Least limiting water range in Oxisol under two conservation tillage systems in sugarcane farming

Cristiano Márcio Alves de Souza[1], *Andrés Hideki Tanaka Suárez*[2], *Sálvio Napoleão Soares Arcoverde*[2*], *Egas Jose Armando*[3], *Paulo Alexandre Graciano Maciak*[4]

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ABSTRACT

The Least Limiting Water Range (LLWR) is an indicator of soil physical quality, contributing in information to propose soil management systems in agricultural farming process. This work aimed to assess the usage of LLWR and critical soil bulk density for physical-water quality evaluations, as well as its effect on sugarcane farming under no-tillage and reduced-tillage, in Oxisol. Undisturbed soil samples were collected in 0.00-0.10 and 0.10-0.20 m soil layers, to determine the following attributes: soil bulk density, soil penetration resistance (PR), volumetric water content at field capacity and permanent wilting point and minimum aeration porosity. The LLWR proved to be a good soil physical water quality indicator in sugarcane farming under conservation tillage system. No-tillage presented a greater range of the LLWR when compared to the reduced-tillage, regardless to the PR value adopted as restrictive for sugarcane roots development, increasing the yield of stalks and sugars contents. The critical soil bulk density under no-tillage is between 1.48 and 1.53 Mg m^{-3} at the RP of 2 and 4 MPa, while under reduced-tillage it is between 1.44 and 1.51 Mg m^{-3}.

Keywords: soil management; critical soil bulk density; crop yield; *Saccharum* spp.; soil moisture.

INTRODUCTION

Brazilian sugarcane production in the last harvest (2017/18) was 646.3 million tons, the farming area was 8.7 million hectares and the average yield was 73.7 Mg ha^{-1}. In the state of Mato Grosso do Sul, the area devoted to the cultivation of sugarcane was 660.4 thousand hectares, with the production of 50,453.68 thousand tons and 76.4 Mg ha^{-1} of the yield (CONAB, 2018).

Sugarcane is semi-perennial crop, with medium cycle of approximately 5 years. The sugarcane farming soil preparation system is usually conventional, what may involve different combinations ploughing, gradations and subsoiling operations. These operations aim to provide the soil with better conditions for budding and initial development of the crop to be implanted. However, by disaggregating the compacted layers of the soil, it can change its physical attributes (Silva Junior *et al*., 2013).

The adoption of conservation systems, such as no-tillage and reduced-tillage systems, which offer minimal soil disturbance, maintenance of surface crop residues, conservation of the structure and reduction of energy expenditure, has been occurring in the sugarcane production system (Arcoverde *et al*., 2019). Including enabling the crop yield and with positive impacts on the technological quality of the raw material when compared to conventional systems (Arcoverde *et al*., 2019).

Understanding soil-crop relationships through indicators is essential to propose sustainable management systems for agricultural farming. Among the indicators with such potential, LLWR is powerful soil physical property integrator, as this allows a better understanding of soil water availability and its relation to practices usage and management for different agricultural crops (Mishra *et al*., 2015; Dias *et al*., 2016).

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[1] Universidade Federal da Grande Dourados, Faculdade de Ciências Agrárias, Dourados, Mato Grosso do Sul, Brasil. csouza@ufgd.edu.br
[2] Agrismart, Trinidad, Beni, Bolivia. hideki_04@hotmail.com
[3] Universidade Eduardo Mondlane, Escola Superior de Desenvolvimento Rural, Vilankulo, Inhambane, Mozambique. earmando24@gmail.com
[4] Agricase, Parque das Nações, Dourados, Mato Grosso do Sul, Brasil. maciak_pagm@hotmail.com
[*]Corresponding author: salvionapoleao@gmail.com

The LLWR is used as soil physical and structural quality indicator defining the interval between the upper and lower limits of water content in the soil, which are minimal limitations for plant growth caused by unavailability water, aeration deficiency and soil resistance to penetration (Fashi *et al*., 2017). With the increase of the soil bulk density, generally, the value of the LLWR decreases, being able to reach the null value, which corresponds to the critical or restrictive soil bulk density, when upper and lower limits are numerically equal (Klein *et al*., 2016).

Klein *et al*. (2016) reported that LLWR, besides of depending on the soil type, assumes different ranges depending on the soil bulk density, water soil retention curve and aeration and porosity. Additionally, the choice of the restrictive value of soil resistance to penetration (PR) to plant growth directly interferes to LLWR values and critical soil bulk density (Gubiani *et al*., 2013).

