Soil quality changes induced by management practices were assessed using the Soil Management Assessment Framework (SMAF), described by Andrews et al. (2004). Soil quality assessment using SMAF was based on three steps:

1. Selection of soil indicators, with at least one indicator for each soil component, i.e., physical, chemical, and biological. The data set was composed by the following physical, chemical, and biological indicators: bulk density and percentage of macroaggregates, pH and available phosphorus and potassium content, and organic carbon content. To compose the dataset for soil health (SH), evaluations by a previous study conducted in this same sugarcane-producing region in Brazil (Cherubin, Karlen, Franco, Tormena, et al., 2016) were used. Therefore, these indicators have been used to assess SH changes induced by land use and management practices in sugarcane crops throughout Brazil (Cherubin, Borsonal, et al., 2021; Cherubin, Karlen, Cerri, Franco, et al., 2016; Lisboa et al., 2019). To calculate the Soil Quality Index (SQI), we attributed equal weights of 33.33% to chemical (pH, P, and K), physical indicator (bulk density), and biological indicator (soil organic carbon) components. This approach aligns with the understanding that a healthy soil results from the balanced interaction of chemical, physical, and biological indicators, regardless of their individual count within each component (Cherubin, Borsonal, et al., 2021; Cherubin, Karlen, Franco, Cerri, et al., 2016).
2. Interpretation of indicators, in which the scoring curves present in the SMAF spreadsheet were used to transform the measured value into a score ranging from 0 to 1, using non-linear scoring curves. The algorithms used for interpreting measured values of pH, P, bulk density, macroaggregation and soil carbon are available in Andrews et al. (2004), while the algorithm for interpreting K values was originally developed by Wienhold et al. (2009) and recently adapted to be used in São Paulo State, Brazil, by Cherubin, Borsonal, et al. (2021). The SMAF scoring curves consider specific factors that affect the interpretation of the indicators, namely: soil type and texture; mineralogy; climate; slope; dominant crop; sampling time; and analytical methods. Therefore, in this study, the class factors assigned to interpret soil organic carbon were: organic matter (4 – low organic matter, typical of highly weathered soils); texture (1 – sandy soils) and climate factor (4 – typical tropical climate, ≥170 degree-days and ≥550 mm average annual precipitation). For transformation of macroaggregate values, the factors used were: organic matter class (4) and texture (4) and the Fe_2O_3 factor (1 – based on the Ultisols soil classification). For bulk density, the texture factor (1) and

mineral class (3) were used considering clay 1:1, and Fe and Al oxides in the soil composition.

For P interpretation, the ion-resin extraction method was used (5); slope factor was 2 (2 and 5% slope) as well as the weathering factor (2 – highly weathered) and the crop was sugarcane (factor 110). The optimum values for P and pH (score = 1) were 40 mg dm^{-3} and 6, respectively (Van Raij et al., 1997). For pH, the crop was sugarcane and the values of pH measured in $CaCl_2$ were converted into pH measured in water as described by Cherubin, Karlen, Cerri, Franco, et al. (2016). The algorithm of K considers only the texture (4). The original SMAF K-score curve was developed based on the response of maize in Midwestern US soils (Wienhold et al., 2009), and therefore adjusted (K-score = $1.0755 \times (1^{-\exp.(-0.0224 \times \text{measured K content})})$) to be consistent with the potassium interpretation classes for sugarcane in Brazil (Van Raij et al., 1997). The K values were expressed in cmol$_c$ dm^{-3} and were converted into mg kg^{-1} by multiplying by 391 (atomic mass) (Cherubin, Borsonal, et al., 2021).

3. Integration of indicator scores into a single soil quality index (SQI) ranging from 0 to 1. The SQI was calculated according to the stratum presented by Cherubin, Karlen, Cerri, Franco, et al. (2016), where the indicators were weighted and integrated according to Equation 2:

$$SQI = \sum_{n-I=1}^{N} \text{WiSi} \tag{2}$$

where SQI = soil quality index; Wi = weighted value of indicators Si = indicator score; and n = number of indicators integrated in the index.

2.4 | Statistical analysis

Statistical analysis was performed according to the design in bands with additional treatment (control). The test aimed to assess whether the covariance matrix presented compound symmetry, i.e., whether the variable was equally correlated over time (cycles) and the variances of the differences between all pairs of measurements were similar. The sphericity condition was accepted for all analyzed variables. Mauchly's sphericity test was used to validate the repeated measures analysis of variance (ANOVA).

Subsequently, the hypothesis of the difference between the control and the other treatments was tested by contrasts of means (control vs. tillage system) in each cover plant for different sugarcane crop cycles (1, 2, 3, and 4) and horizons (A – 0.00–0.20 m, AB – 0.20–0.30 m, and Bt – 0.30–0.70 m). The contrasts were orthogonal, and, for the ANOVA, the F test was applied at a 5% significance level ($p < .05$).

To evaluate the relationship between tillage and cycles for the same cover crop, an ANOVA was performed with an F test ($p < .05$), followed by means compared by Tukey's test ($p < .05$) using plots subdivided into bands, in which the plot was the tillage system and the subplot, the cycle of the sugarcane crop.

3 | RESULTS

3.1 | Soil quality indicators

In the band analysis, the difference between treatments for bulk density occurred only in horizon A of the soil when grass plants (millet and sorghum) were used as cover crops (Figure 2). In an area under millet and sorghum, it was found that MT and MT/DS promoted the lowest bulk density values in the first cycle of sugarcane culture (2015/16), ranging from 1.59 to 1.63 g cm^{-3}. However, these were short-term effects, as the bulk density values in the fourth cycle of the crop increased approximately 10%. In an area with no-tillage, bulk density remained stable, around 1.66 g cm^{-3}, from the first to the fourth production cycle (2018/19) (Figure 2).

For the means obtained for potassium concentration in the soil of the control treatment and the others, a significant difference was obtained when millet was used as cover crop, in all studied horizons (Table 2). Regarding legumes, a difference was obtained when peanuts and sunn hemp were used in the fourth cycle of the crop, horizons A and AB (Table 2).

The results for the band analysis among treatments (Figure 3) show that soil potassium levels are generally above the value indicated as a reference for Brazilian soils (Van Raij et al., 1997) to achieve yields of 100 Mg ha^{-1} of the sugarcane crop, which would be 80 kg ha^{-1}, i.e., 160 mg dm^{-3}. This can be explained by the NPK fertilization (00–25-15) made in the 2016/2017 cycle, and then K was made available in the soil after its stabilization.

