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Hydrophysical Quality of an Oxisol and Sugarcane Yield in Chisel Plow-Based Sugarcane Ratoon Management

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ABSTRACT: Mechanical harvesting has increasingly been used in sugarcane production units, and it has often resulted in reduced structural quality of the soil due to soil compaction caused by machine traffic. Thus, sugarcane ratoon crops have often been chiseled to overcome such a problem. The aim of the current study is to assess some physical properties of a *Latossolo Vermelho Distroférrico* (Rhodic Hapludox) that was chiseled after the third harvest in a sugarcane ratoon crop. The study was conducted in a commercial crop area throughout the 2011/2012 crop year. A randomized block experimental design was used, with five replications. The treatments consisted of five chiseling operations in sugarcane ratoon crops, namely: T1 - single-shank ripper with chiseling to a depth of 0.15 m; T2 - single-shank ripper with chiseling to a depth of 0.30 m; T3 - two-bar ripper with chiseling to a depth of 0.15 m, T4 - two-bar ripper with chiseling to a depth of 0.30 m; and T5 - control group, with no chiseling. Overall, soil chiseling is effective for improving the physical quality of the soil to a depth of 0.15 m, regardless of the equipment and the depth. Two-bar-ripper-based soil chiseling to a depth of 0.30 m provides increased sugarcane yield.

Keywords: least limiting water range, load-bearing capacity, pre-compacting pressure, water behavior.

INTRODUCTION

The large number of mechanized operations in sugarcane plantations results in soil compaction, as well as in damage to physical quality of the soil (Souza et al., 2012). Increased use of large-sized machinery during harvest is one of the aspects that may limit sugarcane yield in the following cycle since it can lead to critical pressures and generate soil compaction under inadequate moisture conditions (Oliveira et al., 2011).

Using soil chiseling between sugarcane ratoon crop rows soon after harvest to reduce problems caused by soil compaction throughout the crop cycle has become common in sugarcane production units. However, although soil chiseling is often practiced in such sites, little is known about its real benefits to soil physical quality (Paulino et al., 2004; Souza et al., 2005).

Assessing and monitoring the physical quality of the soil throughout successive sugarcane crop-growing seasons - which often extend for at least five years - is essential for defining management systems able to reduce physical degradation of the soil (Cavalieri et al., 2011). The physical quality of the soil in sugarcane-cultivated sites has been evaluated through physical properties such as soil porosity (Garbiate et al., 2011), aggregate stability (Souza et al., 2005), soil bulk density (Carvalho et al., 2011), and water infiltration into the soil. However, assessment of soil physical quality must integrate different properties in a small number of parameters that express the physical environment plants are living in (Silva et al., 1994).

The least limiting water range (LLWR) has been recommended for assessing the physical and structural quality of the soil. It integrates the soil physical properties that directly influence crop development, and such property interrelations depend on the structural condition of the soil and, therefore, on the degree of structural degradation it is subjected to (Pacheco and Cantalice, 2011). However, although LLWR is sensitive to soil compaction, it is inaccurate as an agronomic compaction management index for measuring crop yield response (Gubiani et al., 2013b). Thus, the LLWR limits should be improved by considering physical factors such as hydraulic conductivity and even by developing new indicators able to enhance representations of variation in soil physical stress and their effect on crop yield (Gubiani et al., 2013a).

The soil preconsolidation pressure also indicates the physical quality of the soil. This value is found through the compression curve, which has been widely accepted as an indicator of soil load-bearing capacity, since the application of pressures greater than the value mentioned may cause additional soil compaction (Kondo and Dias Júnior, 1999). Characterizing the compression process helps define management actions to prevent or minimize degradation of soil physical quality. Measuring pressure levels in the soil is a way toward sustainable development of the sugar-ethanol sector and the possibility of avoiding soil structural degradation, as well as adapting activities to be consistent with limitations in the production environment (Souza et al., 2012).

Evaluating soil compressibility and soil load-bearing capacity under different moisture conditions and under several management systems is of great importance not only for determining the maximum pressures that the soil is able to bear under such conditions, but also to minimize soil compaction risks in cultivated soils (Silva and Cabeda, 2006).

Including soil bulk density (BD) in *load-bearing capacity* (LBC) models as a way to reflect the state of soil compaction makes the models more reliable in finding the structural conditions that restrict root growth. Another possibility, besides integrating BD, regards the addition of LLWR to the LBC model. Thus, it is possible to obtain the critical pressure for plant growth described by Imhoff et al. (2001) using the maximum pressure that can be applied to the soil without causing conditions restrictive to root growth or additional deformation in the soil.

With the hypothesis of which mechanization under inadequate conditions may compact the soil, it is expected that chiseling can change the physical quality of the soil, appraised by the least limiting water range and load-bearing capacity.

The aim of the present study is to investigate the effect of different rippers at two operating depths through correlation between the least limiting water range and the load-bearing capacity of a *Latossolo Vermelho Distroférrico* cultivated with sugarcane, as well as to determine the critical pressure values that can be applied to the soil without causing restrictive conditions to the sugarcane growth process or inducing additional compaction in sugarcane-growing soils.

MATERIALS AND METHODS

The study was conducted in a commercial crop site in the municipality of Ponta Porã, Mato Grosso, Brazil, during the 2011/2012 agricultural year. The site is located at latitude 22° 14' 08" S, longitude 54° 59' 13" W, at an altitude of 435 m. The climate is Cwa, according to the Köppen classification system.

