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OPTIMUM WATER RANGE AND LOAD-BEARING CAPACITY IN SOIL MANAGEMENT SYSTEMS, STRAW REMAINING, AND CHISELING IN SUGARCANE

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KEYWORDS

available water, compressibility, soil density, pre-consolidation pressure.

ABSTRACT

Sugarcane requires planning aimed at maintaining production levels, technological quality, and longevity of the sugarcane field, as it is a semi-perennial crop. To this end, the adoption of soil management systems associated with the maintenance of remaining straw are some of the strategies aimed at protecting the soil structure and its properties vital to the sustainability of agricultural systems. In this context, this study aimed to evaluate the influence of soil management systems and remaining straw with and without ratoon chiseling on the optimum water range (OWR) and load-bearing capacity (LBC) of the soil. The experimental design consisted of randomized blocks in a split-plot scheme, with four replications. The plots were composed of no-tillage and conventional tillage, the subplots consisted of three levels of remaining straw (0, 50, and 100%), and the sub-subplots consisted of the use or not of chiseling. Samples with preserved structures were collected at depths of 0.05 and 0.15 m for the analysis of the physical indicators OWR and LBC. Maintaining 100% straw associated with the use of chiseling resulted in an increase in OWR in both soil management systems and depths. Maintaining straw at 50 and 100% also led to lower LBC values in the evaluated soil management systems and depths, suggesting an improvement in soil physical quality. The use of chiseling of ratoons in conventional tillage promoted higher LBC values, indicating possible additional soil compaction in these areas.

INTRODUCTION

Sugarcane is one of the main crops produced in the world, being cultivated in more than 100 countries. Approximately 83% of sugarcane production is concentrated in ten countries, with Brazil considered the world's largest producer of this crop, with around 37% of production, which represents 746 million tons per year (FAO, 2021). Sugarcane is a high-energy biomass crop, with the sugar stored in its stalk and the lignocellulosic residue remaining after sugar extraction used for producing biofuels or other bioproducts (Awe et al., 2020).

Sugarcane is characterized as a semi-perennial crop, with an average cycle of approximately 5 years. Conventional tillage is normally used for planting sugarcane, presenting different combinations of plowing, harrowing, and subsoiling (Silva Junior et al., 2013). These operations aim to provide better conditions for the soil for the sprouting and initial development of the crop that will be planted and disaggregate the compacted soil layers (Silva Junior et al., 2013; Arcoverde et al., 2019) caused by the traffic of heavy machinery on the sugarcane fields (Vischi Filho et al., 2017).

Research with the aim of proposing conservation practices for soil management in different edaphoclimatic environments for sugarcane production is essential for the sustainability of these systems, especially in environments with soil under physical and/or chemical restrictions and water deficit during periods of the year. Thus, management practices for soil cultivated with sugarcane can be selected to provide the appropriate balance between soil sustainability, high yields, and minimized costs (Marasca et al., 2016). In this context, no-tillage can be a

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viable alternative and its use has demonstrated promising results in terms of sugarcane productivity (Arcoverde et al., 2023), in addition to being a more economical type of cultivation than the conventional tillage system (Moraes et al., 2017; Arcoverde et al., 2019).

Along with conservationist soil management practices, the maintenance of remaining straw after mechanized harvesting of sugarcane on the soil surface influences some chemical, physical, and biological properties in the agricultural environment, such as the increase in soil organic matter (Bordonal et al., 2018), decreased thermal fluctuations in the surface soil layers (Santos et al., 2022), increased water infiltration, conservation of water content in the soil (Santos et al., 2022), and reduced susceptibility soil compaction (Castioni et al., 2019), as straw maintenance on the soil can preserve its structural quality, increasing the productivity and longevity of sugarcane (Silva et al., 2022).

However, the intense traffic of machinery during the mechanized harvesting of sugarcane throughout the crop cycles is responsible for causing additional compaction to soils managed under these production systems (Vischi Filho et al., 2017). The water content during these mechanized operations is the main factor responsible for maximizing impacts on the soil structure in the traffic lines (Guimarães Júnnyor et al., 2019). This compaction generally occurs close to the planting row, where there is a predominance of roots in the surface layers (up to 40 cm) and close to the clumps, up to 30 cm (Sá et al., 2016). Sugarcane root growth is concentrated close to the center of the planting row and mechanical chiseling between ratoon rows can mitigate soil compaction, and improve physical-hydraulic attributes and nutrient availability to plants (Souza et al., 2022).

Therefore, understanding soil-crop relationships through indicators is fundamental to assertively proposing sustainable management systems for agricultural production. The optimum water range (OWR), which integrates soil physical properties using the approach of the range of least water limitation, allowing for better knowledge of soil water availability and its relationship with use practices and management for different crops, is among the indicators with this potential (Mishra et al., 2015; Dias et al., 2016; Silva et al., 2017; Vischi Filho et al., 2017).

The load-bearing capacity (LBC) is another indicator of structural quality used in studies in areas included in the sugarcane production system. It relates the pre-consolidation pressure to soil moisture, reducing the internal soil resistance and making it more susceptible to the compressive process. This indicator depends on the pressure applied to the soil and its structure and, therefore, the application of pressures higher than the soil load-bearing capacity causes non-recoverable deformations, which results in its structural degradation (Vischi Filho et al., 2017; Moraes et al., 2019). Therefore, it is an important indicator in characterizing the compressive process of soils to prevent their physical degradation and provide development and productivity of crops (Guimarães Júnnyor et al., 2019), being fundamental for determining the most appropriate humidity conditions for the execution of agricultural operations (Pereira et al., 2015).

In this context, this study aimed to evaluate the influence of soil management systems and remaining straw with and without chiseling of sugarcane ratoons on the optimum water range (OWR) and load-bearing capacity (LBC) of the soil.

MATERIAL AND METHODS

The study was carried out in the 2015/2016 agricultural year in an experimental area of Embrapa Western-Region Agriculture in partnership with São Fernando Mill in the municipality of Dourados, MS, Brazil. The site is located at latitude −22°25′86″ S and longitude −54°97′47″ W, at an altitude of 410 m (Figure 1). According to the Köppen classification, the regional climate is Am, that is, a tropical monsoon climate with rainy seasons in the summer and dry seasons in the winter (Alvares et al., 2013). The soil was classified as a very clay-textured Oxisol (Santos et al., 2018).