Generally, between the third and fourth cycle of the crop there was a reduction in potassium concentrations, mainly in the soil horizon A (Figure 3). For peanuts, there was a decrease in the area with no-tillage MT of around 36% from 1 year to the next, and 15% with MT/DS. For sunn hemp, the greatest difference was obtained in the no-tillage system, with a decrease from 587.1 to 323.4 mg dm^{-3}. In the areas with millet and sorghum, the greatest decrease occurred in the area under MT, showing a reduction of approximately 48% and 28%, respectively.

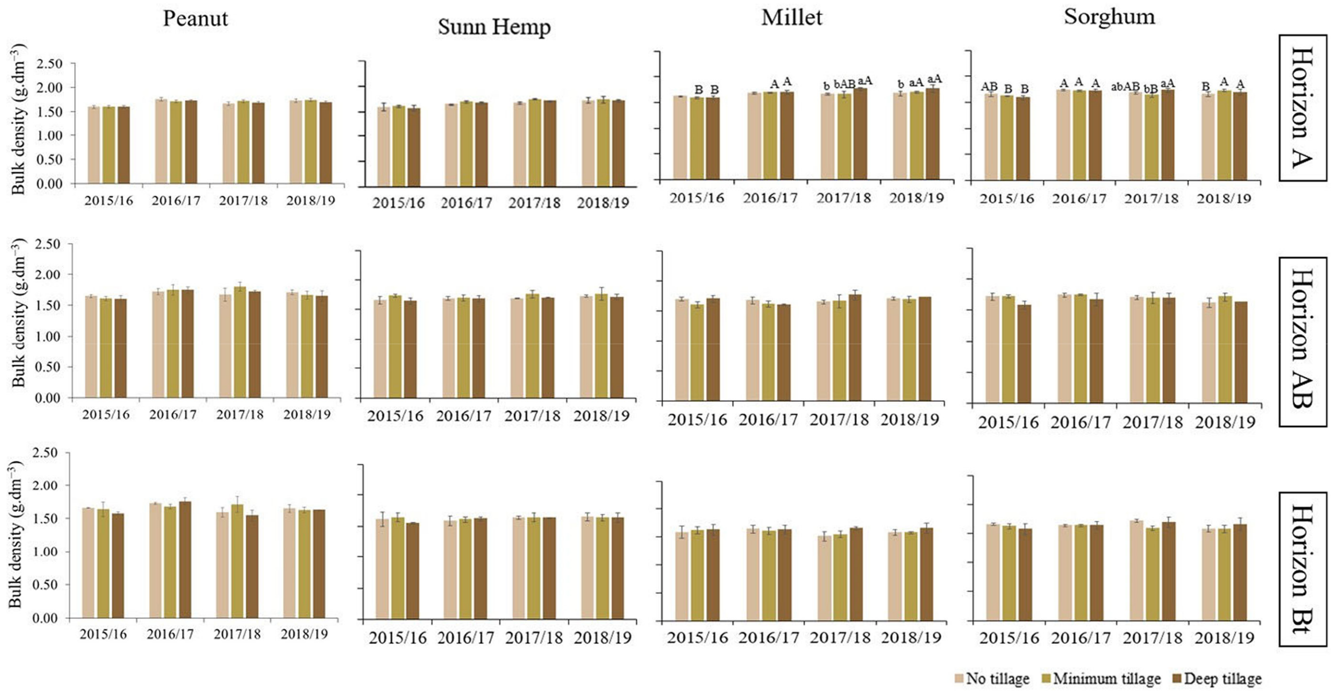

FIGURE 2 Bulk density ($g\,cm^{-3}$) over 4 years of sugarcane production in an experimental area located in the municipality of Ibitinga, São Paulo State, Brazil, under different cover crops and soil tillage systems. Means followed by the same uppercase letter statistically differ between years; lower-case treatments differ within each crop year, according to Tukey's test ($p < .05$). Bars indicate the standard deviation {$n = 3$}.

TABLE 2 Orthogonal contrast analysis between the mean potassium concentration of the control treatment and the other treatments, in the experimental area located in the municipality of Ibitinga, São Paulo, Brazil.

Cover plant	CC1 vs the others	CC2 vs the others	CC3 vs the others	CC4 vs the others
Horizon A				
Peanut	NS	NS	NS	**
Sunn hemp	NS	NS	NS	***
Millet	NS	NS	***	NS
Sorghum	NS	NS	NS	NS
Horizon AB				
Peanut	NS	NS	NS	*
Sunn hemp	NS	NS	**	***
Millet	***	NS	*	***
Sorghum	***	***	NS	NS
Horizon Bt				
Peanut	NS	NS	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	*	NS	NS	NS
Sorghum	NS	NS	*	NS

Abbreviations: CC1, control of cycle 1; CC2, control of cycle 2; CC3, control of cycle 3; CC4, control of cycle 4; NS, not significant difference between control and other treatments.

*$p < .05$; **$p < .01$; ***$p < .001$.

For phosphorus, the differences between the mean concentrations of the control treatment and the others were highlighted when cover cropping with millet, in the soil horizons A and AB, in cycle 1 (2015/16) and in cycle 3 (2017/18) of sugarcane production, as was observed for potassium (Table 3).

