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Article

Least limiting water range in Oxisols under different levels of machine traffic

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Abstract

This work aimed, to evaluate the structural behavior of Oxisols based on the least limiting water range (LLWR) and establish relations with corn crop. The experiment was carried out in a randomized block design with five treatments and four replications. Soil samples collected at the layer of 0-0.20 m depth in a Haplustox (LVd) and an Eutrustox (LVef) were used. The compaction treatments consisted of T0= no additional compaction; T1 and T2= two and four passes with a 4 t tractor, respectively; T3 and T4 = two and four passes with a 10 t tractor, respectively. The range of LLWR variation in the LVd was the lowest one and varied from 0.01 to 0.04 m^3 m^{-3}, whereas in the LVef varied from 0.03 to 0.13 m^3 m^{-3} for the critical soil penetration resistance (PRc) of 2 MPa. It was observed that critical bulk density (BDc) values were 1.76 and 1.40 Mg m^{-3} in the LVd and the LVef, respectively. The highest frequency of bulk density (BC ≥ BDc) occurred from the T1 to T4 (LVd) and from the T2 to T4, however, a reduction in corn yield was not observed. The determination of the LLWR was efficient and complementary for identifying more favorable or more impeditive conditions to compaction in the LVef for the corn crop development in relation to the LVd.

Keywords: Soil compaction, tractor traffic, soil structure

Introduction

As natural ecosystems are being replaced by intense and continuous agricultural activities, the soil physical properties may undergo temporary or permanent changes and consequently may lead to unfavorable conditions for the plant development. Therefore, the soil physical degradation is established and generally related to the losses of organic matter and structural integrity of the soils (Guimarães et al., 2013).

The soil bulk density, porous system, soil penetration resistance, soil aggregation, S-index, soil water retention, the degree of compaction, water infiltration, least limiting water range (LLWR) etc., are the most commonly attributes to evaluate soil degradation. Therefore, laboratory analyses are still performed, although they are expensive and time-consuming, mainly, when there is a high number of samples and attributes evaluated. This is because, the visual quantification of the soil structural behavior in a given agricultural management is a hard task (Omuto, 2008).

The LLWR is a soil quality index that integrates into a single variable (soil bulk density) the factors that directly affect the plant growth. The decreasing of LLWR reduces the range in which soil moisture can vary without restricting plant growth, related to water availability, aeration, and soil penetration resistance.

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Therefore, it can be considered a well-established index to evaluate the quality of cultivated soils (Cavalieri et al., 2011). However, for Gubiani et al. (2013) the use of LLWR is imprecise to estimate the risk of losses in grain production related to soil compaction.

Another way to evaluate the use of LLWR is through of the critical soil bulk density (BDc), which occurs when the LLWR is zero, that is, the one in which the lower limit crosses the upper limit of the interval. From this condition, severe restrictions to planting growth occur. In a medium-textured red Oxisol, Freddi et al. (2009) found that the BDc was 1.46 kg dm^{-3} at the layer of 0-0.30 m depth in different compaction levels induced by tractors. At the same soil class after the third growth cycle of sugarcane, Cavalieri et al. (2011) found that the BDc values were 1.76 and 1.77 Mg m^{-3}, at the layers of 0-0.20 (292 g kg^{-1} clay) and 0.20-0.40 m (365 g kg^{-1} clay) depth, respectively. These differences exist because the LLWR estimator is the soil bulk density, which varies according to the soil management.

The aim of this study was to evaluate the compaction in a Haplustox (LVd) and an Eutrustox (LVef) by means of the least limiting water range (LLWR) for corn crop.

Materials and Methods

The experiment was carried out in Jaboticabal county, São Paulo state, Brazil, located at the geographic coordinates of 21° 14'05 "S, 48 ° 17'09" W, and altitude of 615 m asl. According to the classification of Köppen, the climate of the region belongs to Cwa type, with hot summers and dry winters, an average annual rainfall of 1428 mm and an average temperature of 21°C (Figure 1).