Thus, Klein & Camara (2007) found that the RP of 2.0 MPa should not be assumed as limiting to soybean root system development, suggesting the use of 3.0 MPa, which better adjusted to limits occurred. Moreover, Betioli Junior *et al*. (2012) reported that the use of RP greater than 2.0 MPa correlates better the LLWR with the crop development, either with restrictive RP of 3.0 or 4.6 MPa. Moreira *et al*. (2014), observed that when using restrictive RP limit of 2 MPa instead of 3 MPa, enabled them to see to spatially variability in order to perform specific management of the soil.

Current research has shown relationship of the LLWR and crop yield (Araújo *et al*., 2013; Silva *et al*., 2017); however, further researches are still in need involving LLWR and crop response to soil conditions and under different soil management systems (Gubiani *et al*., 2013), to generate important information for agricultural management practices. Thus, this work aims evaluate the usage of the LLWR and the soil critical bulk density for the assessment of soil physical water quality in an Oxisol under no-tillage and reduced-tillage management, evaluating its effect on sugarcane farming.

MATERIAL AND METHODS

Study area and installation of the experiment

The study was conducted at the Experimental Farm of the Federal University of Grande Dourados, located in Dourados, Mato Grosso do Sul (MS), Brazil (22°13’58"S, 54°59’57W”, altitude 418 m). The climate of the area is classified as Am type, monsoon, with dry winter, an annual rainfall average of 1500 mm and an average annual temperature average of 22 ºC (Alvares *et al*., 2013). The soil of the area is classified as a clayey Latosol (Oxisol) with a clay-like texture, and the layer down to 0.30 m deep is characterized by 603 g kg^{-1} clay, 147 g kg^{-1} silt and 250 g kg^{-1} sand (Arcoverde *et al*., 2019).

The trial was conducted under a completely randomized design, with two treatments: no-tillage system and reduced-tillage, with four replications. Each experimental plot accomplished 300 m^2 of area, with 40 m long and 7.5 m wide.

The farming area had been implanted in the last 14 years ago under soybean and corn, in crops succession system, with no soil revolving. Thus, presented homogeneity of the environmental conditions, located at flat topography, without variation of the soil type and management techniques. The reduced-tillage system consisted of heavy ploughing, with an off-set harrowing-plough of 16 discs of 0.76 m (30") diameter in each section, at a depth of 0.15 m. For the No-tillage system consisted of mechanized weed control (weeding), followed by furrows opening at planting. Thus, was used a straw crusher equipped with rotor of steel curved knives that work in high rotation and furrower to open the grooves for planting. Manual planting of sugarcane cultivar RB966928, early cycle, was performed on July 21, 2016, at a density of 15 buds per meter.

Soil sampling

In March 2018, 180 days after sugar plant harvest, were collected non-deformed soil samples using volumetric rings of about 55.7 mm diameter and 44.1 mm height. Thus, were opened parallel trenches in the planting rows and were collected soil samples in two layers, 0.00-0.10 m and 0.10-0.20 m at the depths of 0.05 and 0.15 m respectively, between the line and the interline of the sugar cane. The aim of sampling in two layers, was trying to characterize the more representative the soil layer in the interval of 0 to 20 cm depth.

Five trenches were opened in each soil preparation system, with seven samples collection per depth, adding up 70 samples per treatment (35 samples at each depth). The samples collected were carefully coated with PVC film, packaged in a Styrofoam box and then kept in the Soil Physics Laboratory, which initially were placed in refrigerator aiming minimizes the possible soil structure variations and soil water condition.

Laboratory analysis and calculations

In the laboratory, the samples were divided into 7 groups of 5 samples, and submitted to the following matrix potentials: -0.006; -0.01; -0.033; -0.066; -0.1; -0.3 and -1.5 MPa, using a tensile table (-0.006 MPa) and to Richards chamber for the other potentials, to determine the retention curve, as described in Silva *et al*. (1994). After reaching equilibrium at each potential, the samples were weighed. The RP was determined by means of an electronic penetrograph with a constant penetration velocity of 0.01 m min^{-1}, base diameter of 4 mm and semi-angle of 30° (Pereira *et al*., 2015). After determination of PR, the samples were taken to greenhouse for drying and then the soil bulk density (sD) was obtained by the relation between the dry soil mass at 110 ºC for 24 h and the volumetric ring volume at which the soil was collected (Arcoverde *et al*., 2019). The total soil porosity was obtained by the difference between the mass of saturated soil and the dry mass of soil in an oven at 110 °C for 24 h (Arcoverde *et al*., 2019).