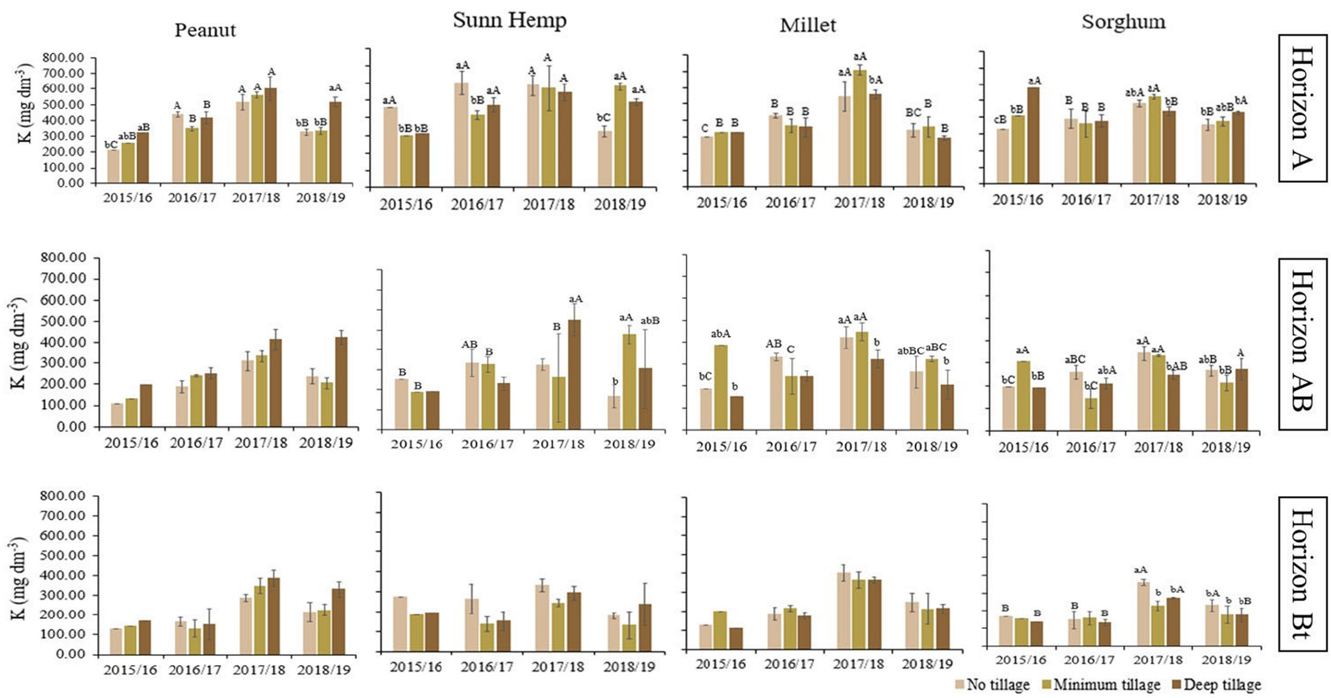

FIGURE 3 Soil potassium ($mg\,dm^{-3}$) over 4 years of sugarcane production in the experimental area located in the municipality of Ibitinga, São Paulo State, Brazil, under different cover crops and soil tillage systems. Means followed by the same capital letter differ statistically between years; lower case treatments differ within each crop year, according to Tukey's test ($p < .05$). Bars indicate the standard deviation {$n = 3$}.

TABLE 3 Orthogonal contrast analysis between the phosphorus content of the control treatment and the other treatments, in the experimental area located in the municipality of Ibitinga, São Paulo, Brazil.

Cover plant	CC1 vs the others	CC2 vs the others	CC3 vs the others	CC4 vs the others
Horizon A				
Peanut	NS	NS	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	**	NS	*	NS
Sorghum	NS	NS	*	NS
Horizon AB				
Peanut	*	**	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	***	*	***	NS
Sorghum	**	NS	NS	NS
Horizon Bt				
Peanut	NS	NS	NS	NS
Sunn hemp	NS	NS	*	NS
Millet	NS	NS	NS	NS
Sorghum	**	NS	NS	NS

Abbreviations: CC1, control of cycle 1; CC2, control of cycle 2; CC3, control of cycle 3; CC4, control of cycle 4; NS, not significant difference between control and other treatments.

*$p < .05$; **$p < .01$; ***$p < .001$.

According to the means obtained for phosphorus contents (Figure 4), all experimental area—regardless of the treatment and evaluated horizon—presented very low levels of P in the soil. According to Van Raij et al. (1997), phosphorus contents in the range of 240 $mg\,dm^{-3}$ are considered limiting for sugarcane yield. A reduction in P

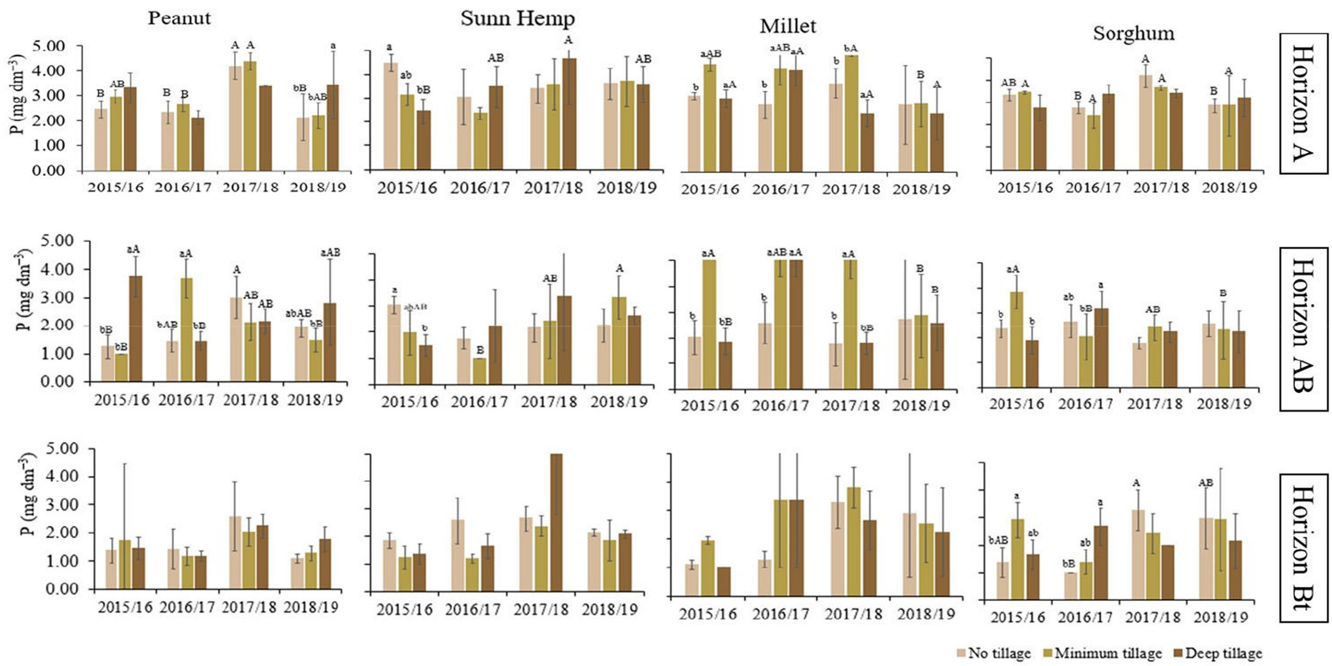

FIGURE 4 Soil phosphorus (mg dm^{-3}) over 4 years of sugarcane production in the experimental area located in the municipality of Ibitinga, São Paulo State, Brazil, under different cover crops and tillage systems. Means followed by the same uppercase and lowercase letter statistically differ between the years and between treatments within each crop year, respectively, according to Tukey's test ($p < .05$). Bars indicate the standard deviation {$n = 3$}.

TABLE 4 Orthogonal contrast analysis between the soil organic carbon of the control treatment and the other treatments, in the experimental area located in the municipality of Ibitinga, São Paulo, Brazil.