The soil in the experimental area was classified as a clayey Rhodic Hapludox, according to the soil taxonomy system (Soil Survey Staff, 2014), and as a *Latossolo Vermelho Distrófico típico* (LVd), according to the Brazilian soil classification system (Santos et al., 2013). The particle size distribution, which was determined through the pipette method (Donagema et al., 2011), was 498.7 g kg^{-1} clay, 197.6 g kg^{-1} silt, and 303.7 g kg^{-1} sand.

The experiment was conducted in an area cultivated with the RB 835 054 sugarcane variety in the ratoon crop (2nd ratoon), with spacing of 1.5 between rows. All the harvests were mechanized, and they were followed by chiseling. An Agrale BX 6180 agricultural tractor with standard tires was used; inflation pressure was 110.24 kPa in the front tires and 137.8 kPa in the rear ones. The chiseling process was carried out with a DMB single-shank ripper (consisting of two semi parabolic subsoiler shanks with wingtips, two 23" coulters, and two clod-breaking rollers) and a DRIA two-bar ripper (composed of two double semi-parabolic subsoiler shanks with straight tips, two 23" coulters, and two clod-breaking rollers).

A randomized block experimental design with five replications was used. The treatments consisted of five chiseling treatments in sugarcane ratoon crops, namely: T1, single-shank ripper with chiseling to a depth of 0.15 m; T2, single-shank ripper, to a depth of 0.30 m; T3, two-bar ripper, to a depth of 0.15 m; T4, two-bar ripper, to a depth of 0.30 m; T5: control group with no chiseling. The plots were 15 m long and 9 m wide; the total area was 135 m^2.

The experiment and the chiseling were carried out in the same day. Undisturbed soil samples were collected a month later, at depths of 0.15 and 0.30 m, and stored in metal cylinders (6.45 cm diameter and 2.54 cm height). The samples were collected 0.45 m distant from the sugarcane ratoon row. Seven samples were collected in each plot at each depth, for a total of 70 samples for each treatment (35 samples from each depth).

The 35 samples per treatment and depth were divided into seven groups of five samples. Each group was exposed to the following matric potentials: -0.006, -0.01, -0.033, -0.066, -0.1, -0.3, and -1.5 MPa. A porous plate apparatus was used for -0.006 MPa and a Richards chamber was used for the other potentials, as suggested by Klute (1986).

After the samples reached equilibrium at the aforementioned tensions, their masses were measured and their resistance to penetration was determined by means of an electronic penetrometer adjusted to constant penetration speed of 1 cm min^{-1}, a base rod diameter of 4 mm and semi-angle of 30°. The values obtained in the upper and lower 5 mm of the sample were discarded in order to eliminate the periphery effect

(Bradford, 1986). Soil resistance to penetration readings were collected at a frequency of every 0.25 s, for a total of 600 readings per sample; the mean value was used. After resistance to penetration was determined, the samples were dried in a laboratory oven at 105-110 °C for 48 h. The volumetric ring method was used to determine water content and soil bulk density. Total porosity and macroporosity were obtained as suggested by Donagema et al. (2011).

The LLWR was determined according to procedures described by Silva et al. (1994). Critical water content values, soil matric potential, penetration resistance, and aeration porosity were represented by water content at field capacity (θ_{FC}), at the potential of -0.01 MPa (Reichardt, 1988); by water content at the permanent wilting point (θ_{PWP}), at the potential of -1.5 MPa (Savage et al.,1996); by the volumetric water content of the soil at soil penetration resistance (θ_{PR}) of 2.0 MPa (Taylor et al., 1966); and by the volumetric water content at air-filled porosity (θ_{AP}) of 0.10 m^3 m^{-3} (Grable and Siemer, 1968), respectively.

The mathematical model [$\theta = \exp(a+bBD)\Psi c$] was used to obtain the θ_{FC} and θ_{PWP} values. This model was suggested by Silva et al. (1994) in order to fit the original data. It incorporates the "soil bulk density" variable to the function used by Ross et al. (1991), wherein θ is the volumetric water content in the soil (m^3 m^{-3}); BD is the soil bulk density (Mg m^{-3}); Ψ is the matric potential (MPa); and the letters 'a', 'b', and 'c' are the empirical parameters to fit the model.

The RP values of all samples, with known θ and BD, were mathematically fitted through the model ($RP = d\theta^e BD^f$) suggested by Busscher (1990), wherein RP is the soil resistance to penetration (MPa); θ is the volumetric water content in the soil (m^3 m^{-3}); BD is the soil bulk density (Mg m^{-3}); and the letters 'd', 'e', and 'f' are the empirical parameters used to fit the model. This equation made it possible to determine the critical value of θ so that RP would not exceed 2.0 MPa (θ_{RP}), depending on the BD. Accordingly, RP was replaced in the equation by 2.0 MPa, which is considered limiting for LLWR calculation purposes.

The θ_{AP} value was obtained through the model [$\theta_{AP} = (1 - (BD/PD)) - 0.10$] wherein θ_{AP} is the volumetric water content in the soil at aeration porosity 0.10 m^3 m^{-3}; BD is the soil bulk density (Mg m^{-3}); and PD is the particle density (Mg m^{-3}). The value 2.65 Mg m^{-3} was adopted as mean particle density.