For the determination of the LLWR, followed the procedures described by Pereira *et al*. (2015), considering the upper limit to be the lowest value among the water content retained in the soil at a matric potential of -0.01 MPa (Reichardt, 1988), corresponding to field capacity (SWF_C) or the value at which the air-filled porosity (SWF_C) was 10% (Grable & Siemer, 1968). In turn which, the lower limit was considered to be the greatest value among the retained water contents at a matric potential of -1.5 MPa (Savage *et al*., 1996) in relation to the permanent wilting point (SW_{PWP}), and the soil moisture content at root penetration (SW_{PR}) reaches 2.0 MPa (Taylor *et al*., 1966; Pereira *et al*., 2015) and 4.0 MPa for sugarcane (Oliveira Filho *et al*., 2016).

The values of water content in the field capacity (SW_{FC}) and at the permanent wilting point (SW_{PWP}) were determined using the mathematical model (Eq. 1) proposed by Silva *et al*. (1994), the original data were adjusted, for which the variable SD was incorporated in the function employed by Ross *et al*. (1991).

$$SW = \psi^c \cdot exp(a + b \cdot SD) \quad (1)$$

where,

SW is the soil water content (m^3 m^{-3});

SD is soil density (Mg m^{-3});

ψ is the soil matrix potential (MPa);

"*a*", "*b*" and "*c*" are the empirical parameters for model adjustment.

The soil penetration resistance values of all samples with known soil water content and SD were mathematically adjusted using the model (Eq. 2) proposed by Busscher (1990). By means of this model it was possible to determine the critical value of soil water content so that the PR did not exceed 2.0 and 4.0 MPa, as a function of SD. Therefore, PR is replaced by the model value of 2.0 to 4.0 MPa, considered initially and fully bound for calculation purposes LLWR, respectively.

$$PR = d \cdot SW^e \cdot SD^f \quad (2)$$

where,

PR is the soil penetration resistance (MPa);

"*d*", "*e*" and "*f*" are the empirical parameters of model adjustment.

The value of volumetric water content in which the aeration porosity is 0.10 m^3 m^{-3} was obtained through the Equation 3, adopting the value of 2.65 Mg m^{-3} as mean particle density (Pereira *et al*., 2015).

$$SW_{AP} = 1 - \frac{sD}{pD} - 0.10 \quad (3)$$

where,

SW_{AP} is the soil volumetric water content in which the aeration porosity is 0,10 m^3 m^{-3};

pD is the density of particles (Mg m^{-3}).

For the determination of the upper limits of the LLWR were used the water content in the field capacity and the water content in which the aeration porosity is 0.10 m^3 m^{-3}, as those adequate to the growth of sugarcane. As lower limits were considered the water contents at the permanent wilting point and in the soil penetration resistance, as those limiting to plant growth. After calculating the upper and lower limits of the LLWR, the critical soil density (SCD) was determined, in other words, when the upper limit of the LLWR is numerically equivalent to the lower limit (Silva *et al*., 1994).

Productivity and technological analysis

In September 2017 and 2018, respectively, at the end of the cycle of plant cane and first ratoon cane was recorded the number of stalks 20 meters and performed manual harvesting of eight beams of 10 stalks in the experimental unit. From the data, the average value of the stem yield (TCH) was obtained. After that, were collected bundles of 10 stalks previously harvested and sent to the Chemical Laboratory to determine the mean values of soluble solids (Brix), total recoverable sugars (TRS) and sucrose content (PCC). The tons of sucrose per hectare (TPH) was obtained by the product between TCH and PCC (Silva *et al*., 2014; Arcoverde *et al*., 2019).

Statistical analysis

The soil physical-water attributes data for the LLWR study were submitted to descriptive statistics to verify the means, standard deviation, minimum and maximum values, and coefficient of variation. To determine the coefficients of the mathematical models, the no-linear regression analysis was applied, with significance of the t test of the coefficients and with significance of the F test, at 1% of probability. For the TCH, TPH, Brix and TRS, the conservationist tillage systems were compared using the t-test for independent samples, at 5% probability.