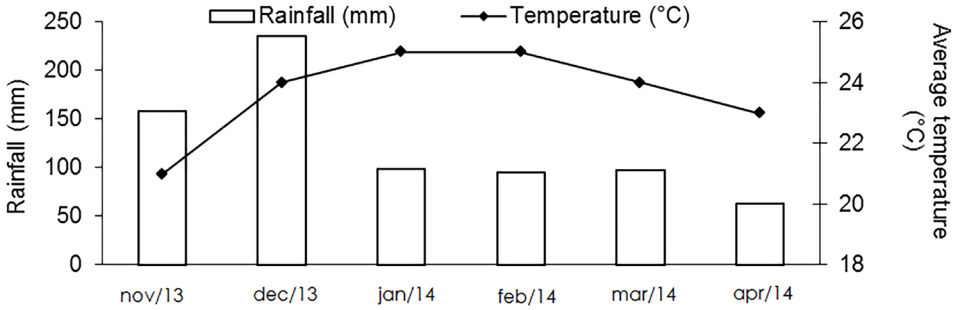

Figure 1. Accumulated rainfall and average monthly temperature during the growth cycle of corn(2013/14).

The soils were characterized by Embrapa (2013) as a medium texture Haplustox ("Latossolo Vermelho distrófico típico" - LVd), moderate A horizon, kaolinite-hypoferric and clayey texture Eutrustox ("Latossolo Vermelho eutroférrico típico" - LVef), moderate A horizon, kaolinite-oxidic . The soils, at the layer of 0-0.20 m depth, showed 348 and 560 g kg^{-1} clay content, 598 and 240 g kg^{-1} sand content, 54 and 200 g kg^{-1} silt content, 2.89 and 2. 74 Mg m^{-3} soil particle density, 14 and 24 g kg^{-1} soil organic matter content, in the LVd and the LVef, respectively. Before the installation of the experiments, the conventional soil preparation at 0,30 m depth was carried out by a disc chisel with 18 discs of 660 mm (26 "); and by a Marchesan Tatu off-set disk harrow, model: ATCR, with seven discs in each section (two), with discs of 0.61 m and distance between disks of 0.23 m.

The experiment was arranged in a randomized block design with five treatments and four replication for each soil class. The plots were constituted by five maize rows with 6 m length, the three central rows were considered the useful plot, and 1.5 m at each end of rows were discarded. The soil compaction induction was performed on November 26, 2013, two days after rainfall, when the soil water content was close to the soil field capacity at the layer of 0-0.20 m depth.

The treatments were: T0 = soil prepared in the conventional tillage system and without additional tractor traffic; T1 and T2 = two and four passes with a 4 t tractor, respectively; T3 and T4 = two and four passes with a 10 t tractor, respectively. Soil compaction was then performed by passing the wheels of these

tractors, covering the whole surface of the plots, so that the tires compressed areas parallel to each other. Therefore, the number of passes by the tractors varied according to the treatment; the traffic was overlapped on the previous one, so that whole area of each plot was passed with an equal number of times.

In order to establish T1 and T2 treatments, a Ford 5610 tractor with 56 kW (70 hp), traction (4 × 2) with 4 t mass, whereby the distribution of 30% of the total mass in the front diagonal wheels and 70% in the rear radial wheels, was used. The inflation pressure in the R1 front tires was 83 kPa whereas in the rear tires (R1 18.4-30) was 96 kPa. For the T3 and T4 treatments, a Caterpillar 924F loading shovel with 105 kW (143 hp), traction (4 × 4), 17.5 R 25 tires, radial (L-3), 10 t mass and with the shovel empty was used.