The non-linear regression method was used to fit the mathematical models and to find coefficients 'a', 'b', 'c', 'd', 'e', and 'f'. The fitted water retention curves had coefficients of determination (R^2), which were subjected to the F-test, according to Blainski et al. (2009; 2012).

After resistance to penetration was determined, these samples were subjected to uniaxial compression tests in the automatic consolidometer, CNTA-IHM/BR-001/07 model, according to Bowles (1986) modified by Dias Júnior (1994). The increasing pressures applied to each sample were: 25, 50, 100, 200, 400, 800, and 1,600 kPa, and each pressure was applied until 90 % maximum deformation was achieved (Taylor, 1948). After each uniaxial compression test, the samples were dried at 105-110 °C for 48 h to determine volumetric water content and BD through the volumetric ring method, according to Donagema et al. (2011).

The soil compression curve was obtained by plotting the applied pressures on the x-axis *versus* the BD, which was found at the end of each pressure application stage on the y-axis. The preconsolidation pressure (σp) of each sample was determined through the method suggested by Dias Júnior and Pierce (1995). Next, the load-bearing capacity (σp) and the water content values (θ) were fitted through descending exponential regression [$\sigma p = 10^{(a + b\theta)}$], which was suggested by Dias Júnior (1994), in order to determine the soil load-bearing capacity (LBC) model. Letters 'a' and 'b' represent the model-fitting empirical coefficients, i.e., the linear and angular coefficients, respectively.

The models were compared to each other through the linear model homogeneity test described by Snedecor and Cochran (1989). The logarithm was applied to the preconsolidation pressure values to find the linear models from the exponential model [$\sigma p = 10^{(a + b\theta)}$], and it resulted in the log-type equation $\sigma p = a + b\theta$. The linear model homogeneity test takes two models into account, and they are compared through the analysis of intercept 'a', of angular coefficient 'b', and of data homogeneity (F).

The number of stalks found in 4 m of the central rows of each plot was counted in order to determine the sugarcane yield at the end of the crop cycle. Subsequently, 20 stalks were randomly selected and weighed to calculate the stalk yield, in kg ha^{-1}. In addition, the mean stalk diameter and stalk height were measured.

The yield results were subjected to analysis of variance and, whenever they were significant, the SNK test was applied at 5 %. The fitted load-bearing capacity curves showed coefficients of determination (R^2), which were subjected to the F-test, according to Blainski et al. (2009, 2012).

RESULTS AND DISCUSSION

The BD value in which there is intersection of the upper and lower limits, i.e., in which the LLWR becomes null, was called critical BD (CBD) by Silva et al. (1994). All the fitted water retention curves showed significant coefficients of determination (R^2) at 1 % (F-test). Thus, it can be said that the adjustment coefficients of the soil water retention curve were statistically significant since their confidence interval did not include zero (0), except for coefficient 'b' (Blainski et al., 2009; 2012), which was significant in T1 and T4 at the depth of 0.15 m.

The confidence interval of the 'e' and 'f' coefficients of the soil-resistance-to-penetration curve fitting did not include zero (0); thus, these coefficients were statistically significant, as per Blainski et al. (2009; 2012), except for the 'f' coefficient in T2. The 'd' coefficient was not significant in any of the treatments studied.

The available water content ($AW = \theta_{FC} - \theta_{PWP}$) was higher than the LLWR in at least one soil density value analyzed in all the treatments, and aeration was the most limiting factor for proper plant growth.

The LLWR values ranged from 0 to 0.085 m^3 m^{-3} at the depth of 0.15 m in T1; from 0.055 to 0.096 m^3 m^{-3} in T2; from 0.030 to 0.095 m^3 m^{-3} in T3; from 0 to 0.097 m^3 m^{-3} in T4; and from 0 to 0.079 m^3 m^{-3} in T5 (Figure 1). These results corroborated those found by Cavalieri et al. (2006), who found LLWR values ranging from 0 to 0.094 m^3 m^{-3} in a *Latossolo Vermelho* growing sugarcane and mechanically harvested.

As for the depth of 0.30 m, the LLWR values ranged from 0 to 0.070 m^3 m^{-3} in T1; from 0.027 to 0.085 m^3 m^{-3} in T2; from 0 to 0.080 m^3 m^{-3} in T3; from 0 to 0.080 m^3 m^{-3} in T4; and from 0 to 0.099 m^3 m^{-3} in T5 (Figure 1). It appears that the treatments with soil chiseling exhibited lower LLWR values than those exhibited by the control (Figure 1). These results corroborate those obtained by Araujo et al. (2004), who also found that chiseling reduced the LLWR at a depth of 0.30 m in a *Latossolo Vermelho Distroférrico* and demonstrated that this practice was not effective in improving soil physical quality at this depth.