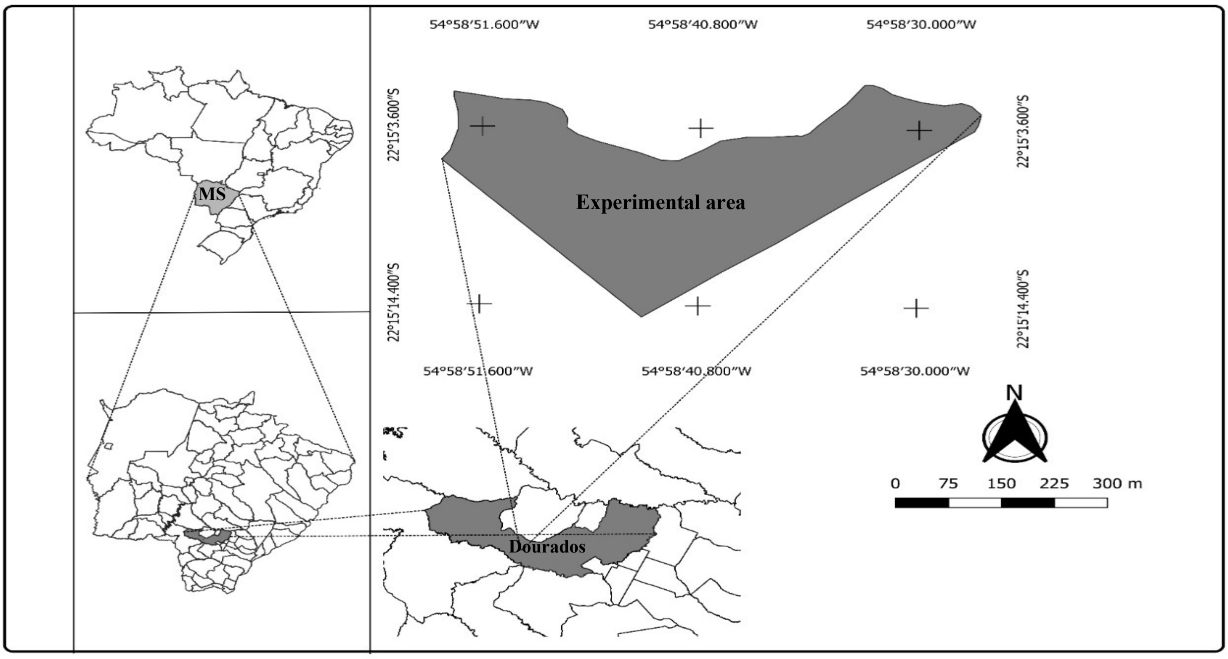


FIGURE 1. Location of the experimental area, which belongs to the São Fernando Mill, Dourados, MS, Brazil.

The experimental design consisted of randomized blocks in a split-plot scheme, with four replications. The plots were composed of management systems (no-tillage and conventional tillage), the subplots consisted of levels of remaining straw, that is, no straw removal (100%), partial straw removal (50%), and total straw removal (0%), and the sub-subplots consisted of mechanical chiseling in the cultivation of ratoons (with and without chiseling between the sugarcane rows). The experimental units were composed of six sugarcane rows with a spacing of 1.5 m and 30 m long (270 m^2).

The experiment was conducted in an area cultivated with sugarcane renewed in 2013, which was subjected to mechanized harvesting, without collecting the remaining straw in the previous cycle (2006 to 2012). Part of the renewed area was conducted under no-tillage with chemical elimination of the regrowth of the last sugarcane ratoon through the application of 6.0 L ha^{-1} of the herbicide glyphosate + 1.8 L ha^{-1} of the herbicide 2,4-D and a spray solution volume of 150 L ha^{-1}. Then, amendments (2.0 Mg ha^{-1} of gypsum and 4.0 Mg ha^{-1} of dolomitic limestone) were applied to the soil surface. In the other part of the area, conventional preparation was carried out with chemical elimination, with the same doses of herbicide used in the direct planting area, regrowth of the last sugarcane ratoon, application of correctives (agricultural gypsum and limestone) in the same sources and doses of direct planting. Still in the area with conventional tillage, these amendments together with the remaining straw were incorporated into the soil through conventional tillage operations, conducted with harrowing with a plow harrow, subsoiling, harrowing with an intermediate harrow, and harrowing with a leveling harrow.

The entire experimental area was cultivated with soybean in the 2012/13 growing season after applying the amendments and preparing the soil under the conventional tillage system. A new sugarcane field was established with the cultivar RB966928, which was planted mechanically at a single spacing of 1.5 m between rows in March 2013 after the soybean harvest.

The aforementioned levels of remaining straw were applied to the subplots after harvesting the plant cane in September 2014. Windrowing operations were carried out with a New Holland AL 1290 rake pulled by a 110-hp tractor. The straw windrows were then baled using a New Holland BB 1290 baler pulled by a 180-hp tractor. Finally, the bales were collected with a New Holland AC 1290 trailer pulled by a 110-hp tractor. Partial collection (50%) was established by adjusting the working height of the straw rake. The implementation of collection treatments (0, 50, and 100%) resulted in average amounts of remaining straw of 1.37, 12.17, and 17.96 Mg ha^{-1}, respectively.

Chisel plow was carried out with a DMB Novo São Francisco cultivator/ratoon fertilizer, equipped with straw cutting discs and scarifying rods that work at an approximate depth of 0.3 m in the center of the sugarcane inter-row.

Soil samples with preserved structure were collected in September 2015, after harvesting the first ratoon (second cut), with the application of total and partial straw collection and ratoon chiseling, using 83-cm^3 metal cylinders (radius of 3.22 cm and height of 2.55 cm), which were placed 5 cm away from the row and centered at depths of 0.05 and 0.15 m. Seven samples were collected from each plot and each depth, totaling 42 samples per treatment, that is, 21 samples at each depth.

The 21 samples from each treatment were divided into 7 groups of 5 samples by depth, with each group subjected to saturation through the gradual raising of a water depth until they reached approximately two-thirds of the height of the metallic cylinder for subsequent stabilization of the water content. Subsequently, they were subjected to matrix potentials using a tension table (−0.006 MPa) and Richards chamber at the following potentials: −0.004, −0.01, −0.033, −0.066, −0.1, −0.3, and −1.5 MPa, as described by Pereira et al. (2015).

Soil penetration resistance was measured when the samples reached equilibrium at the aforementioned tensions using an electronic penetrometer with a constant penetration speed of 0.01 m min^{-1} (cone base diameter of 4 mm and semi-angle of 30°).

The procedures described by Pereira et al. (2015) were adopted to determine OWR. The critical values of water content associated with matric potential, soil resistance to root penetration, and soil aeration porosity were represented by water content at field capacity (θ_{FC}), with a potential of −0.01 MPa; the water content at the permanent wilting point (θ_{PWP}), with a potential of −1.5 MPa; the volumetric water content in which the soil resistance to root penetration (θ_{PR}) reaches 2.0 MPa; and the volumetric water content in which the aeration porosity (θ_{AP}) is 0.10 m^3 m^{-3}.

The θ_{FC} and θ_{PWP} values were determined using the mathematical model $\theta = \exp^{(a+bDs)}$ (ψc), described by Pereira et al. (2015), in which the original data were adjusted by incorporating the variable Ds into the function used by Ross et al. (1991), where θ is the soil water content (m^3 m^{-3}), Ds is the soil density (Mg m^{-3}), ψ is the soil matric potential (MPa), and the letters a, b, and c are the empirical model adjustment parameters.

The PR values of all samples with known θ and Ds were adjusted mathematically using the model $PR = d\theta^e Ds^f$, described by Pereira et al. (2015), where RP is the soil penetration resistance (MPa) and the letters d, e, and f are the empirical model adjustment parameters. This model allowed determining the critical value of θ so that the PR did not exceed 2.0 (θ_{PR}) as a function of Ds. For this purpose, RP is replaced in the model by the value of 2.0 MPa, considered initially and totally limiting to calculate OWR.

The θ_{AP} value was obtained using the model $\theta_{AP} = 1 - (Ds/Dp) - 0.10]$, in which θ_{AP} is the volumetric water content of the soil in which the aeration porosity is 0.10 m^3 m^{-3} and Dp is the particle density (Mg m^{-3}), with the value of 2.65 Mg m^{-3} being adopted as the average particle density (Pereira et al., 2015).

The upper limits of OWR were considered to be θ_{FC} or the one at which θ_{AP} is considered adequate for plant growth and development. The θP_{WP} or θ_{PR} that are limiting to the growth and development of the crop root system was considered when determining the lower limits. The critical soil density (Dsc), which is the soil density at which OWR equals zero, was established after determining the OWR limits, as the upper limit is numerically equivalent to the lower limit.

The adjustments of the mathematical models and parameters a, b, c, d, e, and f were carried out using the non-linear regression method. Moreover, the adjusted water retention curves presented coefficients of determination (R^2) that were subjected to the F-test (Pereira et al., 2015).