Corn sowing (Maximus simple hybrid) was carried out on December 03, 2013, using a no-tillage seeder-fertilizer machine with five rows. In this case and for other cultivation practices, a Massey Fergusson 620 tractor with 77 kW (105 hp), traction (4 x 2 front wheel drive assist), 7 t mass whereby the distribution of 40% of the total mass in the front radial wheels and 60% in the rear radial wheels, was used. The inflation pressure in the front tires (14.9-24R1) was 95 kPa whereas in the rear tires (19.4-34R1) was 110 kPa. The seed density ranged from five to six seeds per linear meter, with row spacing of 0.90 m. Fertilizer application at sowing consisted of 250 kg ha^{-1} of the N-P-K formulation (8-28-16) and 30 kg ha^{-1} of zinc sulfate to obtain 6-8 Mg ha^{-1} expected corn yield. The top-dressing fertilizer application was performed at V6 growth stage with 230 kg ha^{-1} of the N-P-K formulation (30-0-10) on the surface, next to the seeding row.

On December 17 and 18, 2013, two groups of six samples per treatment were collected in each soil in the row spacing using 53.16 10^{-6} m^3 cylinders (0.032 m high and 0.046 m diameter), at the layers of 0-0.05, 0.05-0.10 and 0.10-0.20 m depth, totaling 360 samples in the experiment. Thereafter, a sample of each group and layer was saturated for 24 h and tensions of -60, -100, -330, -600, -1000 and -3000 hPa matric potential were applied, using a pressure plate apparatus (Richards). At equilibrium, the samples were weighed and soil penetration resistance (PR) was determined. The PR was determined by using a static electronic penetrometer with a constant penetration velocity of 1 cm min^{-1}, a cone with a 30º angle and a base area of 4.909 10^{-6} m^2, equipped with a linear actuator and a 20 Kg load cell coupled to a microcomputer for data acquisition. The results were obtained in kgf and transformed in MPa using the following equation: readings / 0.046 × 0.098. The samples were dried in a stove at 105 °C for 24 h in order to determine the water content at each soil tension and bulk density (BD) (Grossman & Reinsch, 2002). Microporosity was obtained in the water retained at -100 hPa matric potential (Flint & Flint, 2002), and macroporosity by the difference between total porosity and microporosity.

For determination of the LLWR, the soil water retention curve was adjusted by the nonlinear model used by Silva et al. (1994) and the soil penetration resistance (PR) curve was adjusted using the Busscher (1990) model, in log-transformed data. SAS software was used to perform the analysis (Statistical analysis system, version 9.2):

$$\ln\theta = a + b\ BD + \ln\psi \qquad \text{Eq.(1)}$$

$$\ln PR = \ln d + e\ \ln + f\ \ln BD \qquad \text{Eq. (2)}$$

where θ: volumetric water content ($m^3\ m^{-3}$); Ψ: soil water tension (hPa); a, b, c, d, e, f: parameters of the model adjusting.

The water content in the field capacity (θ_{FC}) is the water retained in the tension of -100 hPa and the permanent wilting point (θ_{PWP}) is the water retained in the tension of -15000 hPa. The θ_{FC} and θ_{PWP} were estimated by equations (3) and (4), respectively, obtained from equation (1):

$$\theta_{FC} = EXP\ (a + b\ BD) * 100^{c} \qquad \text{Eq. (3)}$$

$$\theta_{PWP} = EXP\ (a + b\ BD) * 15.000^{c} \qquad \text{Eq. (4)}$$

The water content from which RP is limiting was estimated by equation (5), obtained from equation (2):

$$\theta_{PR} = ((PRc)/(EXP^{d} * (BD^{e})))^{1/f} \qquad \text{Eq. (5)}$$

where PRc is the critical PR of 2 MPa.

The water content in which the aeration porosity is 10% was calculated by the equation (6):

$$\theta_{AP} = [(1 - (BD/Pd)] - 0.10 \quad \text{Eq. (6)}$$

where Pd is soil particle density (g dm^{-3}).

The θ_{AP}, θ_{FC}, θ_{PWP} and θ_{PR} were plotted as a function of the BD, forming the LLWR, representative of the three layers (0-0.20 m), since it was equivalent in all layers, thus, the average value was used.