According to the CBD assessment at the depth of 0.15 m, T2 and T3 did not reach the CBD values; however, T1, T4, and T5 showed CBD values of 1.56, 1.58, and 1.57 Mg m^{-3}, respectively. Soil bulk density values higher than the critical bulk density (BD > CBD) promote highly restrictive physical conditions that may be caused by low aeration or by excessive soil resistance to penetration (Blainski et al., 2009). Thus, the higher the CBD is, the lower the plant probability of remaining under stress conditions (Calonego and Rosolem, 2011). Treatments T2 and T3, which showed no CBD values, and T4,

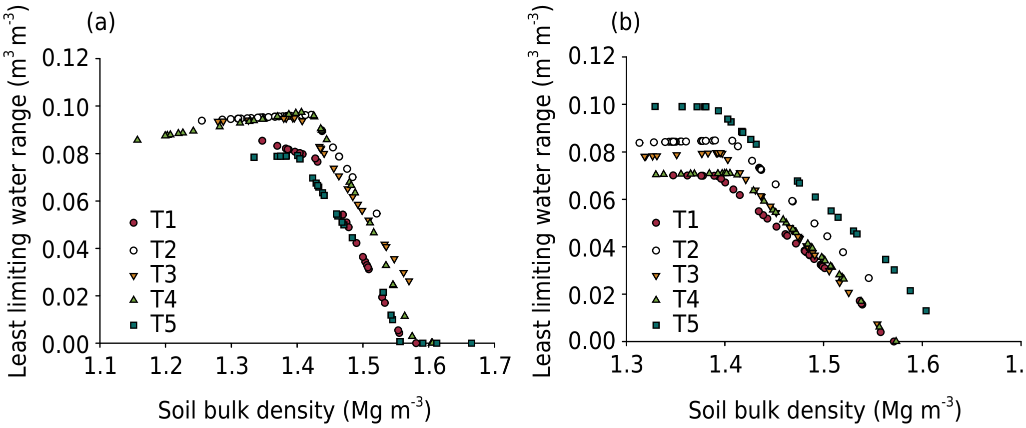

Figure 1. Variation in the least limiting water range according to the soil bulk density of a Latossolo Vermelho Distroférrico (Rhodic Hapludox) at the depths of 0.15 (a) and 0.30 m (b), in the following treatments: T1 – single-shank ripper with chiseling at the depth of 0.15 m; T2 – single-shank ripper with chiseling at the depth of 0.30 m; T3 – two-bar ripper with chiseling at the depth of 0.15 m; T4 – two-bar ripper with chiseling at the depth of 0.30 m; T5 – control without chiseling.

which showed a CBD value greater than that of the control (T5), were the most effective treatments in improving soil physical conditions at the depth of 0.15 m. Only T2 and T5 showed no CBD values at the depth of 0.30 m. The other treatments showed CBD values of 1.54 (T1), 1.53 (T3), 1.56 (T4), and 1.57 Mg m^{-3} (T5). These values indicate the critical limit to proper plant growth and development (Lima et al., 2012), whereas higher values indicate restrictive physical conditions (Tormena et al., 2007).

The LBC models were compared to each other through the linear model homogeneity test (Snedecor and Cochran, 1989) at different depths in order to assess possible soil structure changes caused by different chiseling-based management practices. The LBC models were not homogeneous at depths of 0.15 m and 0.30 m. Thus, these depths showed different LBCs. The management systems with chiseling in ratoon crops significantly interfered in the LBC models, regardless of the studied depth, according to the F-test for data homogeneity by Snedecor and Cochran (1989).

The σp (LBC) showed significant and inverse variation in the θ in all LBC models of the treatments studied. The σp decreases as soil moisture increases because water reduces the cohesion between solid particles, thus reducing friction between them, and this results in an exponential decrease in σp as moisture increases (Pacheco and Cantalice, 2011).

The comparisons between the LBC models of soil chiseling at depths of 0.15 and 0.30 m that did not statistically differ were fitted to all the σp and θ values in a single equation in order to obtain a single LBC model. The following groups were formed at the depth of 0.15 m: T1, T5, and T2 = T3 = T4. The depth of 0.30 m formed the following groups: T1 = T3 and T2 = T4 = T5.

The BD values were incorporated in the LLWR and LBC results through data modeling in a 3D response surface to determine the water contents and the pressures that caused no sugarcane root growth reduction and, consequently, caused no decrease in sugarcane crop yield.

The inclusion of BD in the load-bearing capacity model was suggested by Imhoff et al. (2001) because it increases data reliability, shows high R^2 values, such as 0.93, 0.92, and 0.91, and high significance of equations ($p<0.0001$) in T1, T5, and T2 = T3 = T4, respectively, at the depth of 0.15 m, as shown in equations 1, 2, and 3.

$$\sigma_p = 769.9533 - 1{,}806.3346\,\theta + 285.6125\,BD \quad (R^2 = 0.93;\ n = 35) \qquad \text{Eq. 1}$$

$$\sigma_p = 1{,}172.6546 - 2{,}032.4068\,\theta + 5.8038\,BD \quad (R^2 = 0.92;\ n = 35) \qquad \text{Eq. 2}$$

$$\sigma_p = 1{,}055.0600 - 2{,}226.3146\,\theta + 32.7497\,BD \quad (R^2 = 0.91;\ n = 105) \qquad \text{Eq. 3}$$

As for the depth of 0.30 m, the R^2 values were 0.91 and 0.93 ($p<0.0001$) in T1 = T3 and T2 = T4 = T5, respectively, as shown in equations 4 and 5.

$$\sigma_p = 866.7074 - 2{,}446.4356\,\theta + 314.5636\,BD \quad (R^2 = 0.91;\ n = 70) \qquad \text{Eq. 4}$$

$$\sigma_p = 647.4061 - 1{,}526.3807\,\theta + 200.4250\,BD \quad (R^2 = 0.93;\ n = 105) \qquad \text{Eq. 5}$$

The soil showed low load-bearing capacity, due to higher water content values, and resistance to deformation increased, due to lower water content values in the soil (Figures 2 and 3). The increase in BD led to increased friction forces and contact points between the particles and, consequently, to lower movement capacity (Imhoff et al., 2001).