RESULTS AND DISCUSSION

Descriptive statistical

It is observed that there was a great range of the soil bulk density (SD) data, resulting in variation of the soil water content (SW) and soil penetration resistance (PR), dues to non-soil disturbance during sugarcane plantation and no-intensive effect of mechanization, either for the sugar cane plant, and for the first ratoon (Table 1). The mean value results of the total aeration porosity agree to those obtained by Arcoverde *et al*. (2019) when evaluating an Oxisol cultivated with cane.

The SD and SW showed low coefficient of variation values (CV), while the PR showed high values. The values of high CV for PR are similar to those found by Silva *et al*. (1994), Tormena *et al*. (1998) and Leão *et al*. (2004), which can be attributed to the variability of SW and SD in the samples. The maximum PR value was 11.09 MPa, which was similar to that obtained by Tormena *et al*. (2007) in Oxisol under no-tillage. The SD and the SW showed similarity to Serafim *et al*. (2008), who worked in Oxisol.

Least Limiting Water Range

The models selected to represent the soil water content under no-tillage (Eq. 4) and with reduced-tillage (Eq. 5) were significant by the analysis of variance of the regression ($p < 0.01$) and the coefficients by the t-test ($p < 0.01$), with coefficient of determination of 0.75 and 0.86, respectively.

$$SW = e^{(-1.85186 + 0.46631 \,.\, sD)}\ \Psi^{-0.059918} \quad (4)$$

$$SW = e^{(-1.65083 + 0.37191 \,.\, sD)}\ \Psi^{-0.043643} \quad (5)$$

Additionally, all models obtained to describe the performance of the soil penetration resistance under no-tillage (Eq. 6) and reduced-tillage (Eq. 7) were validated by the significance of the F regression test ($p < 0.01$) and by the t-test of the coefficients ($p < 0.01$), with the determination coefficient of 0.75 and 0.65, respectively.

$$PR = 0.6469 \,.\, 10^{-5} \,.\, SW^{-7.3336} \,.\, SD^{11.965} \quad (6)$$

$$PR = 0.019495 \,.\, SW^{-2.10885} \,.\, SD^{6.77195} \quad (7)$$

Moreover, the Figure 1 shows an increase of SD there is an increase of the LLWR until the SW in the aeration porosity (SW_{AP}) covering the SW in the field capacity (SW_{FC}), or, the mechanical resistance to the penetration of the roots covering the SW in the permanent wilt point (SW_{PWP}), similarly to the results obtained by several authors under different soils and management (Betioli Junior *et al*., 2012; Araújo *et al*., 2013; Guedes Filho *et al*., 2013; Pereira *et al*., 2015; Dias *et al*., 2016; Fashi *et al*., 2017) .

Critical value selection of the PR interferes with the range of the LLWR and the value of the critical soil bulk density - SCD (Moreira *et al*., 2014). Klein *et al*. (2016) state that the use of the value of 2.0 MPa as restrictive under no-tillage appears to be inadequate, once crops seek ways for lower restriction for their growth cycle, thus, under these systems largest values of PR are commonly observed. Several authors studying the LLWR consider that a different critical PR of 2.0 MPa (Tormena *et al*., 1998; Betioli Junior *et al*., 2012; Araújo *et al*., 2013; Moreira *et al*., 2014). Oliveira Filho *et al*. (2016) observed that values of PR less than 4.0 MPa should not cause damage to sugarcane plants growth. Araújo *et al*. (2013), observed that raising the PR critical limit to 4.0 MPa in Oxisol, the LLWR would provide better conditions to the development of the sugarcane plants.

Additionally, the increase of the SD increases the LLWR, for in the two systems under soil preparation. For no-tillage (Figure 1a), there was an increase in the sW_{AP} replace the SW_{FC} at SD of 1.34 Mg m^{-3}, and the SW_{PR} covering the SW_{PWP}, at the SD of 1.44 Mg m^{-3}. Similarly, under reduced-tillage (Figure 1b) was increasing of the LLWR, SW_{AP} replace the SW_{FC} on SD of 1.34 Mg m^{-3}, but the lower limit has been completely represented by SW_{PWP}.