The samples were taken to a CNTA-IHM/BR-001/07 automatic oedometer for the uniaxial compression test after determining the soil penetration resistance, as described by Pereira et al. (2015). The increasing pressures applied to each sample were 25, 50, 100, 200, 400, 800, and 1,600 kPa, each one applied until 90% of the maximum deformation was reached (Guimarães Júnnyor et al., 2019). The samples were taken to an oven at 105–110 °C for 48 hours after each uniaxial compression test to determine the volumetric moisture and soil density using the volumetric ring method, as described by Teixeira et al. (2017).

The soil compression curve was obtained by placing the pressures applied on the abscissa axis versus the soil density obtained at the end of each stage of application of each pressure on the ordinate axis, determining the pre-consolidation pressure (σp) for each sample using the method proposed by Dias Junior & Pierce (1996). The letters a and b represent the empirical adjustment coefficients of the model, that is, the linear and angular coefficients, respectively.

Comparisons between models were performed according to the linear model homogeneity test described in Snedecor & Cochran (1989). The logarithm was applied to the pre-consolidation pressure values to obtain linear models from the exponential model $\sigma p = 10(a+b\theta)$, resulting in a log equation $\sigma p = a + b\theta$. This linear model test considers two models, which are compared by analyzing the intercept a, the angular coefficient b, and data homogeneity (F) (Pereira et al., 2015; Guimarães Júnnyor et al., 2019).

The adjusted load-bearing capacity curves presented coefficients of determination (R^2) that were subjected to the F-test (Pereira et al., 2015).

RESULTS AND DISCUSSION

All fitted soil water retention curves had significant coefficients of determination (R^2) by the F-test.

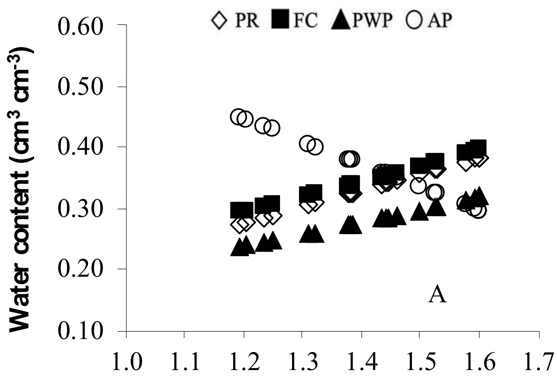
The confidence intervals of the adjusted coefficients in the no-tillage and conventional tillage were significant in most treatments, as they do not include a value equal to zero (Pereira et al., 2015). They did not present significance for some treatments, except for parameter b at both no-tillage depths. The coefficient b was only significant for the treatments 0 and 50% straw without chiseling at a depth of 0.05 m, but only the treatment with 0% straw with chiseling had a significant effect at a depth of 0.05 m. In the conventional tillage, the water retention adjustments for parameters a and c were significant for both depths, while coefficient b was only significant for the 0% straw treatment without chiseling.

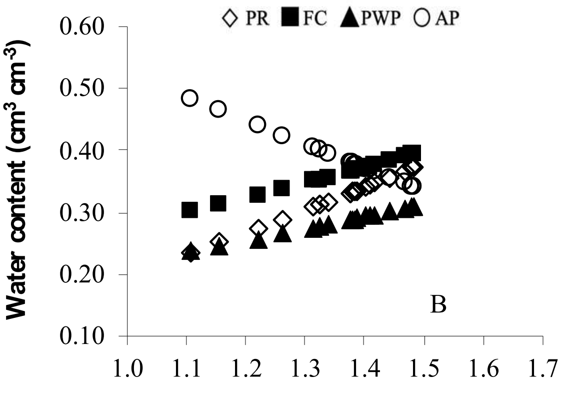
The coefficients of the penetration resistance curve in the no-tillage for the values of confidence interval showed a variation between the parameters, and the coefficient d at both depths showed no significance. The coefficient f showed no significance for the treatments of 0% straw with chiseling and 100% straw with and without chiseling at a depth of 0.05 m, and no significant equations were observed in the treatments of 50% straw with and without chiseling at a depth of 0.15 m. In the conventional tillage, among the coefficients of confidence interval, the parameter d was significant only for treatments with 100% straw without chiseling at a depth of 0.05 m, whereas the only significant treatments for de depth of 0.15 m were 0 and 50% straw with chiseling and 100% straw without chiseling.

Variations in matric tensions at the critical limits corresponding to the field capacity (FC) (0.006 MPa) (θ_{FC}), represented by the permanent wilting point (PWP) (1.5 MPa) (θ_{PWP}), the aeration porosity (AP) of 0.10 m^3 m^{-3} (θ_{AP}), and the moisture at which the soil penetration resistance (PR) is 2.0 MPa (θ_{PR}) were plotted for each soil density value at a depth of 0.05 m in the no-tillage (Figure 2).

The values of θ_{FC}, θ_{PWP}, and θ_{PR} increased and θ_{AP} decreased with an increase in soil density in all treatments. An increase in OWR was observed in all treatments with chiseling and a higher range in the treatment with 100% straw and chiseling, in which there was no critical soil density (Dsc), as the water content was available throughout the entire range. Similarly, Garbiate et al. (2016) observed an improvement in OWR attributes with chiseling, which provided soil with physical attributes favorable to root growth.

The upper limit of treatments with 0% straw with and without chiseling (Figures 2A and 2B) was defined by θ_{FC} and the other treatments with remaining straw showed that θ_{AP} replaced θ_{FC} as the upper limit of water content close to the density of 1.3 g cm^{-3}. In contrast, the lower limit was defined by θ_{PWP} in all treatments, except for 100% straw without chiseling, in which θ_{PR} limited the water content. Similar results have been observed in different soils and management systems (Pereira et al., 2015; Dias et al., 2016; Fashi et al., 2017).