Soil bulk density was used as a soil compaction factor by taking into consideration the management practices applied to the soil and soil properties, such as texture. Thus, using the CBD value to calculate σp made it possible to define the soil load-bearing capacity by taking into consideration the structural quality of the soil for plant growth (Imhoff et al., 2001).

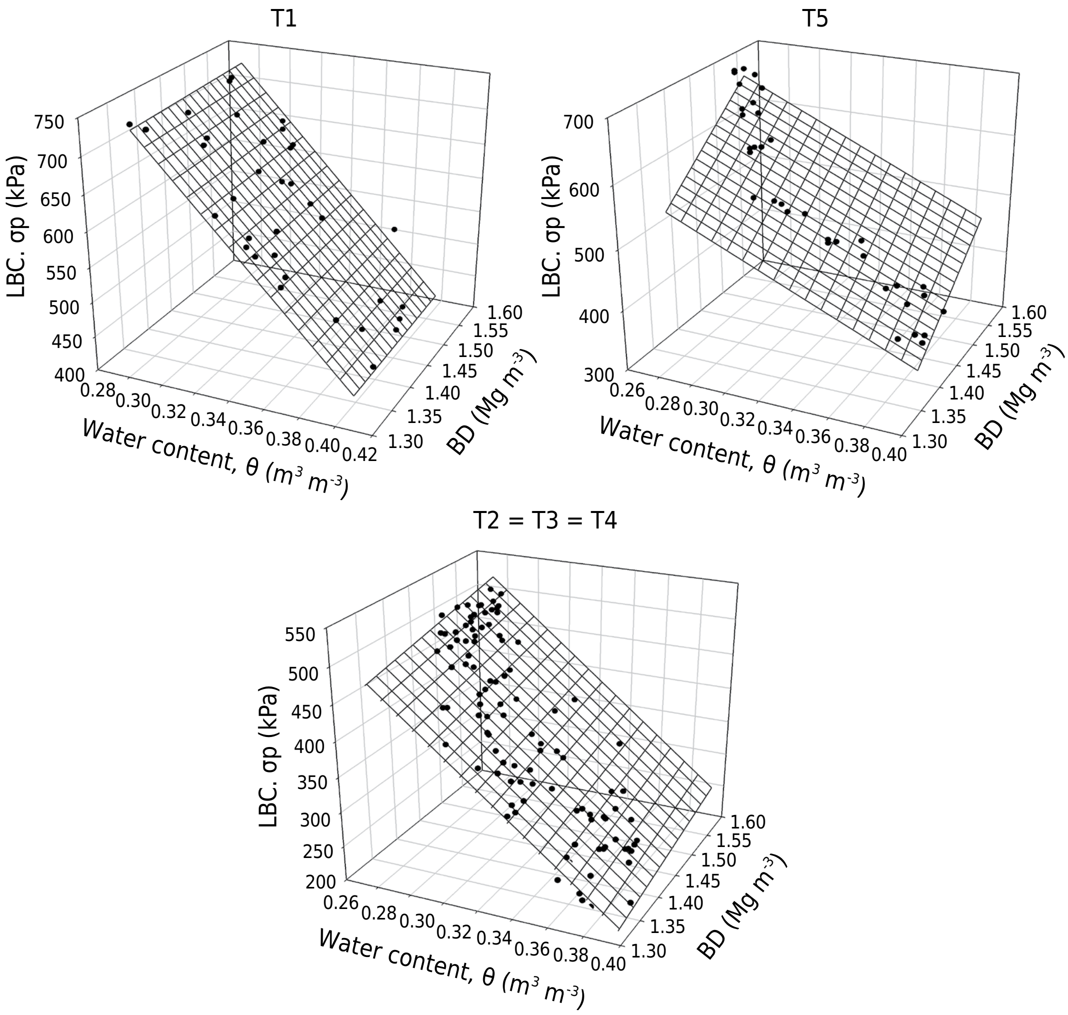

Figure 2. Variation in the load-bearing capacity (LBC) values with the volumetric water content (θ) and soil bulk density (BD) of a Latossolo Vermelho Distroférrico (Rhodic Hapludox) at the depth of 0.15 m, in T1, T5, and T2 = T3 = T4. T1 – single-shank ripper with chiseling at the depth of 0.15 m; T2 – single-shank ripper with chiseling at the depth of 0.30 m; T3 – two-bar ripper with chiseling at the depth of 0.15 m; T4 – two-bar ripper with chiseling at the depth of 0.30 m; T5 – control without chiseling.