Table 1 - Descriptive statistics of the soil water content attributes, soil bulk density and soil resistance to penetration determined in the samples under non-deformed soil structure for LLWR obtained in the 0.00-0.20 m-deep layer under no-tillage and reduced-tillage

Variable	Mean	Standard deviation	CV	Minimum	Maximum
			No-tillage		
SD	1.540	0.133	8.6	1.192	1.767
SW	0.384	0.056	14.8	0.223	0.484
PR	3.810	2.378	63.6	0.477	11.09
AP	0.418	0.134	8.6	0.333	0.550
			Reduced-tillage		
SD	1.572	0.120	7.6	1.202	1.764
SW	0.390	0.036	9.4	0.274	0.451
PR	3.949	1.710	43.3	0.936	9.670
AP	0.406	0.120	7.7	0.334	0.546

SD - soil bulk density (Mg m^{-3}); SW - soil water content (m^3 m^{-3}); PR - soil penetration resistance (MPa); AP - aeration porosity (m^3 m^{-3}); CV - coefficient of variation (%).

The Figure 2 shows that the increase of SD increased the LLWR to determined value of SD. Moreover under no-tillage (Figure 2a), the upper limit of the LLWR was the SW_{FC} until was replaced the by SW_{AP}, SD of 1.33 Mg m^{-3}, and the lower limit was replaced SW_{PWP} until was replaced by SW_{PR}, in the SD of 1.34 Mg m^{-3}. Under reduced-tillage (Figure 2b), the upper limit of the LLWR was SW_{FC} being replaced by SW_{AP}, SD of 1.34 Mg m^{-3}, and the lower limit was replaced SW_{PWP} until SW_{PR}, in the SD of 1.37 Mg m^{-3}.

The LLWR began to be limited the by the SW_{PWP}, at SD of 1.34 Mg m^{-3}, in both soil management systems. The upper limit SW_{FC} the is replaced sW_{AP}, and the SW_{PWP} is replaced SW_{RP} (Figure 2). These results are in agreement to Pereira *et al*. (2015) when working with the Hapludox clayey soil and Araújo *et al*. (2013) in clayey Latosol soil.

Under no-tillage system, there was a greater impact of PR on the lower limit of the LLWR, due to the high relation of the SD and PR. Dias *et al*. (2016), working with sugarcane, finding that these typical results due to high soil bulk density or compacted soils, relating to high water content so that the PR does not reach the limiting value. Several authors also observed that the influence of SW_{RP} to the LLWR of soil in different soil management systems (Leão *et al*., 2004; Moreira *et al*., 2014; Silva *et al*., 2017; Fashi *et al*., 2017) and texture classes (Pereira *et al*., 2015; Dias *et al*., 2016; Klein *et al*., 2016).

In both the soil tillage systems, all SD values are below the SCD, the upper limit of the LLWR was always defined by SW_{FC}, revealing that SW_{AP} was not a limiting factor in the soil, agreeing to Fashi *et al*. (2017) when evaluating the LLWR under conventional and conservation soil tillage systems. The results corroborate with those found by Silva *et al*. (2017) in a Red Hapludox under no-tillage, highlighting that the high total porosity in Latosols minimizes the possible soil aeration problems, which may appear, possibly in cases of severe compaction, excess moisture or high content clay.