Cover plant	CC1 vs the others	CC2 vs the others	CC3 vs the others	CC4 vs the others
Horizon A				
Peanut	NS	NS	NS	NS
Sunn hemp	NS	**	NS	NS
Millet	NS	**	*	NS
Sorghum	*	NS	NS	NS
Horizon AB				
Peanut	*	NS	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	NS	***	NS	NS
Sorghum	**	NS	NS	NS
Horizon Bt				
Peanut	***	NS	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	**	*	*	NS
Sorghum	NS	NS	**	NS

Abbreviations: CC1, control of cycle 1; CC2, control of cycle 2; CC3, control of cycle 3; CC4, control of cycle 4; NS, not significant difference between control and other treatments.

*$p < .05$; **$p < .01$; ***$p < .001$.

concentrations in the crop area throughout the cycles was also observed (Figure 4). In the soil horizon AB, for example, the treatment millet + MT in the first cycle (2015/16) was 7.81 mg dm^{-3}, with a decline of approximately 63% until the fourth cycle (2018/19), showing 2.87 mg dm^{-3}. In the case of phosphorus, even with the use of 300 kg.ha^{-1}

of NPK 10–51-00 and, later, in June 2016, of 400 kg ha^{-1} of NPK 00-25-15, this nutrient did not reach a labile form and was not available in the soil.

When peanut and millet were used as cover crops, there was significant difference in the soil organic carbon between control and the treatments. This emphasized the use of millet, in which carbon concentrations were different in samples collected in cycle 2 in horizons A, AB, and Bt, and in cycle 3 in horizons A and Bt (Table 4).

In Horizon A, statistical differences between treatments were obtained in areas where sunn hemp, millet and sorghum were used as cover crops (Figure 5). In general, higher carbon concentrations were found in samples collected in the cycle 2 (2016/17). The results obtained in the areas with sunn hemp and sorghum in this cycle showed that, in association with MT/SP, the values were higher than the other tillage systems, with an average of 0.69% and 0.66%, respectively (Figure 5). With the use of millet, the highest value found was in association with MT (0.71%). A similar result occurred in the AB horizon, in which the millet + MT treatment had the highest average of 0.79%, approximately 55% higher than the no-tillage and MT/DS treatments.

For the Bt horizon, organic carbon averages differed in areas where peanuts and millet were used (Figure 5). Regardless of the tillage systems, there was an increase in carbon in depth over time, as well as in the more superficial horizons. In the area where millet was used, as well as in the AB horizon, the highest amount of carbon was found in association with MT (0.57%), being higher than in the no-tillage area (0.53%) and MT/DS (0.48%), in the last crop cycle. In the peanuts-covered area, soil carbon values in the last year of the study did not differ between tillage systems, but an increase was observed after the years of cultivation.

The results that showed statistical differences also indicated an increase in soil carbon—regardless of the treatment used—from the first sugarcane cycle to the last cycle studied (2018/19). In the millet-covered area, in which a statistical difference was obtained in the three horizons studied, a greater carbon increment was observed when associated with MT, showing 30% and 66% increases in the most superficial and deeper layers, respectively. Similarly to this, when sorghum was used as a cover crop associated with MT, there was an increase of approximately 58% from the first to the fourth production cycle, showing that the straw left under the surface and the production of dry biomass of the plant, regardless of being leguminous or grassy, reflected in the amount of organic matter and consequently in the total carbon (Farhate et al., 2022).

Similar to the case for soil organic carbon values, when using millet and peanuts as a cover crop associated with

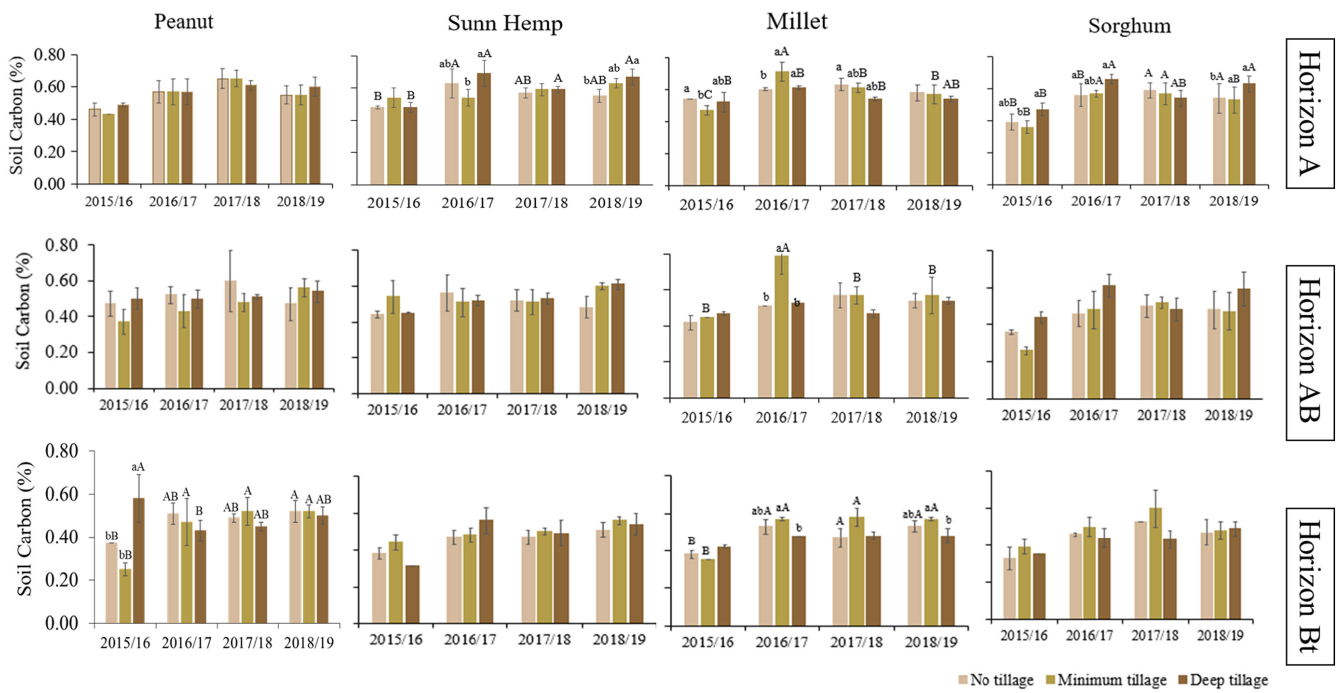

FIGURE 5 Organic soil carbon (%) over 4 years of sugarcane production in an experimental area located in the municipality of Ibitinga, São Paulo State, Brazil, under different cover crops and tillage systems. Means followed by the same uppercase and lowercase letter statistically differ between years and between treatments within each crop year, respectively, according to Tukey's test ($p < .05$). Bars indicate the standard deviation $\{n = 3\}$.