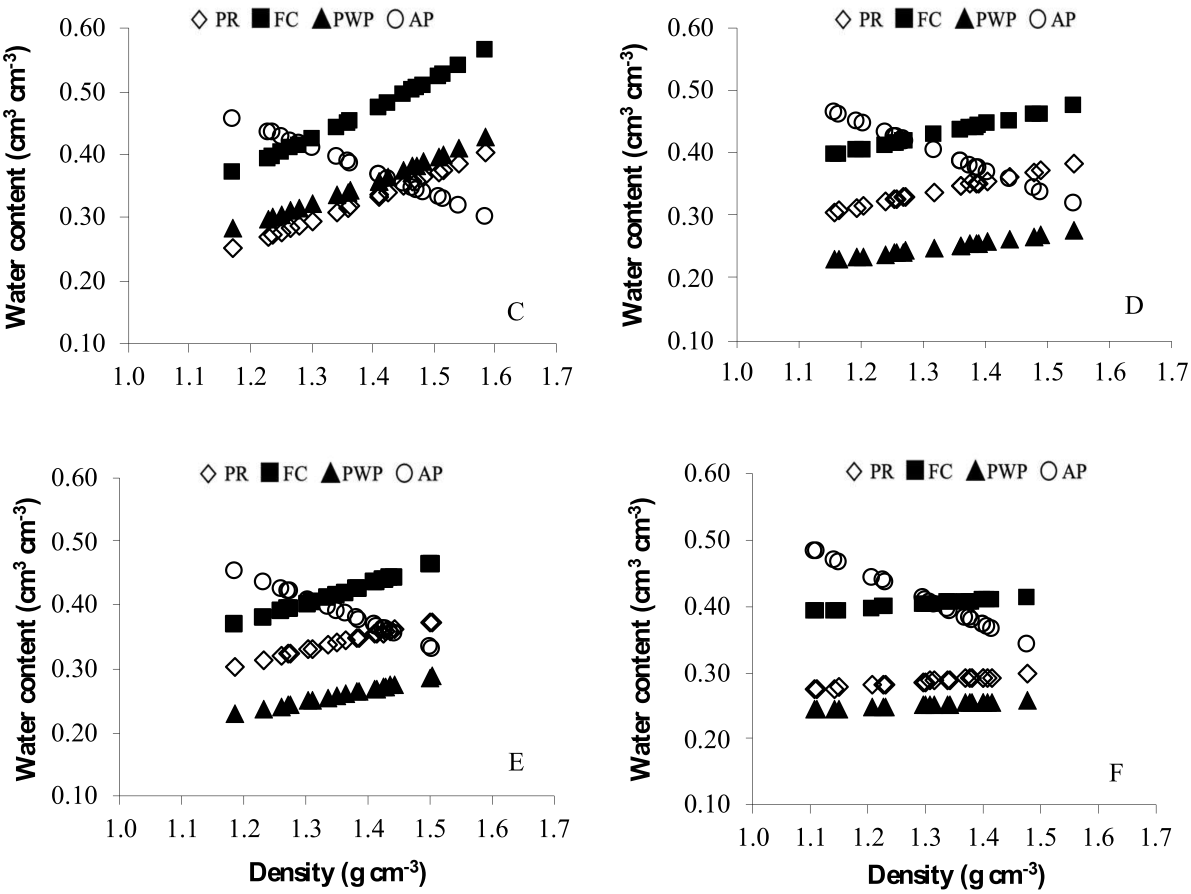
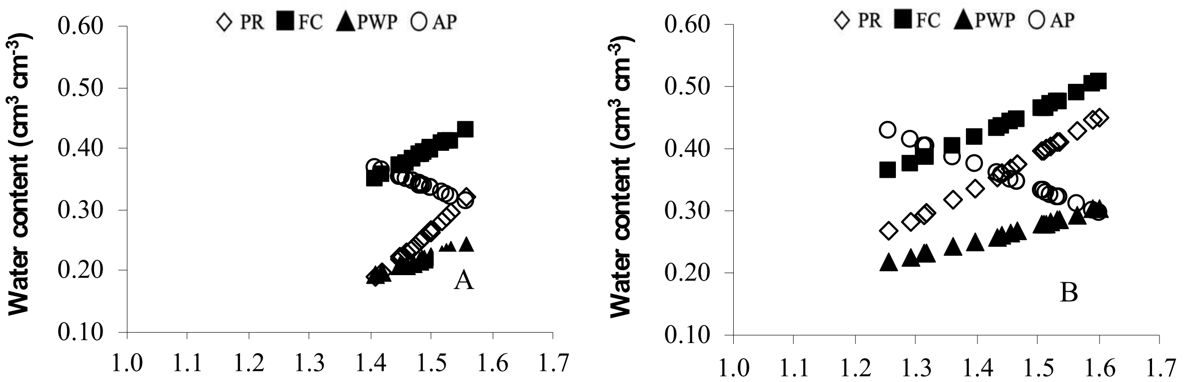


FIGURE 2. Variation of water content at field capacity (θ_{FC}), permanent wilting point (θ_{PWP}), aeration porosity of 0.10 m^3 m^{-3} (θ_{AP}), and soil penetration resistance of 2.0 MPa (θ_{PR}) as a function of the density of an Oxisol at a depth of 0.05 m subjected to different levels of straw and chiseling of sugarcane under no-tillage. A: 0% straw without scarification, B: 0% straw with chiseling, C: 50% straw without chiseling, D: 50% straw with chiseling, E: 100% straw without chiseling, F: 100% straw with chiseling.

The Dsc for treatments evaluated at a depth of 0.15 m was obtained close to the density of 1.4 g cm^{-3} for most treatments, except for 0% straw without chiseling and 100% straw with chiseling (Figures 3A and 3F), which indicated Dsc at densities of 1.5 and 1.6 g cm^{-3}, respectively.

Treatments with chiseling showed a change in OWR, and the system with 100% straw with chiseling (Figure 3F) showed again a higher range in OWR than the others at a depth of 0.15 m.

The upper limit for no-tillage at a depth of 0.15 m (Figure 3) was defined by θ_{FC} up to a density of 1.3 g cm^{-3}, being replaced from this point by θ_{AP}, except for treatments with 0% straw without chiseling and 50% straw with chiseling (Figures 2A and 2D), in which θ_{AP} limited the water content throughout the OWR limit. θ_{PR} restricted OWR in all treatments for the lower limit. The results corroborate those found by Silva et al. (2017), who evaluated an Oxisol under no-tillage and observed that the high total porosity in Oxisols minimizes possible aeration problems, which may eventually appear in cases of severe compaction, excess moisture, or high clay content.



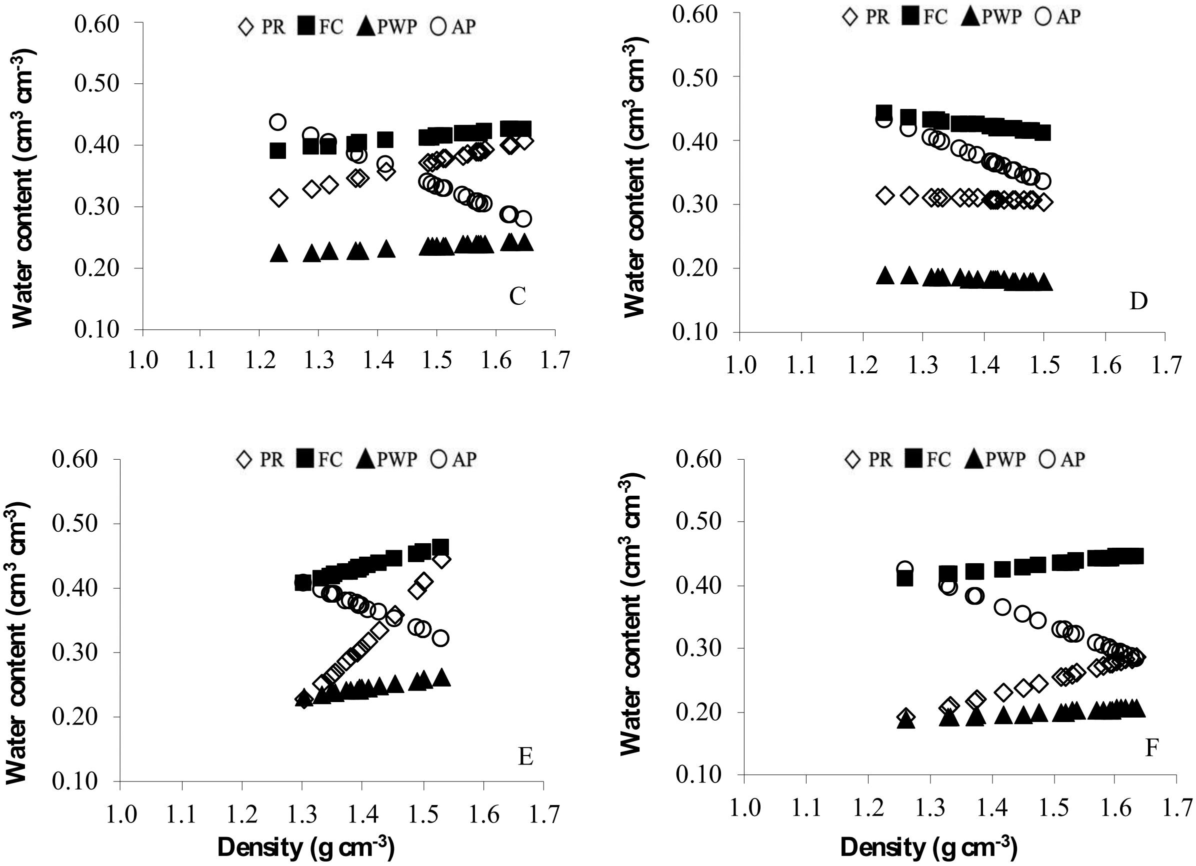
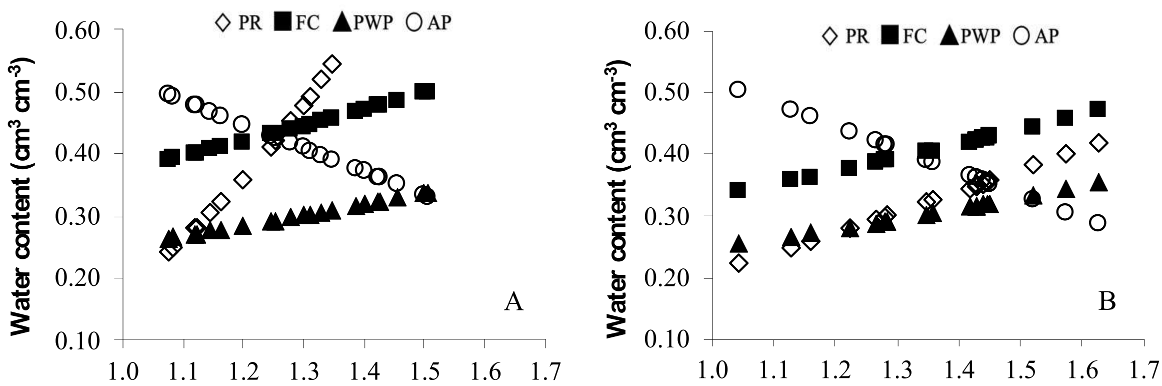