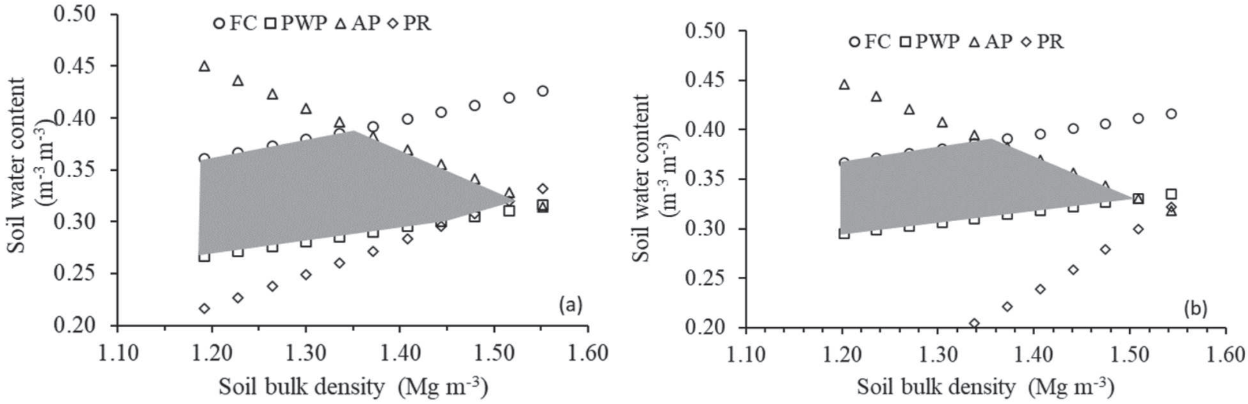

Figure 1: Soil water content as under of soil bulk density at the critical levels of field capacity (y = -0.01 MPa), permanent wilting point (y = -1.5 MPa), aeration porosity of 10% and penetration resistance of 4.0 MPa, as a function of soil bulk density in Oxisol, (a) No-tillage, (b) Reduced-tillage, in the 0.00-0.20 m-deep layer. FC-field capacity. PWP-permanent wilting point. AP-aeration porosity. PR-soil penetration resistance. The hatching area represents the optimum soil water interval.

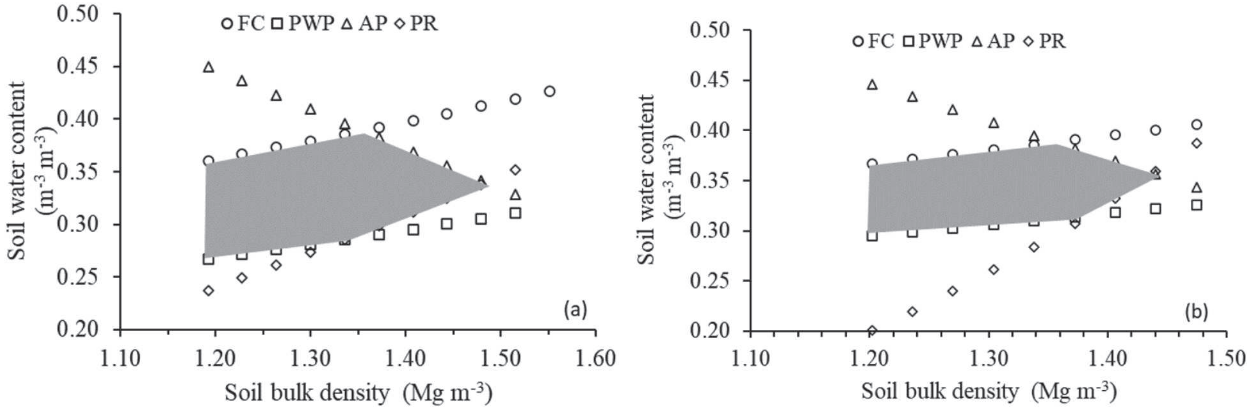

Figure 2: Soil water content as under of soil bulk density at the critical levels of field capacity (y = -0.01 MPa), permanent wilting point (y = -1.5 MPa), aeration porosity of 10% and penetration resistance of 2.0 MPa, as a function of soil bulk density in Oxisol, (a) no-tillage, (b) reduced-tillage, in the 0.00-0.20 m-deep layer. FC-field capacity. PWP-permanent wilting point. AP-aeration porosity. PR-soil penetration resistance. The hatching area represents the optimum soil water interval.

The LLWR increase increased the SD up to 1.37 Mg m^{-3} under no-tillage and 1.34 Mg m^{-3} under reduced-tillage, decreasing its values after that SD, with critical PR of 4.0 MPa. The SCD under no-tillage was 1.53 Mg m^{-3} and the reduced-tillage was 1.51 Mg m^{-3} (Figure 3a).

Additionally, in both soil tillage systems, for no-tillage that increase of SD positively affected the LLWR up to the SD of 1.37 Mg m^{-3}, higher SD values negatively affected the LLWR. Under the reduced-tillage, the SD positively affected the LLWR up to the SD of 1.33 Mg m^{-3}, from which it represents limitation to the LLWR.

The Figure 3b shows that the increase of the SD positively affected the LLWR in the two soil preparation systems, up to the SD of 1.34 Mg m^{-3} for no-tillage and up to 1.37 Mg m^{-3} under reduced-tillage. It is observed that higher values lead to lower values of LLWR and greater restriction on the growth of roots. SCD was 1.48 Mg m^{-3} under no-tillage, and 1.51 Mg m^{-3} under reduced-tillage.