MT, there was a carbon stock increase over the years, regardless of the horizon studied (Figure 6). The greatest increase was observed in the Bt horizon, around 35% in the area under millet and almost 50% in the peanut treatment. When sorghum was used, there were statistical differences over the years regardless of the preparation system, with an increase of approximately 30%. For the area with sunn hemp, no statistical differences were observed between treatments (Figure 6). In the analysis of contrasts of means, for the treatment using millet as a cover crop, there was a statistical difference in the horizons studied in cycle 2 of the production crop; similar behaviour was observed in the peanuts-covered area, but in the year with sugarcane plants (Table 5). In the last year of production, a statistical difference was still observed between the control treatment and the area under millet, both in the most superficial horizon and in the deeper layers, the Bt horizon.

3.2 | Soil quality index and sugarcane yield

The averages obtained for the soil quality index (SQI) of the control treatment were statistically different from the values obtained in the treatment using millet as vegetation cover (Table 6). The contrast was significant in cycle 1 (2015/16), cycle 2 (2016/17), and cycle 3 (2018/18) of the sugarcane crop, on the AB horizon. Regardless of the treatment used in the area, studied layer, and sugarcane crop cycle, the SQI ranged from 0.49 to 0.59, without substantial reduction throughout the production cycles (Figure 7).

In areas where legumes were used as vegetation cover, the averages found for SQI were statistically significant only in the area with peanuts, for the values found in the A horizon (Figure 7). In no-tillage areas, the indices differed over the years, ranging from 0.56 to 0.51 from the first to the fourth year of sugarcane production, which represents an almost 9% decline in quality. In cycle 4 (2018/19), there were differences among soil tillage systems used in the area, in which MT/DS in association with peanuts had the highest value (0.55) in relation to the area with MT (0.53) and no-tillage (0.51) (Figure 7).

In the systems with peanut, sunn hemp and sorghum, average crop yield was higher in the system with MT/DS for the fourth crop cycle, with values of 92, 101, and 99 Mg ha^{-1}, respectively, superior to no-tillage, with 84, 85 and 79 Mg ha^{-1}, and to MT, with 72, 88, and 86 Mg ha^{-1}. Given the results, higher figures are observed in the MT/DS system, regardless of the studied layer and the crop production cycle, expressing the effects of subsoiling on soil decompaction, which was reflected in the quality indicators used to generate the indices (Figure 7).

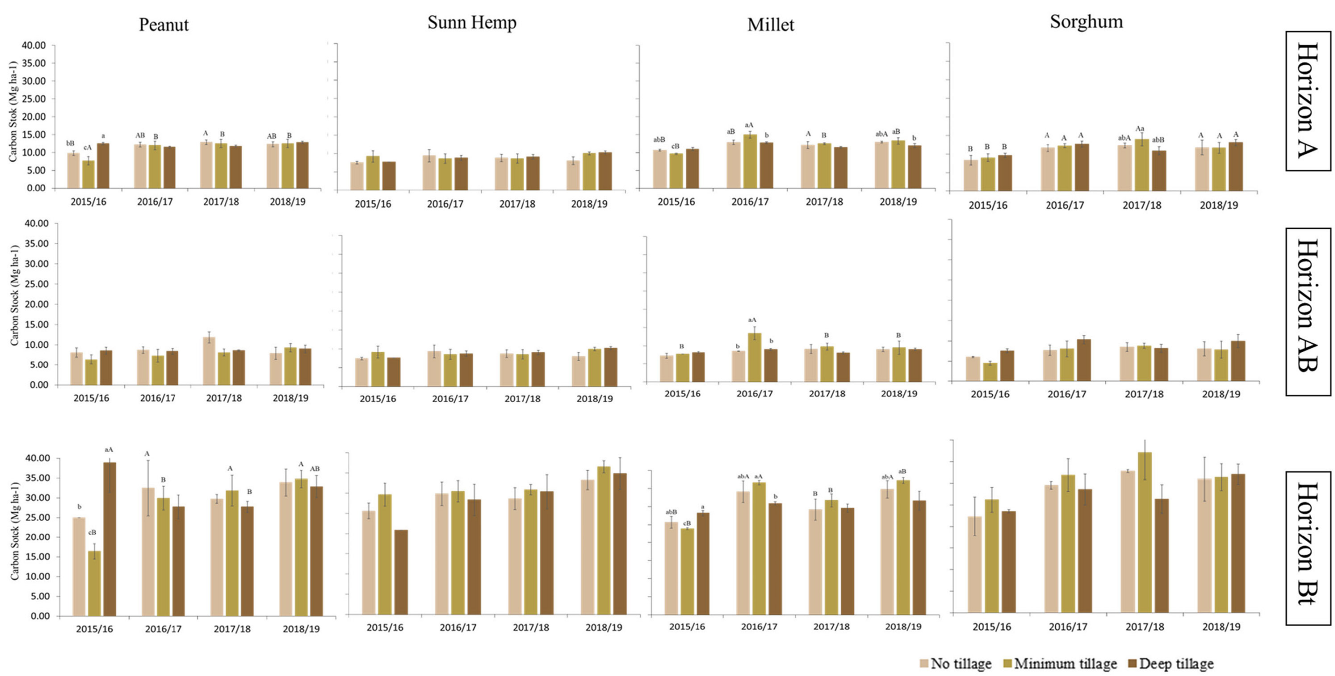

FIGURE 6 Carbon Stock (Mg ha^{-1}) over 4 years of sugarcane production in an experimental area located in the municipality of Ibitinga, São Paulo State, Brazil, under different cover crops and tillage systems. Means followed by the same uppercase and lowercase letter statistically differ between years and between treatments within each crop year, respectively, according to Tukey's test ($p < .05$). Bars indicate the standard deviation {$n = 3$}.

TABLE 5 Orthogonal contrast analysis between the carbon stock of the control treatment and the other treatments, in the experimental area located in the municipality of Ibitinga, São Paulo, Brazil.