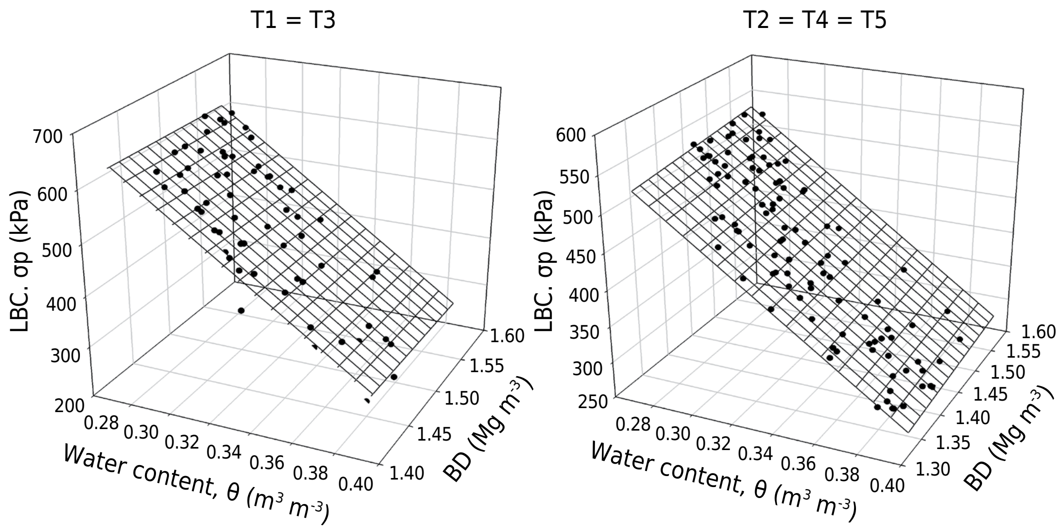

Figure 3. Variation in the load-bearing capacity (LBC) values with the volumetric water content (θ) and soil bulk density (BD) of a Latossolo Vermelho Distroférrico (Rhodic Hapludox) at the depth of 0.30 m, in T1 = T3 and T2 = T4 = T5. T1 – single-shank ripper with chiseling at the depth of 0.15 m; T2 – single-shank ripper with chiseling at the depth of 0.30 m; T3 – two-bar ripper with chiseling at the depth of 0.15 m; T4 – two-bar ripper with chiseling at the depth of 0.30 m; T5 – control without chiseling.

The CBD values were used to estimate the soil load-bearing capacity. Since the σp also varied due to soil water content, it was necessary to define the moisture values of greater interest, as was mentioned by Imhoff et al. (2001). Thus, the moisture range that incorporated the plant growth limitations due to aeration, water availability, and soil resistance to penetration, ranging from 0.15 to 0.50 $m^3 m^{-3}$, represented depths of 0.15 and 0.30 m.

The LBC decreased at the depth of 0.15 m due to the increased water content in the soil in the upper and lower LLWR, and it ranged from 315.19 to 947.41, from 165.56 to 876.90, and from 165.56 to 772.53 kPa in T1, T5, and T2 = T3 = T4, respectively (Figure 4). As for the depth of 0.30 m, there was also a decrease in LBC from the upper to lower LLWR due to increased soil water content; it ranged from 131.06 to 987.31 and from 194.87 to 729.10 kPa in T1 = T3 and T2 = T4 = T5, respectively (Figure 5).

By considering the amplitude of water content of LLWR from 0.24 to 0.34 $m^3 m^{-3}$ and from 0.28 to 0.35 $m^3 m^{-3}$ at depths of 0.15 and 0.30 m, respectively, the range of LBC values can be observed, which represent the critical pressures for plants (Pcr), as described by Imhoff et al. (2001). Thus, the critical pressure for plant growth (Pcr) may be defined, according to Imhoff et al. (2001), as the maximum pressure that can be applied to the soil without causing restrictive conditions for root growth and without causing additional soil deformation.

The Pcr range, i.e., the maximum LLWR amplitude, ranged from approximately 604.21 to 784.84 kPa in T1, from 490.74 to 693.98 kPa in T5, and from 349.53 to 572.16 kPa in T2 = T3 = T4 at the depth of 0.15 m (Figure 4). As for the depth of 0.30 m, the LLWR amplitude ranged from 498.03 to 669.27 kPa in T1 = T3 and from 423.83 to 530.67 kPa in T2 = T4 = T5 (Figure 5).

Although the LLWR is a breakthrough in soil compaction relations through directly relating physical properties to plant growth, Gubiani et al. (2013a) highlight the importance of developing new indices capable of integrating the variation in the soil physical factors throughout the plant growth cycle since the LLWR alone is often not enough to predict biological responses, especially in relation to grain yield. This corroborates the study by van Lier and Gubiani (2015), who highlight the