The range of the LLWR is greater under no-tillage for both the restrictive PR of 2.0 MPa, as 4.0 MPa. According to Tormena *et al*. (1998) when studying the LLWR under different PR critical values (1.5, 2.0 and 3.0 MPa), PR is the factor that assumes greater importance in terms of limitations of the plants growth. However, in this study, it should be considered that aeration porosity has also been limiting in some cases. Klein & Camara (2007) observed that PR 2.0 MPa should not be considered as restrictive to sugarcane growth compared to soybean and using 3.0 MPa PR is a better environmental limit. Betioli Junior *et al*. (2012), on the other hand, the use of PR greater than 2.0 MPa correlates best with the LLWR for several crops growth when compared to PR 3.0 to 4.6 MPa.

Figure 4a shows a comparison of the LLWR when adopting PR of 2.0 or 4.0 MPa under no-tillage, showing that when PR is equal to 4.0 MPa, the soil has a water content higher than 2.0 MPa, thus, the range of the LLWR is greater than the restrictive PR. These corroborate to the results obtained by Moreira *et al*. (2014), when working with LLWR Rhodic soil under grains no-tillage, founding that the critical PR of 3 MPa value has a greater range of LLWR, due to the higher value SCD than adopting the critical PR of 2 MPa.

Figure 4b shows the comparison of the LLWR when the PR is equal to 2.0 MPa and 4.0 MPa, showing that in both cases with the increase of SD, the decrease the LLWR occurs at the SD of 1.36 Mg m^{-3}, but in the PR equal to 4.0 MPa there is a greater range of water retention until

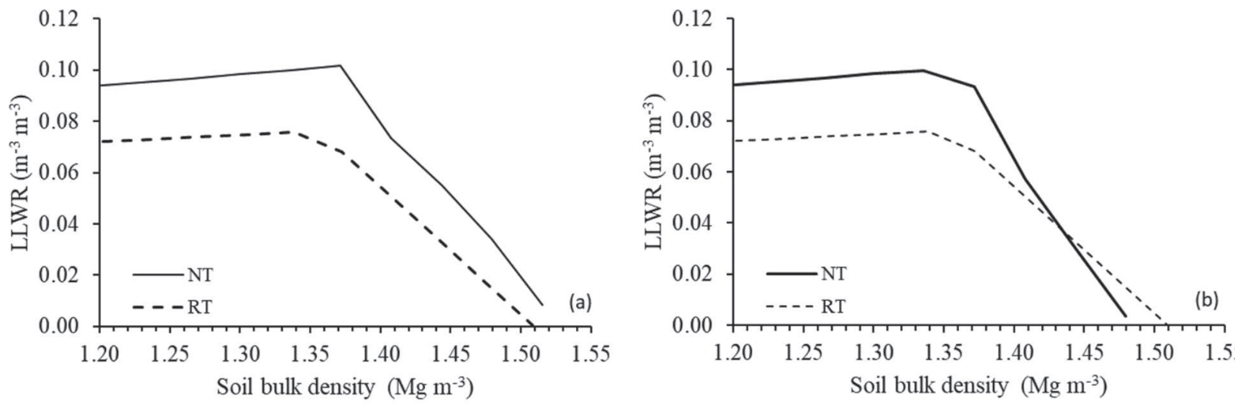

Figure 3: Least limiting water range (LLWR) as function of soil bulk density in an Oxisol under no-tillage (NT) and reduced-tillage (RT), for soil penetration resistance of 4.0 MPa (a) and 2.0 MPa (b), in the 0.00-0.20 m-deep layer.