Cover plant	CC1 vs the others	CC2 vs the others	CC3 vs the others	CC4 vs the others
Horizon A				
Peanut	***	NS	NS	NS
Sunn hemp	*	NS	NS	**
Millet	**	***	NS	***
Sorghum	NS	NS	NS	NS
Horizon AB				
Peanut	**	*	**	NS
Sunn hemp	NS	NS	NS	NS
Millet	NS	***	NS	NS
Sorghum	***	NS	NS	NS
Horizon Bt				
Peanut	***	NS	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	**	**	NS	*
Sorghum	NS	NS	**	NS

Abbreviations: CC1, control of cycle 1; CC2, control of cycle 2; CC3, control of cycle 3; CC4, control of cycle 4; NS, not significant difference between control and other treatments.

*$p < .05$; **$p < .01$; ***$p < .001$.

TABLE 6 Orthogonal contrast analysis between the soil quality index of the control treatment and the other treatments, in the experimental area located in the municipality of Ibitinga, São Paulo, Brazil.

Cover plant	CC1 vs the others	CC2 vs the others	CC3 vs the others	CC4 vs the others
Horizon A				
Peanut	NS	NS	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	NS	NS	NS	NS
Sorghum	NS	NS	NS	NS
Horizon AB				
Peanut	NS	NS	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	*	**	*	NS
Sorghum	NS	*	NS	NS
Horizon Bt				
Peanut	NS	NS	NS	NS
Sunn hemp	NS	NS	NS	NS
Millet	NS	NS	NS	NS
Sorghum	NS	NS	*	NS

Abbreviations: CC1, control of cycle 1; CC2, control of cycle 2; CC3, control of cycle 3; CC4, control of cycle 4; NS, not significant difference between control and other treatments.

*$p < .05$; **$p < .01$; ***$p < .001$.

Where millet was used as cover crop, the highest rates were found when associated with minimum tillage + subsoiling at 0.40 m (MT) in the third crop cycle in all horizons studied, with a 0.59 value (Figure 7). The smallest drop in crop yield over the cycles occurred for millet as a cover crop with MT during the first cycle, with a 100 Mg ha^{-1} yield, that decreased over time and reached 96 Mg ha^{-1} in the fourth cycle, which represents a 4% yiled reduction. For the no-tillage area, yield decreased from 113 Mg ha^{-1} in cycle 1 to 86 Mg ha^{-1} in cycle 4: for MT/SP, from 111 to 83 Mg ha^{-1}.

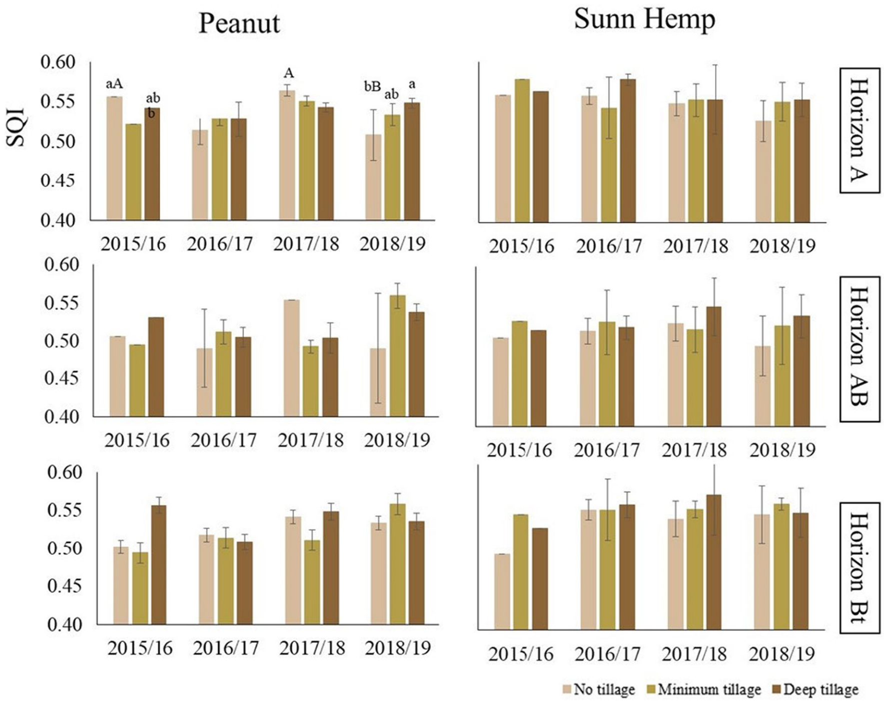

FIGURE 7 Soil quality index for peanut and sunn hemp cover crops over 4 years of sugarcane production in the experimental area located in the municipality of Ibitinga, São Paulo State, Brazil. Means followed by the same uppercase and lowercase letter statistically differ between years and between treatments within each crop year, respectively, according to Tukey's test ($p < .05$). Bars indicate the standard deviation {$n = 3$}.

4 | DISCUSSION

4.1 | Soil quality indicators

Throughout the sugarcane cultivation cycles, soil compaction (i.e., increased bulk density) was observed, regardless of the tillage system adopted. When comparing the conventional tillage with the other treatments, there were subtle differences among figures, suggesting that the different tillage systems tested in this study were not efficient in controlling long-term compaction of the soil. According to Guimarães-júnior et al. (2022), conventional tillage showed compaction before the first sugarcane harvest in this study area, resulting in greater mechanical resistance, since the effects of tillage were altered by the peanut harvesting machinery. Conventional tillage briefly decreases soil compaction, subsequently increasing bulk density and load-bearing capacity, but has a lower potential for soil compaction, about 33% compared to treatments using peanut and sorghum as cover crops (67%) (Guimarães-júnior et al., 2022).

Even in the area under MT/DS at 0.70 m, evidence of long-term soil compaction was observed, in which bulk density values were lower in the sugarcane-plant cycle, but degradation occurred over time, resulting in a progressive increase in bulk density. Cherubin, Karlen, Franco, Cerri, et al. (2016) and Barbosa et al. (2019) reached similar outcomes, in which the tillage with harrows and subsoiler for the planting of sugarcane mitigated the effects of compaction only in the sugarcane-plant cycle, indicating that the transit of machinery in the crops annuls the effects of the soil tillage system over the years of production, mainly promoting the reduction of soil aeration and, thus, increased bulk density.

Furthermore, the soil in the experimental area was characterized as sandy loam in the surface layers, which indicates a greater susceptibility to soil compaction and erosion processes. According to Lima et al. (2013), up to a depth of 0.3 m, soils with this textural class present higher penetration resistance values. This is because there is a greater distribution of particle size fractions, which, due to the rearrangement of particles of different sizes, may have contributed to this effect. Pacheco and Cantalice (2011) state that soils with a diversity of particle sizes can have the spaces between the pores filled with smaller particles and the spaces between them filled again with even finer particles, which can lead to the formation of compacted layers when subjected to pressure. In Brazil, sugarcane is widely cultivated in different regions, consequently, in soils with different physicochemical properties, with 47% of it cultivated in the state of São Paulo under Oxisol.