FIGURE 3. Variation of water content at field capacity (θ_{FC}), permanent wilting point (θ_{PWP}), aeration porosity of 0.10 m^3 m^{-3} (θ_{AP}), and soil penetration resistance of 2.0 MPa (θ_{PR}) as a function of the density of an Oxisol at a depth of 0.15 m subjected to different levels of straw and chiseling of sugarcane under no-tillage. A: 0% straw without chiseling, B: 0% straw with chiseling, C: 50% straw without chiseling, D: 50% straw with chiseling, E: 100% straw without chiseling, F: 100% straw with chiseling.

The upper limit in the conventional tillage was defined by θ_{FC} in all treatments up to a Dsc of 1.4 g cm^{-3} at a depth of 0.05 m, except for 0% straw with chiseling (Figure 4B), in which θ_{AP} was replaced as an upper limit of water content. Similarly, Vischi Filho et al. (2017) evaluated OWR attributes in mechanized sugarcane systems with conventional tillage. Importantly, the fact that the upper limit of OWR is always defined by θ_{FC} for all Ds values below Dsc reveals that θ_{AP} was not a limiting factor in the soil. It agrees with Fashi et al. (2017), who evaluated soil OWR under conventional and conservationist tillage.



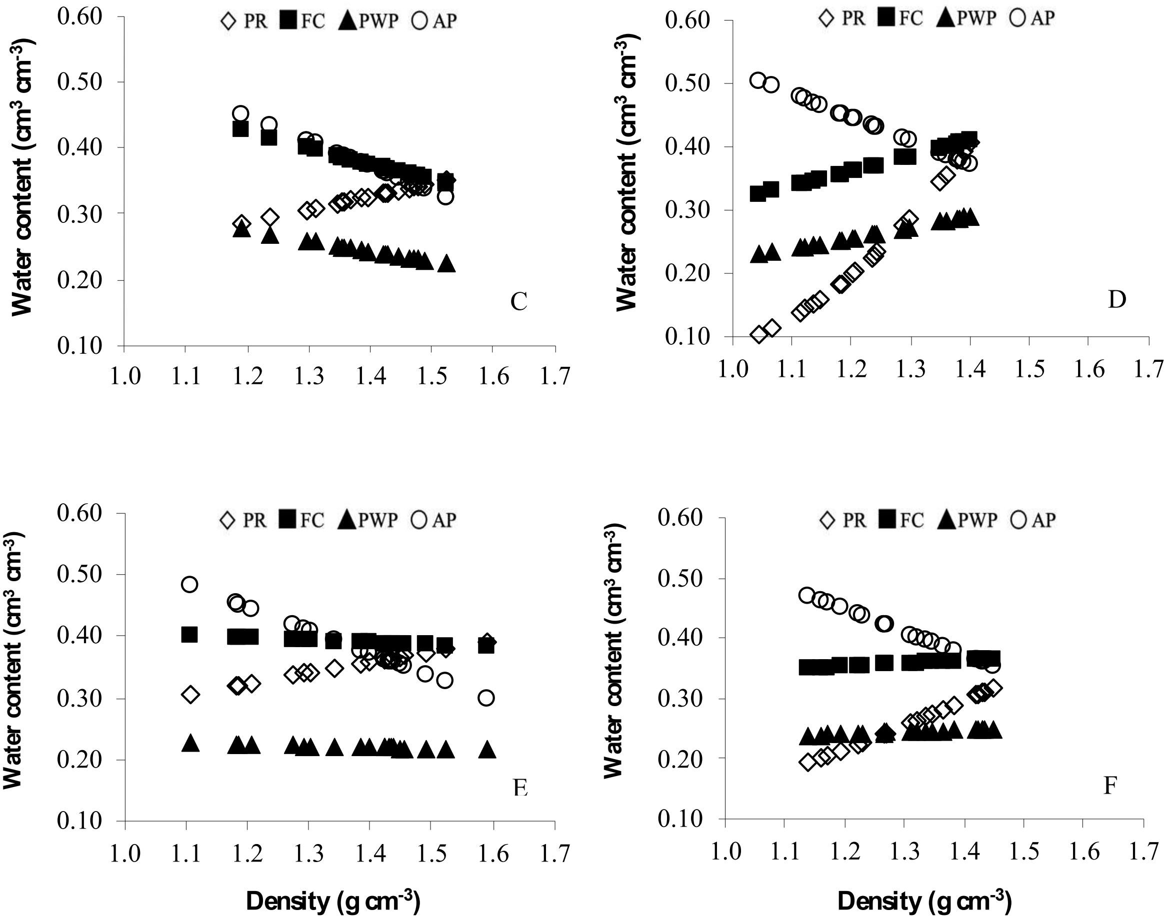


FIGURE 4. Variation of water content at field capacity (θ_{FC}), permanent wilting point (θ_{PWP}), aeration porosity of 0.10 m^3 m^{-3} (θ_{AP}), and soil penetration resistance of 2.0 MPa (θ_{PR}) as a function of the density of an Oxisol at a depth at a depth of 0.05 m subjected to different levels of straw and chiseling of sugarcane under conventional tillage. A: 0% straw without chiseling, B: 0% straw with chiseling, C: 50% straw without chiseling, D: 50% straw with chiseling, E: 100% straw without chiseling, F: 100% straw with chiseling.

The θ_{PR} for the lower limit of treatments without chiseling (Figures 4A, 4C, and 4E), limited the range of OWR due to the strong relationship between Ds and PR. Several authors have found the influence of θ_{PR} on soil OWR in different management systems (Silva et al., 2017; Fashi et al., 2017) and textural classes (Pereira et al., 2015; Dias et al., 2016; Klein et al., 2016). On the other hand, treatments with chiseling in crop management (Figures 4B, 4D, and 4F) had limits initially defined by θ_{PWP} up to a density of 1.2 g cm^{-3}, and θ_{PR} began to limit OWR from this point.

A significant increase was observed in the range of OWR at a depth of 0.15 m in the conventional tillage with chiseling (Figure 5).