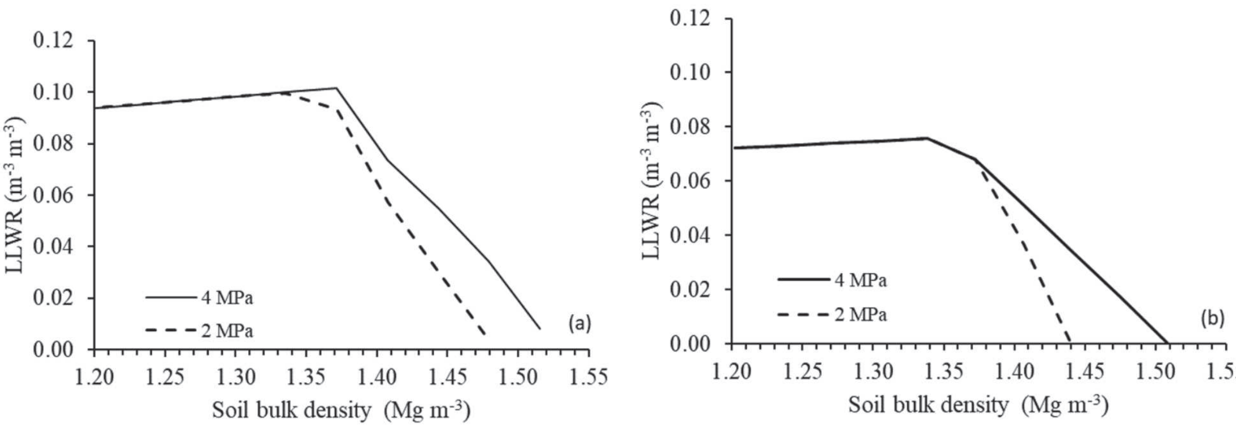

Figure 4: Least limiting water range (LLWR) as function of soil bulk density in an Oxisol under no-tillage (a) and reduced-tillage (b), in penetration resistance from 2.0 and 4.0 MPa, in the 0.00-0.20 m-deep layer.

Table 2 - Sum of the mean yield values (TCH, Mg ha^{-1}), tons of sucrose per hectare (TPH, Mg ha^{-1}), total recoverable sugars (TRS, kg Mg^{-1}) and soluble solids (Brix%) for sugarcane for the crop cycle and first ratoon, in Oxisol, under no-tillage and reduced-tillage

Soil tillage system	TCH	TPH	TRS	Brix
No-tillage	269.50 a	39.87 a	303.86 a	35.70 a
Reduced-tillage	211.02 b	32.87 b	295.46 b	36.46 a

The letters compare the treatments, when different indicate that the values differ by t-test ($p < 0.05$).

the SCD of 1.51 Mg m^{-3}, agreeing to Moreira *et al*. (2014). Gubiani *et al*. (2013) that observed that Oxisol, under no-tillage, for critical PR of 2, 3 and 4 MPa, respectively, SCD of 1.31; 1.40 and 1.44 Mg m^{-3}, closer to the values obtained under no-tillage.

According to Figure 3 and 4, the adoption of a restrictive value of the PR to the crop growth has a direct consequence on the LLWR, demonstrating that such values must be very well studied in order to be more reliable when taking decision on the best management of soil in the sugar cane cultivation (Klein *et al*., 2016).

Productivity and technological quality

Regarding to the production attributes and technological quality of the sugarcane, for cane-plant and first ratoon, is a significant difference between soil tillage systems, except for Brix (Table 2).

It should be noted that the cane-plant cycle was determinant to differentiate the performance of the cultivar RB966928 between the soil preparations, significantly reducing the cycle of ratoon, agreeing with Silva *et al*. (2014). Arcoverde *et al*. (2019) when evaluating the performance of eight cultivars, in cane-plant, observed that in for RB966928, the TCH of 158.5 Mg ha^{-1} and TPH of 24.1 Mg ha^{-1}, under no-tillage, against TCH of 175.0 Mg ha^{-1} and TPH of 27.3 Mg ha^{-1}, under no-tillage, where lower values of soil resistance to penetration and higher values of moisture were observed in the soil layers up to 0.40 m.

The results obtained regarding to the best performance of sugarcane under no-tillage correspond to the greater range of the LLWR obtained in this preparation in comparison to the reduced-tillage system, independently, to the value of soil resistance penetration adopted as restrictive to the sugarcane growth. Researches have shown the relationship of the LLWR with the yield in different crops (Araújo *et al*., 2013, Silva *et al*., 2017).

However, some studies suggest limiting the use of LLWR as an indicator of soil physical quality, since it may not be related to crop yield (Gubiani *et al*., 2013; Cecagno *et al*., 2016; Mishra *et al*., 2015). Despite the controversial results, there is great scope and need for new studies to better understand the relationships between soil tillage systems and crop production, without doubt, and may help decision making regarding the adoption of conservation management systems for soil management farming of sugarcane.

CONCLUSIONS

The LLWR proved to be a good soil physical water quality indicator in sugarcane farming under conservation tillage system.

No-tillage presented a greater range of the LLWR when compared to the reduced-tillage, regardless to the PR value adopted as restrictive for sugarcane roots development, increasing the yield of stalks and sugars contents.

The critical soil bulk density of a cultivated cane Oxisol under no-tillage is between 1.48 and 1.53 Mg m^{-3} at the PR of 2 and 4 MPa, while under reduced-tillage it is between 1.44 and 1.51 Mg m^{-3}, respectively.

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