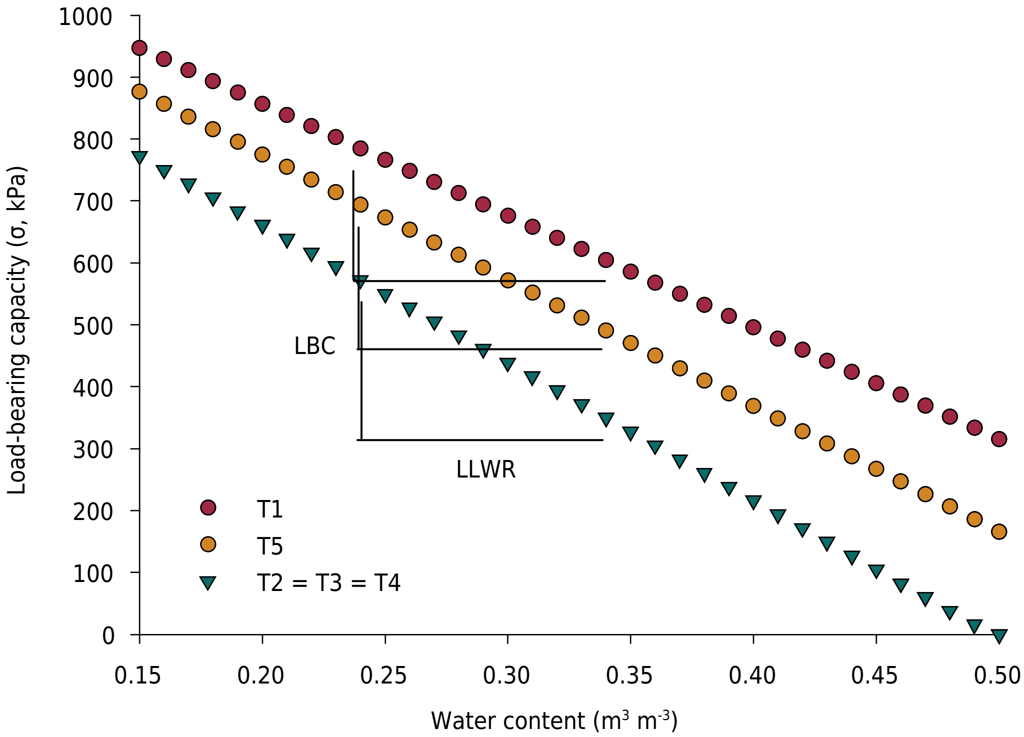

Figure 4. Variation in the load-bearing capacity (LBC) with water content (θ) for a critical soil bulk density (BD) value of 1.57 Mg m^{-3} in a Latossolo Vermelho Distroférrico (Rhodic Hapludox) at the depth of 0.15 m, in T1, T5, and T2 = T3 = T4. T1 – single-shank ripper with chiseling at the depth of 0.15 m; T2 – single-shank ripper with chiseling at the depth of 0.30 m; T3 – two-bar ripper with chiseling at the depth of 0.15 m; T4 – two-bar ripper with chiseling at the depth of 0.30 m; T5 – control without chiseling. LLWR: least limiting water range.

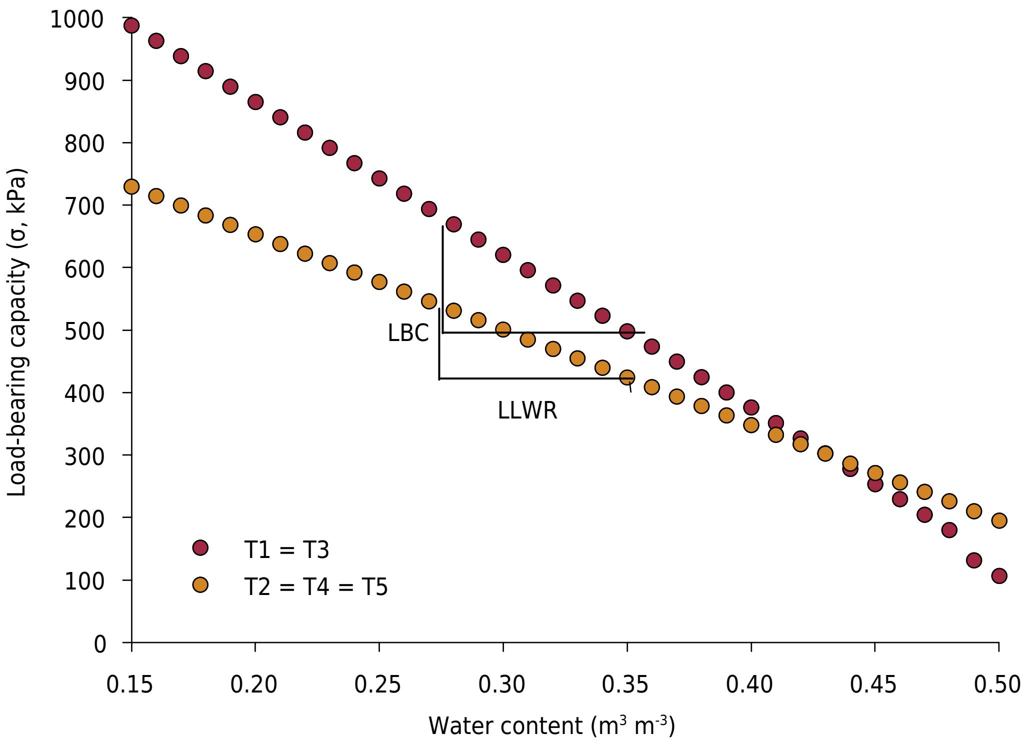

Figure 5. Variation in the load-bearing capacity (LBC) with water content (θ) for a critical soil bulk density (BD) value of 1.55 Mg m^{-3} in a Latossolo Vermelho Distroférrico (Rhodic Hapludox) at the depth of 0.30 m, in T1 = T3 and T2 = T4 = T5. T1 – single-shank ripper with chiseling at the depth of 0.15 m; T2 – single-shank ripper with chiseling at the depth of 0.30 m; T3 – two-bar ripper with chiseling at the depth of 0.15 m; T4 – two-bar ripper with chiseling at the depth of 0.30 m; T5 – control without chiseling. LLWR: least limiting water range.

effectiveness of LLWR has not yet been proven, due to the simple way it is treated, especially in determination of its limit values.