Treatments with 0 and 50% straw without chiseling (Figures 5A and 5C) had their upper limits defined by θ_{AP} and the others were limited by θ_{FC} up to densities of 1.15, 1.31, 1.35, and 1.22 g cm^{-3} (Figures 5B, 5D, 5E, and 5F), being replaced by θ_{AP} from this point. All treatments had θ_{PR} as lower limits, except for 100% straw with chiseling (Figure 5F), in which θ_{PWP} limited close to the density of 1.2 g cm^{-3}. Similarly, Garbiate et al. (2016) found an increase in OWR in treatments with straw maintenance associated with chiseling of ratoons, which was attributed to the mechanical action of the implement combined with the benefits of organic matter, as a consequence of the more significant mitigation of negative effects of compaction, reflected by relief of θ_{PR} and θ_{AP}.

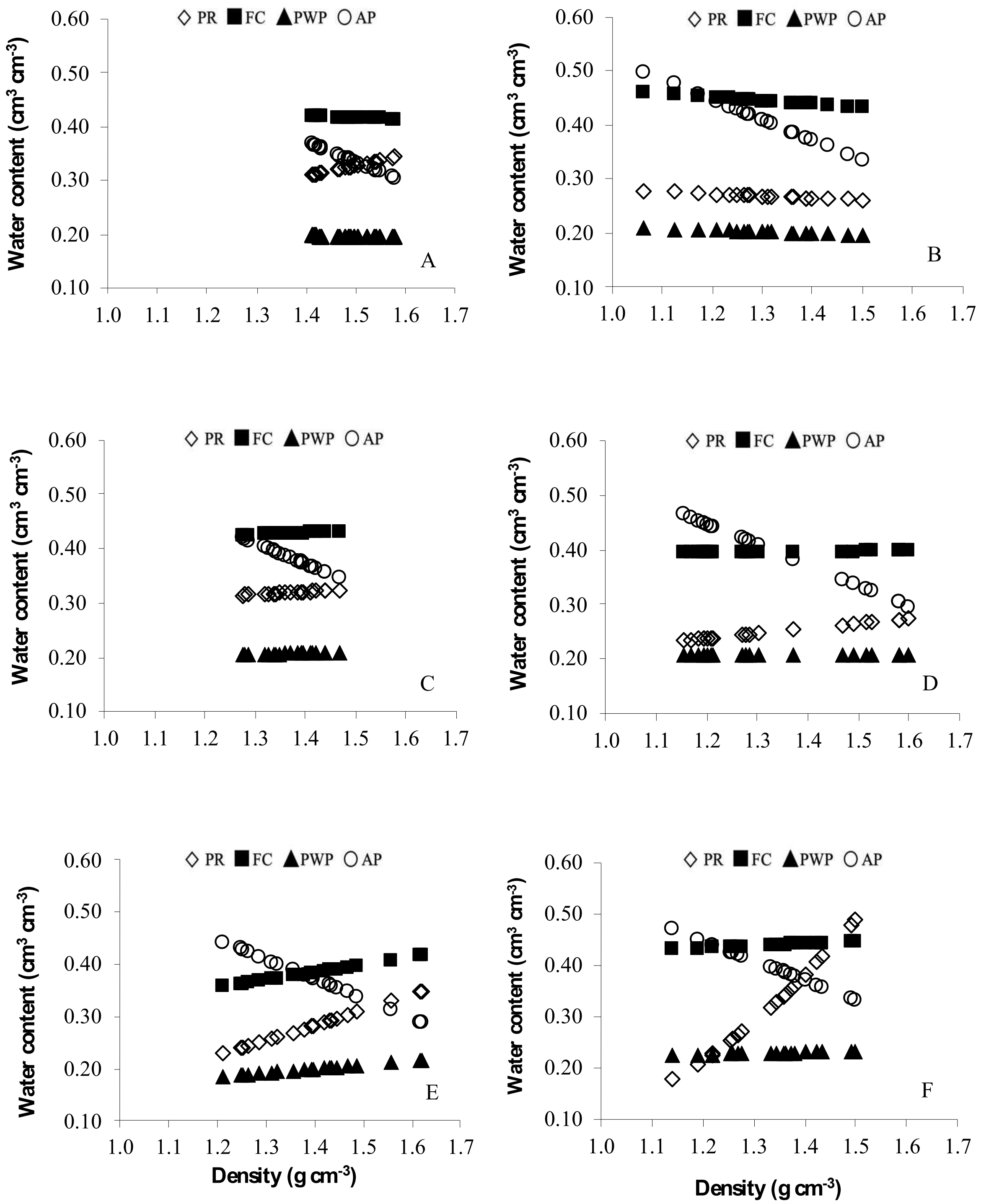


FIGURE 5. Variation of water content at field capacity (θ_{FC}), permanent wilting point (θ_{PWP}), aeration porosity of 0.10 $m^3\ m^{-3}$ (θ_{AP}), and soil penetration resistance of 2.0 MPa (θ_{PR}) as a function of the density of an Oxisol at a depth of 0.15 m subjected to different levels of straw and chiseling of sugarcane under conventional tillage. A: 0% straw without chiseling, B: 0% straw with s chiseling, C: 50% straw without chiseling, D: 50% straw with chiseling, E: 100% straw without chiseling, F: 100% straw with chiseling.

All adjusted curves of the LBC models presented significant coefficients of determination (R^2) at 1% ($p<0.01$) by the F-test. The confidence interval of the model adjustment coefficients was significant, as it did not include a value equal to zero, except for the coefficient b in treatment T2 at a depth of 0.05 m in the no-tillage of sugarcane.

Treatment T3 (50% straw without chiseling) presented the lowest coefficient values at a depth of 0.05 m compared to the other treatments, while treatment T6 (100% straw with chiseling) indicated lower values of coefficients in the no-tillage at a depth of 0.15 m. According to Pereira et al. (2015), this treatment may have a lower LBC range when coefficient estimates present lower values for both the angular and linear coefficients.

The confidence intervals of the model adjustment coefficients for conventional tillage are significant for all treatments, except for coefficient b at a depth of 0.05 m for T2 and T4.

Treatment T4 presented the lowest coefficient values for the angular coefficient (b) at a depth of 0.05 m and the linear coefficient (a) at a depth of 0.15 m and, therefore, a lower LBC range, according to Pereira et al. (2015).

The homogeneity test of linear models proposed by Snedecor & Cochran (1989) was used to compare changes in soil structure caused by different levels of straw remaining on the soil and the use of chiseling in the no-tillage and conventional tillage of sugarcane in the LBC models.

Treatments T1, T2, T3, and T5 were similar at a depth of 0.05 m of no-tillage, showing the effect of the absence of straw in the treatment with 0% and chiseling in treatments with 50 and 100% straw. Treatments T3, T4, and T6 were homogeneous for a depth of 0.15 m.

Comparisons between LBC models that did not differ from each other and, therefore, were homogeneous and adjusted to a new equation for each data set, considering all LBC and θ values (Figure 6). The groups T1=T2=T3=T5 (1st) and T3=T4=T6 (2nd) were formed for a depth of 0.05 m (Figure 6A), whereas the groups T1=T2=T4=T5 (1st) and T3=T5=T6 (2nd) were formed at a depth of 0.15 m (Figure 6B) in the no-tillage system.