On April 29, 2014, after the stage of physiological maturity of the grains, the grain mass was evaluated in 20 plants per plot. When grain moisture was greater than 25%, corn cobs of two useful row with 2.0 m length were harvested (0.5 m was discarded at each end of the 3.0 m row), for the threshing and the grain mass determination. Corn grain yield was obtained by extrapolating grain yield from the useful plot area to 1 ha, adjusting grain moisture to 13%. The analysis of variance and Tukey's test ($p < 0.05$) were performed. Also, correlations between soil bulk density, and plant height and corn yield were performed.

Table 1. F values calculated by the analysis of variance for the physical attributes of an LVd and an LVef in different layers and compaction levels.

Sources of variation	Macroporosity	Microporosity	Bulk density	Penetration resistance
		LVd		
Treatment (T)	2.61^{ns}	4.32^{ns}	4.54^{ns}	1.73^{ns}
Layer (L)	1.24^{ns}	0.72^{ns}	1.75^{ns}	0.08^{ns}
T x L	0.48^{ns}	0.70^{ns}	0.77^{ns}	0.71^{ns}
CV (%)[1]	27.18	12.85	8.24	22.05
CV (%)[2]	26.47	10.57	4.64	24.99
		LVef		
Treatment (T)	6.54*	7.30*	5.31*	2.42^{ns}
Layer (L)	1.40^{ns}	0.64^{ns}	0.27^{ns}	1.17^{ns}
T x L	0.98^{ns}	0.66^{ns}	0.89^{ns}	1.38^{ns}
CV (%)[1]	18.53	2.74	3.61	21.98
CV (%)[2]	24.66	3.36	4.43	24.58

CV (%)[1]: coefficient of variation related to the treatments; CV (%)[2]: coefficient of variation related to the layers. * Significant ($p<0.05$), ^{ns} non- significant.

Table 2. Average values and standard errors of physical attributes in a Haplustox ("Latossolo Vermelho Distrófico" - LVd) in different layers and compaction levels.

	LVd				
Layer	T0	T1	T2	T3	T4
m			Macroporosity (m^3 m^{-3})		
0-0.05	0.239 ± 0.10[(1)]	0.138 ± 0.02	0.129 ± 0.02	0.163 ± 0.01	0.144 ± 0.05
0.05-0.10	0.227 ± 0.03	0.133 ± 0.02	0.114 ± 0.00	0.090 ± 0.04	0.122 ± 0.02
0.10-0.20	0.217 ± 0.05	0.143 ± 0.02	0.145 ± 0.00	0.100 ± 0.00	0.103 ± 0.01
Average	0.228 ± 0.06 a	0.138 ± 0.02 a	0.129 ± 0.00 a	0.118 ± 0.02 a	0.123 ± 0.03 a
			Microporosity (m^3 m^{-3})		
0-0.05	0.176 ± 0.05	0.195 ± 0.02	0.219 ± 0.02	0.210 ± 0.01	0.204 ± 0.02
0.05-0.10	0.163 ± 0.01	0.193 ± 0.00	0.228 ± 0.00	0.254 ± 0.02	0.213 ± 0.02
0.10-0.20	0.177 ± 0.02	0.209 ± 0.02	0.220 ± 0.00	0.222 ± 0.00	0.229 ± 0.00
Average	0.172 ± 0.03 a	0.199 ± 0.02 a	0.222 ± 0.00 a	0.229 ± 0.01 a	0.215 ± 0.01 a
			Bulk density (kg dm^{-3})		
0-0.05	1.54 ± 0.13	1.72 ± 0.01	1.73 ± 0.09	1.67 ± 0.02	1.91 ± 0.04
0.05-0.10	1.55 ± 0.08	1.78 ± 0.06	1.84 ± 0.06	1.75 ± 0.06	1.92 ± 0.08
0.10-0.20	1.56 ± 0.18	1.65 ± 0.00	1.68 ± 0.02	1.79 ± 0.02	1.87 ± 0.03
Average	1.55 ± 0.13 b	1.72 ± 0.02 ab	1.75 ± 0.06 ab	1.74 ± 0.03 ab	1.90 ± 0.05 a
			Penetration resistance (MPa)		
0-0.05	2.90 ± 0.73	4.29 ± 0.87	4.04 ± 0.47	1.95 ± 0.20	4.52 ± 1.01
0.05-0.10	3.19 ± 0.79	3.93 ± 0.02	3.60 ± 0.14	2.12 ± 0.29	3.78 ± 0.22
0.10-0.20	2.55 ± 1.03	3.85 ± 1.86	3.32 ± 1.23	4.10 ± 0.13	3.31 ± 0.93
Average	2.88 ± 0.85 a	4.02 ± 0.92 a	3.65 ± 0.61 a	2.72 ± 0.21 a	3.87 ± 0.72 a