The combination of LLWR and LBC defines the critical pressure (Pcr) indicator for plant growth without deterioration of soil physical quality (Imhoff et al., 2001). Overall, soil LBC at the depth of 0.15 m follows the order T1 > T5 > (T2 = T3 = T4) (Figure 4). The reduction in soil LBC in the treatment group (T2 = T3 = T4) may be attributed to the lower soil density values found at the time these treatments were applied.

The T1 treatment showed the highest σp values (Figure 4). Soil compaction in sugarcane production sites may not be generated by harvest alone, but also by farming practices in which machine tires make pressure between rows, which may diminish the beneficial effects of subsoiling (Pacheco and Cantalice, 2011). Thus, it can be said that, unlike the other treatments (T2, T3, and T4), chiseling using a single-shank ripper at the depth of 0.15 m (T1) was not enough to reduce the impacts of compression generated by tractor traffic at the time of chiseling.

The control without chiseling (T5) showed higher LBC than the treatments with soil chiseling (T2, T3, and T4), and this can easily be explained by the compaction generated by the intense traffic of machines during sugarcane harvest, as reported by Garbiate et al. (2011). A high degree of compaction gives the soil greater ability to bear higher pressures; however, such a condition may restrict plant development.

The lowest soil LBCs were obtained in T2, T3, and T4 throughout the volumetric moisture interval, and they were the management practices most efficient in reducing the effects of soil compaction.

From a practical point of view, with the aim of achieving sustainable soil structure conditions, monitoring soil moisture in an attempt to carry out mechanized activities only under a moisture condition lower than the limiting one indicated in the LBC model is effective in reducing the risk of compaction caused by machine traffic (Souza et al., 2012). Thus, mechanized operations only carried out in soil with water content below the limiting level observed in the LBC model may prolong the beneficial effects of chiseling on the physical quality of the soil.

The highest σp values at the depth of 0.30 m were found in the T1 = T3 treatments (Figure 5). This is a result of the depth (0.15 m) at which the rippers operated in these treatments. Thus, their effects were restricted to the uppermost layer of the soil. However, these treatments (T1 = T3) showed higher σp values than the T2 = T4 = T5 treatments.

These results may be explained by the low efficiency of chiseling in improving the physical quality of the soil when this was performed at the depth of 0.15 m, regardless of the equipment used. In addition, the tractor wheels may have generated additional soil compaction during the operation, which was not sufficiently attenuated by the effect of chiseling. Tillage operations may lead to additional soil compaction since machine tires make pressure between the crop rows (Pacheco and Cantalice, 2011).

The group of treatments with chiseling at the depth of 0.30 m and the control without chiseling (T2 = T4 = T5) had the same LBC. This shows that the rippers have no differentiated effects on the LBC at this depth (Figure 5). Since this group of treatments included the control without chiseling, it showed that this management practice in sugarcane ratoon crops shows no benefits for the physical quality of the soil below the depth of 0.15 m. Similar results were reported by Araujo et al. (2004), who assessed the effect of chiseling on the physical quality of a *Latossolo Vermelho Distroférrico*.

The treatments with chiseling of sugarcane ratoon crops did not show significant differences in plant height, stalks per ha, or stalk diameter. However, they influenced yield (Table 1). The T1 treatment had a lower yield than that of the control without chiseling (T5). This

Table 1. Plant height (PH), number of stalks per site, stalk diameter, and yield for the treatments assessed

Treatment	PH	Stalk	Stalk diameter	Yield
	m	No. ha^{-1}	mm	kg ha^{-1}
T1	1.55 a	92,090 a	20.27 a	51,913 c
T2	1.61 a	104,260 a	20.30 a	57,582 b
T3	1.63 a	99,000 a	20.63 a	60,778 b
T4	1.66 a	108,900 a	20.46 a	68,838 a
T5	1.57 a	95,370 a	20.70 a	60,335 b
CV (%)	8.56	9.24	7.09	6.24

T1 – single-shank ripper with chiseling at the depth of 0.15 m; T2 – single-shank ripper with chiseling at the depth of 0.30 m; T3 – two-bar ripper with chiseling at the depth of 0.15 m; T4 – two-bar ripper with chiseling at the depth of 0.30 m; T5 – control without scarification. Means followed by the same letter in the column do not differ from each other by the SNK test at 5 % probability. CV: coefficient of variation.

occurrence may be due to the low efficiency of this treatment in improving the physical quality of the soil and to the additional compaction caused by the treatment. The T4 treatment had the highest sugarcane yield. Costa et al. (2007) assessed root system distribution in different sugarcane varieties and found greater root development in the first 0.18 m depth, with greater root length in this layer. Thus, the better yield values found in T4 may reflect the better physical quality provided by this treatment at the depth of 0.15 m. These results corroborate those obtained by Souza et al. (2005), who found increased stalk production in areas that were chiseled after mechanized harvesting. Neither T2 or T3 showed any difference in comparison to the control without chiseling (T5). Similar results were found by Paulino et al. (2004), who studied chiseling in a ratoon crop in a *Latossolo Vermelho distroférrico* and found no significant differences in sugarcane yield in ratoon crops, regardless of the operating depth of the ripper.

CONCLUSION

Chiseling changes the least limiting water range and load-bearing capacity of the soil, improves the physical quality of the soil, and promotes increased yield in sugarcane ratoon crops.

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