Conservation tillage systems, such as minimum tillage and no-tillage, have been used as a way to avoid possible damage to soil structure; however, studies state that they cannot eliminate soil compaction in sugarcane areas (Ambrosano et al., 2011; Cavalcanti et al., 2019; Lima et al., 2015; Oliveira et al., 2019; Scarpare et al., 2019). Thus, our outcomes indicate that the use of subsoiler in sugarcane areas breaks deeper layers and reduces soil density, consequently, decreasing the effects of compaction. However, the effects of this implement are temporary due to the traffic of machinery in the harvest, which can also nullify the benefits of cover crops (Guimarães-júnior et al., 2022; Shukla et al., 2017).

The chemical indicators used to compose the soil quality index were phosphorus and potassium. According to the classification of nutrient contents indicated by Van Raij et al. (1997), the potassium values obtained in our study are high and the phosphorus values are low, regardless of the cover crop or tillage system. NPK fertilization (00-25-15), carried out in June 2016, may have played a role in this outcome, as it promoted K increases in the subsequent cycle of the 2017/18 crop, increasing the K levels in the soil.

Phosphorus values found in the soil of the experimental area before land conversion, i.e., pasture to sugarcane crop, were already at low levels and very close to those found after years of sugarcane production (Farhate et al., 2020). Therefore, cover cropping could not increase the availability of nutrients in the soil; also, the fertilization (10-51-00) could not raise the levels of available phosphorus in the soil. Note that approximately 25% of agricultural areas in Brazil are located in phosphorus-fixing soils that represent a great constraint to sugarcane production as this type of soil makes P less available to plants, requiring large amounts of inorganic fertilizers to help overcome this obstacle and increase available supply of P (Roy et al., 2016; Soltangheisi et al., 2019). The use of phosphorus, particularly in soils with low P concentration, stimulates root growth, favours the emergence of tillers and influences plant growth, resulting in higher yields and furrow quality (Gichangi et al., 2009; Labajo & Pabiona, 2022).

According to this study outcomes, the cover crop with the greatest influence on phosphorus and potassium concentrations was millet, considering the treatment with significant difference in relation to the averages obtained for these nutrients in an area under conventional system. Grasses are important in the production of phytomass and in protecting the soil from erosion and nutrient loss. For millet, dry matter production was 10 $Mg\,ha^{-1}$, and sorghum, the other grass species, yielded 21 $Mg\,ha^{-1}$ (Farhate et al., 2020, 2022), a fact that contributed to the rise in the levels of these nutrients in the soil. This very aspect was also observed by Crusciol et al. (2015), who reported the efficiency of *marandu* grass (*Brachiaria brizantha*), a grass species with a deep root system that allows for the absorption of nutrients in the subsurface layers, and which accumulated about 17 $Mg\,ha^{-1}$ of dry matter, presenting figures higher than those of the area without cover crops, which presented only 9 $Mg\,ha^{-1}$.

Also, the results show that the use of peanuts and sunn hemp provided an increase in potassium concentrations over the years. This implies that the lower C:N ratio of legumes favoured the release of nutrients into the soil, such as N, P, Ca and Mg, making the soil richer in nutrients during sugarcane planting (Pacheco et al., 2011). Moreover, according to Cherubin et al. (2015), the change of land use from pasture to sugarcane crops provides increased nutrient levels and reduced soil acidity, due to the use of fertilizers and limestone that improve soil fertility.

Overall, the values found for total soil carbon were low. Therefore, the maintenance of straw on the soil surface, provided by mechanized harvesting, is essential to increase soil carbon contents, as it is a significant source of this element, in addition to favouring the cycling of other nutrients, erosion control, water storage, aggregate stabilization, and even invasive species control (Carvalho et al., 2017; Castioni et al., 2019).

Furhermore, the results of this study showed that the use of millet as cover crop induced significant differences, increasing soil carbon content compared to the conventional tillage. Grass-type cover crops can increase soil carbon content compared to commercial crops and present greater efficiency in nutrient cycling because of their more extensive root system, which explores deeper soil horizons (Carvalho et al., 2016). In a study carried out by Calvo et al. (2010), the authors observed that millet had a greater capacity for phytomass production and soil cover in its initial development compared to sorghum. In addition, the same authors observed that millet also proved efficient as to its rapid development and better yield of straw compared to legumes.

The use of sorghum associated with minimum tillage for sugarcane planting also induced an increase in total carbon from the sugarcane plant cycle (2015/16) to subsequent cycles. The results of dry matter produced by this plant, about 21 $Mg\,ha^{-1}$ in an experimental area, showed its ability to produce soil vegetation cover compared to other plants, such as peanuts, which presented only 5 $Mg\,ha^{-1}$ (Farhate et al., 2022). This result corroborates the data by Segnini et al. (2013), who found greater accumulation of carbon in an area without soil disturbance, with a soil carbon accumulation rate of 1.63 $Mg\,ha^{-1}$ per year with no-tillage and 0.69 $Mg\,ha^{-1}$ per year with conventional system. Such find proves that a large part of the carbon accumulated during sugarcane cultivation cycles is lost during sugarcane renewal.

Thus, maintaining straw on the soil surface and adopting sustainable management practices such as no-tillage can increase carbon sequestration in sugarcane fields (Lisboa et al., 2019; Segnini et al., 2013). The adoption of soil conservation tillage, such as minimum tillage to replace conventional sugarcane cultivation, preserves the physical quality of the soil, due to less soil disturbance, which is reserved for the planting row, and most of it remains with crop residues (Cherubin, Carvalho, et al., 2021).

The use of conservation tillage associated with cover crops is a sustainable alternative for farmers in Brazil, since soil attributes can be maintained or even improved if the use of agricultural soils is rationally planned, which is widely reported in the literature (Farhate et al., 2020; Oliveira et al., 2019; Segnini et al., 2013; Shen et al., 2018; Weidhuner et al., 2021).

4.2 | Soil quality index

Comparing conventional tillage (control treatment) to other treatments, a difference was observed in the SQI when millet was used as cover crop in the AB horizon (Table 6). Our results based on SMAF corresponded to those obtained by Farhate et al. (2020), who developed a SQI for the same experimental areas, based on ranking and weighting indicators using principal component analysis (PCA). The authors observed that the use of millet improved the physical quality of the soil in association with deep tillage and no-tillage, in horizons AB and Bt, in the sugarcane cycle until the second ratoon cycle.