[(1)] The determination was performed with the water content retained at field capacity (-100 hPa). Average values sharing the same letter do not differ (Tukey's test $p<0.05$). T0= soil prepared in the conventional tillage; T1 and T2= two and four passes with a 4 t tractor, respectively; T3 and T4= two and four passes with a 10 t tractor.

Results and Discussion

There was no interaction between compaction treatments and the soil layers, in the LVd and LVef for the soil bulk density (BD), macroporosity, microporosity, and soil penetration resistance (PR) (Table 1). The lowest BD average value was found in the T0 (without additional machine traffic), however, it was statistically different only compared to the T4 (four passes with a 10 t tractor) in the LVd (Table 2). Even so, macroporosity in this soil was similar for all treatments.

It was verified that the increase in the number of passes and the tractor mass in both soils, LVd and LVef (Table 3) did not cause changes in the BD values for the T1 (two passes with a 4 t tractor), T2 (four passes with a 4 t tractor), T3 (two passes with a 10 t tractor) and T4. This occurs due to the first pass of the tractor on the surface layer of the soil promotes a greater compaction in comparison to the subsequent passes, since the larger pores undergo a greater degradation with the initial traffic. After that, there is the presence of a larger number of smaller pores and more resistant to soil deformation.

Table 3. Average values and standard errors of physical attributes in an Eutrustox ("Latossolo Vermelho Eutroférrico " - LVef) in different layers and compaction levels.

	LVef				
Layer	T0	T1	T2	T3	T4
m	Macroporosity (m^3 m^{-3})				
0.05-0.08	0.179 ± 0.03[(1)]	0.137 ± 0.00	0.095 ± 0.01	0.079 ± 0.01	0.077 ± 0.03
0.12-0.15	0.118 ± 0.03	0.118 ± 0.00	0.089 ± 0.01	0.095 ± 0.01	0.098 ± 0.00
0.15-0.18	0.141 ± 0.03	0.128 ± 0.02	0.124 ± 0.02	0.113 ± 0.00	0.118 ± 0.02
Average	0.146 ± 0.03 a	0.128 ± 0.00 ab	0.103 ± 0.01 ab	0.096 ± 0.00 b	0.098 ± 0.02 ab
	Microporosity (m^3 m^{-3})				
0.05-0.08	0.373 ± 0.02	0.382 ± 0.01	0.408 ± 0.01	0.405 ± 0.03	0.410 ± 0.01
0.12-0.15	0.388 ± 0.02	0.388 ± 0.00	0.410 ± 0.01	0.373 ± 0.02	0.404 ± 0.00
0.15-0.18	0.378 ± 0.00	0.382 ± 0.00	0.404 ± 0.00	0.403 ± 0.01	0.385 ± 0.01
Average	0.380 ± 0.01 b	0.384 ± 0.00 ab	0.407 ± 0.00 a	0.394 ± 0.02 ab	0.400 ± 0.00 ab
	Bulk density (kg dm^{-3})				
0.05-0.08	1.32 ± 0.08	1.36 ± 0.01	1.51 ± 0.08	1.45 ± 0.03	1.51 ± 0.07
0.12-0.15	1.42 ± 0.08	1.41 ± 0.01	1.49 ± 0.05	1.43 ± 0.02	1.40 ± 0.01
0.15-0.18	1.35 ± 0.02	1.40 ± 0.03	1.45 ± 0.02	1.45 ± 0.00	1.40 ± 0.01
Average	1.36 ± 0.06 b	1.39 ± 0.02 ab	1.48 ± 0.05 a	1.44 ± 0.02 ab	1.44 ± 0.03 ab
	Penetration resistance (MPa)				
0.05-0.08	0.83 ± 0.53	0.99 ± 0.03	2.11 ± 0.44	2.39 ± 0.53	2.99 ± 1.13
0.12-0.15	1.66 ± 0.19	1.49 ± 0.04	1.76 ± 0.53	1.91 ± 0.17	1.51 ± 0.09
0.15-0.18	1.14 ± 0.40	1.19 ± 0.45	1.23 ± 0.35	1.80 ± 0.06	1.99 ± 0.09
Average	1.21 ± 0.37 a	1.22 ± 0.17 a	1.70 ± 0.44 a	2.03 ± 0.25 a	2.16 ± 0.44 a