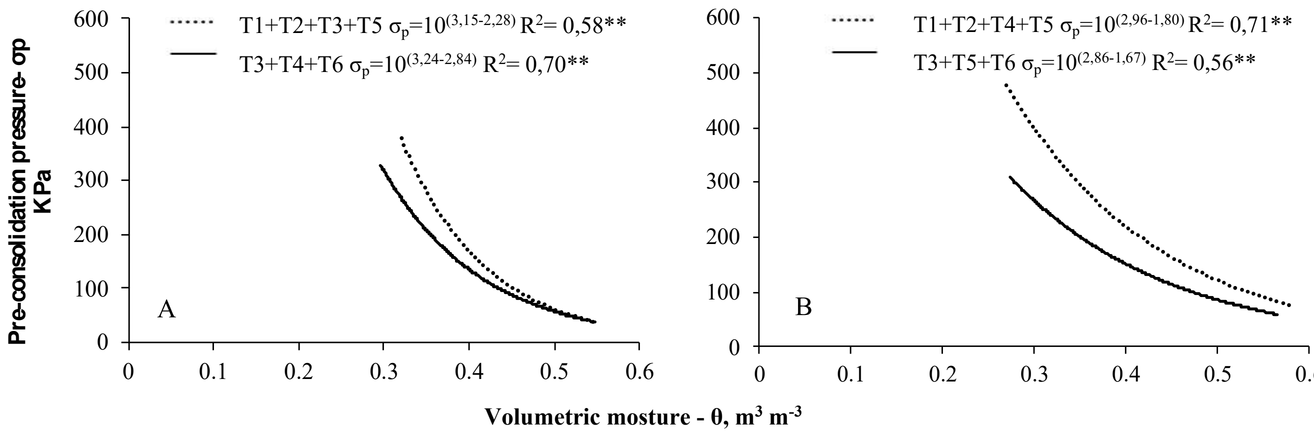


FIGURE 6. Load-bearing capacity models for an Oxisol subjected to no-tillage at depths of 0.05 m (A) and 0.15 m (B) under different levels of straw and chiseling of sugarcane ratoons. T1: 0% straw without chiseling, T2: 0% straw with chiseling, T3: 50% straw without chiseling, T4: 50% straw with chiseling, T5: 100% straw without chiseling, and T6: 100% straw with chiseling.

Thus, the adequate straw level on the soil was 50% at a depth of 0.05 m, and the treatment with only 100% straw was similar with the use of chiseling to promote the best LBC values. Therefore, the total removal of straw and the absence of chiseling in the no-tillage of sugarcane can aggravate problems with compaction and, consequently, reduce crop productivity.

Higher LBC values were observed at a depth of 0.15 m in the first grouping than compared to the second grouping, which is due to the positive effect of the remaining straw in the evaluated systems to minimize the influence of mechanized management carried out in the area before and after sugarcane planting, thus reducing soil compaction at this depth.

All treatments were homogeneous in the conventional tillage at a depth of 0.05 m (Figure 7A), except for T5 (0% straw without chiseling), which was not similar to the other treatments. Treatments T3 and T4 (50% straw without and with chiseling) at a depth of 0.15 m (Figure 7B) were not homogeneous compared to the others. A single equation was adjusted to all LBC and θ values for treatments that did not differ from each other, and a single LBC model was obtained.

According to the Snedecor & Cochran (1989) test, the treatments were grouped as follows: T1=T2=T3=T4=T6 (1st) and T5 (2nd) (Figure 7A). Only T5 (100% straw without chiseling) showed a lower LBC range. In this case, chiseling may be an additional compaction agent, possibly caused by the execution of this management practice under inadequate moisture conditions or even due to a possible increase in soil moisture promoted by the remaining straw and its effects on reducing density, increased macroporosity, and lower load-bearing capacity, conditions that would provide higher susceptibility to soil compaction resulting from harvester and tractor + transshipment combination traffic in the scarified rows.

Similarly, Moraes et al. (2019) evaluated the effect of different soil management systems and observed a negative effect of mechanical chiseling, which caused changes in the soil structure with increased compaction. In addition, Guimarães Júnnyor et al. (2019) studied soil compaction under different soil management systems and harvesting cycles and found that mechanized sugarcane harvesting for conventional tillage promoted additional compaction in the crop inter-rows after the second cycle.

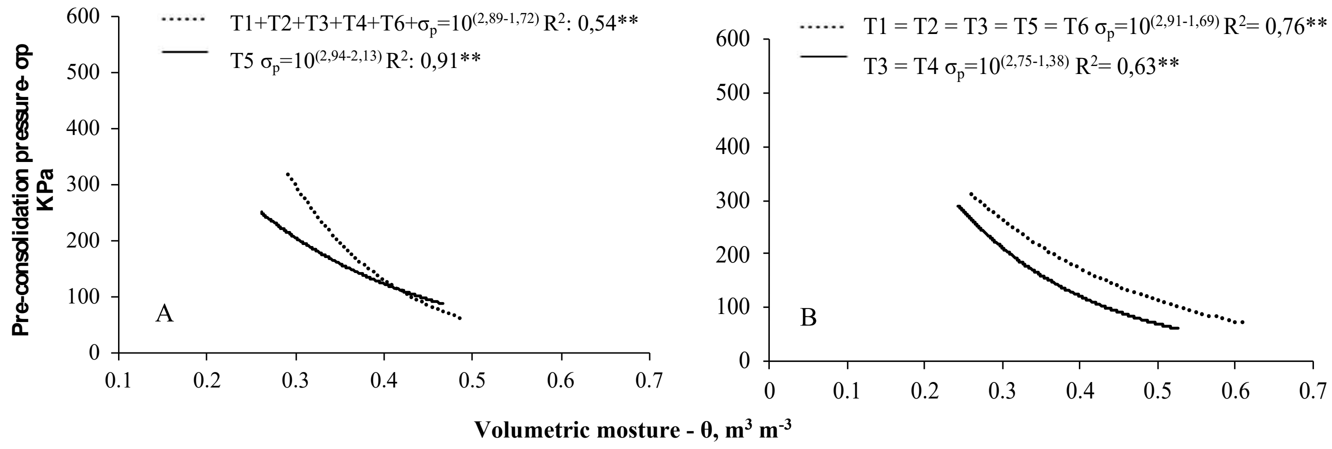


FIGURE 7. Load-bearing capacity models for an Oxisol subjected to conventional tillage at depths of 0.05 m (A) and 0.15 m (B) under different levels of straw and chiseling of sugarcane ratoons. T1: 0% straw without chiseling, T2: 0% straw with chiseling, T3: 50% straw without chiseling, T4: 50% straw with chiseling, T5: 100% straw without chiseling, and T6: 100% straw with chiseling.

Two groups were formed for a depth of 0.15 m between treatments in the conventional tillage: T1=T2=T3=T5=T6 (1st) and T3=T4 (2nd) (Figure 7B). Treatments T3 and T4 (50% straw without and with chiseling) presented the lowest LBC values at this depth compared to the others, showing that they are the most efficient management systems in reducing the effects of soil compaction. The maintenance of intermediate amounts of remaining straw during the sugarcane cycle benefits soil physical quality (Castioni et al., 2019). According to these authors, the total removal of residues provided an increase in soil compaction (increase in density, increase in penetration resistance, and reduction in the weighted average diameter of aggregates).

Therefore, the treatment with 50% straw at higher depths in the conventional tillage was more efficient in reducing the effects of compaction regardless of the use of chiseling.

Regarding the volumetric moisture at a depth of 0.15 m in the conventional tillage, the 1st group with the highest compaction levels had its lowest LBC range at a moisture of 0.61 $m^3\ m^{-3}$, with a pressure of 65.73 kPa, the same observed in the T3=T4 group. However, the necessary moisture was lower in these treatments at this same pressure, and the lowest moisture was observed at 0.52 $m^3\ m^{-3}$.

Importantly, knowledge of load-bearing capacity models is essential to determine the most appropriate moisture conditions for adopting implements in agricultural operations. The use of management practices that minimize soil density, with the consequent reduction in compaction, is recommended when operations are carried out at high water levels in the soil or when the equipment is at a pressure above the pre-consolidation pressure (Pereira et al., 2015).