In this study, in the second ratoon cycle (2017/18), a higher SQI score was obtained with the association between millet and minimum tillage with subsoiling at 0.40 m—probably because of the higher potassium, phosphorus, and carbon levels in this cycle. Millet is a highly efficient grass regarding nutrient cycling and phytomass production, helping in the formation and stability of soil aggregates (Calvo et al., 2010; Costa et al., 2014). In addition, according to Nunes et al. (2020), conventional tillage presents the lowest values of soil organic carbon, aggregate stability, and high-bulk density, which reflect in a low SQI compared to different soil tillage systems, such as minimum tillage and no-tillage.

Overall, the soil quality index did not present substantial declines over the years, ranging from 0.49 to 0.59. According to Cherubin, Karlen, Franco, Cerri, et al. (2016), the SQI values found in the sugarcane planting area, that is, in the first harvest, ranged 0.65–0.77, low values when compared to others in the literature, possibly because of the low levels of phosphorus and soil carbon obtained.

The exception occurred in a no-tillage area using peanuts as a cover crop, which presented a 9% reduction between the third and fourth cycle of sugarcane production. However, from cycle 1 (2015/16) to cycle 3 (2017/18), the SQI of this treatment was higher compared to the area with MT and MT/SP. Although unexpected, since peanuts produce less biomass and soil disturbance are common during harvest, these results are in line with those found by Farhate et al. (2020), in which the cultivation of peanuts associated with no-tillage in straw promoted superior physical quality compared to conventional tillage. In grain production systems, Nunes et al. (2020) emphasize that the no-tillage system can be a practice with the potential to maintain or improve soil health over the years, as it obtains superior SQI figures compared to the deep tillage and conventional tillage systems.

In the last production cycles studied (2017/18 and 2018/19), the results showed that the highest index were obtained when peanuts, sunn hemp, and sorghum were associated with the deep tillage system (MT/SP). The use of deep tillage in these areas possibly allowed for greater root growth and deepening, due to decompaction promoted by the use of this implement, increasing water and nutrient infiltration and absorption capacity (Scarpare et al., 2019). Furthermore, cover crops, in general, improved soil attributes, even if only occurring in the first years of production, reflecting on soil quality outcomes. According to Schipanski et al. (2014), cover crops can improve a number of soil ecosystem factors, such as: biomass production, soil carbon storage, and even erosion control.

The maintenance of straw on the soil surface is another important factor that can gradually restore and increase soil quality (Cherubin, Carvalho, et al., 2021), as observed in the third production cycle (2017/18). Regardless of the type of soil, excessive straw removal must be avoided, mainly due to the increase in bulk density and the loss of soil organic carbon, which are the main factors for the decline of soil health in sugarcane production areas (Cherubin, Borsonal, et al., 2021).

The SMAF tool was also used in other studies (Cherubin, Borsonal, et al., 2021; Cherubin, Karlen, Cerri, Franco, et al., 2016; Cherubin, Karlen, Franco, Cerri, et al., 2016; Lisboa et al., 2019; Luz et al., 2019; Nunes et al., 2020). The use of this tool enabled quantifying and detecting changes in soil quality induced by the systems used in Brazil (Luz et al., 2019). It was effective to assess changes in soil health by scoring curves (Nunes et al., 2020) and to properly transform indicator values expressed in different units into unitless scores (ranging from 0 to 1), generating SQI scores that helped in the assessment of soil functioning (Cherubin, Karlen, Franco, Cerri, et al., 2016).

The use of this tool can advance studies in soil quality assessment, being a method to maintain information for agricultural managers. Karlen et al. (2019) believe that farmers can employ the advances in techniques and technologies to interpret soil quality indicators, leading them to more sustainable production systems that will thus help mitigate and prevent future degradation.

4.3 | Sugarcane crop yield

An annual reduction in sugarcane crop yield was observed regardless of the soil tillage system adopted in the area, which was expected, as production tends to fall over the years with ratoon sugarcane.

Several studies report the damages caused by heavy machinery traffic in sugarcane fields, mainly leading to soil physical degradation (Bordonal et al., 2018; Cherubin, Karlen, Franco, Tormena, et al., 2016; Esteban et al., 2019; Guimarães Júnnyor et al., 2019). Cultivation operations during sugarcane replanting, such as harrowing and subsoiling, generally every 5 years, have a positive short-term effect on soil physical quality; however, over time, they decrease erosion resistance and increase structural degradation (Cherubin, Karlen, Franco, Tormena, et al., 2016).

From the third production cycle (2017/18), some soil attributes showed higher quality, which was reflected in increased final yield. This is due to the deposition of straw on the soil, which provides benefits such as increased biological activity, carbon stock, and nutrient cycling (Cherubin et al., 2018). In addition, crop residues act as mechanical barriers, protecting the soil against the impact of raindrops, reducing erosion risks, controlling soil water evaporation, and also acting as thermal insulators (Lisboa et al., 2019).

The maintenance of straw on the soil surface, the use of rotative cover crops, and the adoption of minimum tillage are essential practices to maintain yields at around 100 Mg ha^{-1} (Bordonal et al., 2018). According to Ambrosano et al. (2011), the use of cover crops for sugarcane cultivation can increase yields by about 35%, with increased number of stalks and higher sugar production, consequently increasing the economic performance of the crop.

After the intensification of mechanization, planting, and harvesting operations, the adoption of these alternative soil tillage practices—such as a minimum tillage system and cover cropping—is crucial to reduce the damages caused by the use of heavy agricultural machinery in sugarcane crops, with consequences over the years. For farmers, it is essential to maintain a high yield and good economic performance of the crop, and, to this end, new cultivation practices must be considered and adopted.

5 | CONCLUSIONS

Considering 1 as the maximum value for the SQI, according to SMAF, the maximum values obtained in the studied area ranged from 0.49 to 0.59, suggesting that the soil is not working at its maximum capacity in the different treatments presented. The use of subsoilers in the soil tillage system promoted better results in compaction management, providing better density results, in addition to an increase in carbon values due to better incorporation of organic matter. Regarding cover crops, millet provided the best outcomes for soil quality, reflected in the SQI and sugarcane yield, which remained at 100 Mg ha^{-1}. The poor functioning of the soil, indicated by the low IQS obtained, reinforces the need to adopt conservation systems that can restore, even partially, soil quality in these sugarcane production areas in the long term.

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DATA AVAILABILITY STATEMENT

The data supporting this study were made available at the time of submission. If there is missing information, the authors will not object to making more details of the data available.

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SUPPORTING INFORMATION

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