[(1)] The determination was performed with the water content retained at field capacity (-100 hPa). Average values sharing the same letter do not differ (Tukey's test $p<0.05$). T0= soil prepared in the conventional tillage; T1 and T2= two and four passes with a 4 t tractor, respectively; T3 and T4= two and four passes with a 10 t tractor.

Macroporosity values close to or higher than 0.10 m^3 m^{-3} were verified after tractor traffic in the LVd and LVef. This value is considered as the minimum necessary for water flowing and gaseous exchanges between the external environment and the soil, and critical for the root growth of most crops.

In the LVd, the BD average absolute values of all treatments were higher than those found in the LVef. This result is due to the mineralogy since the sand content and the particle density (2.89 Mg m^{-3}) in the LVd are higher than in the LVef. This is due to the predominance of quartz and kaolinite with massive structure, which confers lower porosity in the LVd. Despite the statistically significant increase of BD for the T4 compared to T0, at the layer of 0-0.20 m depth, in the LVd, it was not observed reducing of corn grain yield (Figure 2a). The corn yield in this soil showed a quadratic behavior as a function of BD, however, it was not significant. From the BD value of 1.73 kg dm^{-3}, the maximum yield of 5.30 t ha^{-1} decreased by 21.32% for the T4. It can be observed in Figure 1 that the development of the crop manifested agronomic changes due to the scarcity of rainfall during the 2013/14 growing season. Rainfall was only 291 mm from January to March 2014 (Figure 1) and probably resulted in water stress.