CONCLUSIONS

Maintaining 100% of the straw concomitantly with the use of chiseling in both no-tillage and conventional tillage systems results in increased OWR at both depths.

Maintaining total or partial straw favors lower LBC values, regardless of the evaluated soil management and depths, thus improving soil physical quality.

The use of chiseling of ratoons in the conventional tillage promoted higher LBC values, indicating possible additional soil compaction in these areas.

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REFERENCES

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22(6):711-728.

Arcoverde SNS, Kurihara CH, Staut LA, Tomazi M, Pires AMM, Silva CJ da (2023) Soil fertility, nutritional status, and sugarcane yield under two systems of soil management, levels of remaining straw and chiseling of ratoons. Revista Brasileira de Ciência do Solo 47: e0220138. http://dx.doi.org/10.36783/18069657rbcs20220138

Arcoverde SNS, Souza CMA, Cortez JW, Maciak PAG, Suárez AHT (2019) Soil physical attributes and production components of sugarcane cultivars in conservationist tillage systems. Engenharia Agrícola 39:216-224. http://dx.doi.org/10.1590/1809-4430-eng.agric.v39n2p216-224/2019

Awe GO, Reichert JM, Fontanela EF (2020) Sugarcane production in the subtropics: Seasonal changes in soil properties and crop yield in no-tillage, inverting and minimum tillage. Soil & Tillage Research 196: 104447. https://doi.org/10.1016/j.still.2019.104447

Bordonal RO, Menandro LMS, Barbosa LC, Lal R, Milori MBP, Kolln OT, Franco HCJ, Carvalho JLN (2018) Sugarcane yield and soil carbon response to straw removal in south-central Brazil. Geoderma 328: 79–90.

Castioni GAF, Cherubin MR, Bordonal RO, Barbosa LC, Menandro LMS, Carvalho JLN (2019) Straw Removal Affects Soil Physical Quality and Sugarcane Yield in Brazil. BioEnergy Research 12:789–800. https://doi.org/10.1007/s12155-019-10000-1

Dias Junior MS, Pierce FJ (1996) O processo de compactação do solo e sua modelagem. Revista Brasileira de Ciência do Solo 20:175-82.

Dias CB, Rocha GC, Assis IR, Fernandes RBA (2016) Intervalo hídrico ótimo e densidade crítica de um Latossolo Amarelo coeso sob diferentes usos no ecossistema Tabuleiro Costeiro. Revista Ceres 63(6):868-878.

FAO - Food and Agriculture Organization of the United Nations (2021) Faostat. Available: http://www.fao.org/faostat/en/#data. Accessed Apr 2, 2022.

Fashi FH, Gorji M, Sharifi F (2017) Least limiting water range for different soil management practices in dryland farming in Iran. Archives of Agronomy and Soil Science 63(13): 1814-1822.

Garbiate MV, Vitorino ACT, Prado EAF do, Mauad M, Pellin DMP (2016) Hydrophysical quality of an Oxisol and sugarcane yield in chisel plow-based sugarcane ratoon management. Revista Brasileira de Ciência do Solo 40: e0150411. https://doi.org/10.1590/18069657rbcs20150411

Guimarães Júnnyor WS, De Maria IC, Araujo-Junior CF, Lima CC, Vitti AC, Figueiredo GC, Dechen SCF (2019) Soil compaction on traffic lane due to soil tillage and sugarcane mechanical harvesting operations. Scientia Agricola 76(6):509-517. http://dx.doi.org/10.1590/1678-992X-2018-0052

Klein VA, Graebin GJ, Bortolanza DR, Daubermann AG (2016) Variabilidade espacial do intervalo hídrico ótimo de solos cultivados em sistema plantio direto Pesquisa Agropecuária Brasileira 51(11):1890-1898.

Marasca I, Fernandes BB, Caterina GL, Denada MS, Lanças KP (2016) Chemical properties of ultisol in different tillage systems under sugarcane cultivation. Energia na Agricultura 31(2): 129-137. https://doi.org/10.17224/EnergAgric.2016v31n2p129-137

Mishra AK, Aggarwal P, Bhattacharyya R (2015) Least limiting water range for two conservation agriculture cropping systems in India. Soil and Tillage Research 150:43-56.

Moraes ER, Mageste JG, Lana RMQ, Torres JLR, Domingues LAS, Lemes EM, Lima LC (2019) Sugarcane Root Development and Yield under Different Soil Tillage Practices. Revista Brasileira de Ciência do Solo 43:e0180090.

Moraes ER, Bernardes RFB, Domingues LAS, Lana RMQ (2017) Productivity and agronomic characteristics of sugarcane under different tillage systems. Scientific Electronic Archives 10(1):75-79.

Pereira AHF, Vitorino ACT, Prado EAF, Bergamin AC, Mauad M, Arantes HP (2015) Least limiting water range and load bearing capacity of soil under types of tractor-trailers for mechanical harvesting of green sugarcane. Revista Brasileira de Ciência do Solo 39:1603-1610.

Ross PJ, Willians J, Bristow KL (1991) Equations for extending water-retention curves to dryness. Soil Science Society of American Journal 55(4):923-927.

Sá MAC, Santos Junior JDG, Franz CAB, Rein TA (2016) Qualidade física do solo e produtividade da cana-de-açúcar com uso da escarificação entre linhas de plantio. Pesquisa Agropecuária Brasileira 51(9):1610-1622. http://dx.doi.org/10.1590/s0100-204x2016000900061

Santos AKB, Popin GV, Gmash MR, Cherubin MR, Siqueira Neto M, Cerri CEP (2022) Changes in soil temperature and moisture due to sugarcane straw removal in central-southern Brazil. Scientia Agricola 79(6): e20200309. http://doi.org/10.1590/1678-992X-2020-0309

Santos HG dos, Jacomine PKT, Anjos LHC dos, Oliveira VA de, Lumbreras J F, Coelho MR, Almeida JA de, Araujo Filho JC de, Oliveira JB de, Cunha TJF (2018) Sistema brasileiro de classificação de solos. 5. ed. rev. e ampl. Brasília, DF: Embrapa.

Silva IDC, Souza ZM, Santos APG, Farhate CVV, Oliveira IN, Torres JLR (2022) Removal of different quantities of straw on the soil surface: effects on the physical attributes of the soil and the productivity of sugarcane yield in Southeast Brazil. Sugar Technology. https://doi.org/10.1007/s12355-021-01082-3

Silva Junior CA, Carvalho LA, Centurion JF, Oliveira ECA (2013) Comportamento da cana-de-açúcar em duas safras e atributos físicos do solo, sob diferentes tipos de preparo. Bioscience Journal 29(1):1489-1500.

Silva LFS, Marinho MA, Boschi RS, Matsura EE (2017) Intervalo hídrico ótimo para avaliação de sistemas de produção e rendimento do feijão. Irriga 22(2): 383-399.

Snedecor GW, Cochran WG (1989) Statistical methods. Ames, Iowa State University Press.

Souza FCA, Fernandes MMH, Coelho AP, Pinheiro DP, Perecin D, Fernandes C (2022) Do Alterations in Soil Physical Attributes Resulting from Chiseling Persist after Sugarcane Planting? Communications in Soil Science and Plant Analysis 53(4):521-532. http://doi.org/10.1080/00103624.2021.2017955

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG (2017) Manual de métodos de análise de solo. Brasília, Embrapa. 573p.

Vischi Filho OJ, Souza ZM, Souza GS, Silva RB, Torres JLR, Lima ME, Tavares RLM (2017) Physical attributes and limiting water range as soil quality indicators after mechanical harvesting of sugarcane. Australian Journal Crop Science 11(02):169-176. http://doi.org/10.21475/ajcs.17.11.02.p215