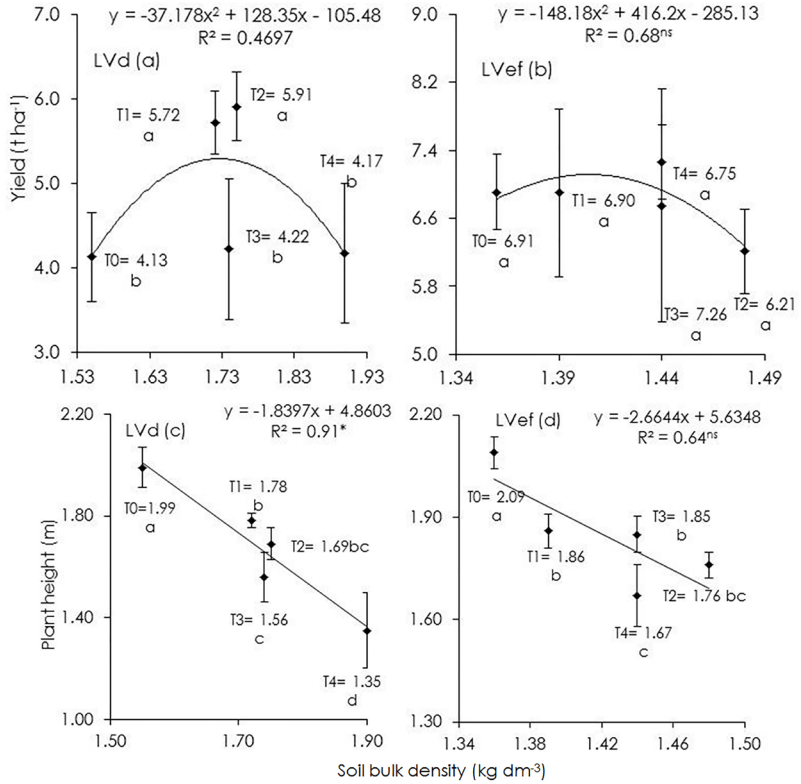

Figure 2. Correlation between soil bulk density, and corn yield, and plant height in an LVd and an LVef. (a, b, c, and d). The bars refer to the standard errors of the means. * Significant ($p < 0.05$) and ^{ns}: non-significant.

In the same way as in the LVd, changes in the BD and PR in the LVef were not justified in relation to corn yield (Tables 2 and 3), mainly in relation to the inferiority of BD in the T0 compared to the T2. It was estimated that when the BD in the LVef reached 1.40 kg dm^{-3}, the maximum yield was 7.12 t ha^{-1} and from that point it was observed an increase of 1.97% and a decrease of 12.78% of yield in the T3 and T2, respectively, despite the non-significant behavior of the regression for these parameters. Observing the absolute values, the crop yield in the LVef showed a greater expression than in the LVd. This occurred due to the higher organic matter content and clay content in the LVef, which favored a greater water adsorption. The corn height showed a linear negative response to the BD in both soils. The T0 showed the best performance, although the coefficient of determination (R^2) was significant only for the LVd condition. Therefore, there is an indication that the plants that received additional compaction found limitations for growing compared to the treatments under conventional tillage.

The coefficients of determination indicate that the water retention curve explained 66 and 84% of the water content (θ), and the soil penetration resistance curve explained 78 and 75% of the PR for the LVd and LVef, respectively (Table 4). The least limiting water range (LLWR) values corresponding to the gray-hatched area in the graphic (Figure 3). The LLWR in the LVef was higher than in the LVd (Figure 3). It was observed a reduction of the LLWR as the BD values increase, as already stated by Silva et al. (1994) and Blainski et al. (2012). The θ and the RP (Table 4) were negatively correlated with the matric potential and positively with the BD, due to the negative sign of the parameters c and e, and the positive sign of the parameters b and f, of each equation in the LVef and LVd. On the other hand, the behavior in the LVd was discordant with respect to the e and f coefficients.

The upper limit of the LLWR (Figure 3) was the water content in the field capacity (θ_{FC}) in the LVd, until PR becomes limiting in the LVd (θ_{PR}). The effect of RP on the LLWR (gray-hatched area) evidences the process of soil physical

Table 4. Soil water retention curve and soil penetration resistance curve for an LVd and an LVef at the layer of 0-0.20 m depth for different agricultural management systems.

Soil	Soil water retention curve	Soil penetration resistance curve
LVd	$\theta = -2{,}18591Bd^{0{,}96151}\psi^{-0{,}07325}$ $R^2=0{,}66^{**}$	$PR = -5{,}27041\theta^{4{,}71292}Bd^{-2{,}39073}$ $R^2=0{,}78^{**}$
LVef	$\theta = -1{,}40337Bd^{0{,}78836}\psi^{-0{,}08478}$ $R^2= 0{,}84^{**}$	$PR = -3{,}98142\theta^{-1{,}42965}Bd^{10{,}03552}$ $R^2=0{,}75^{**}$

** significant at 1%.

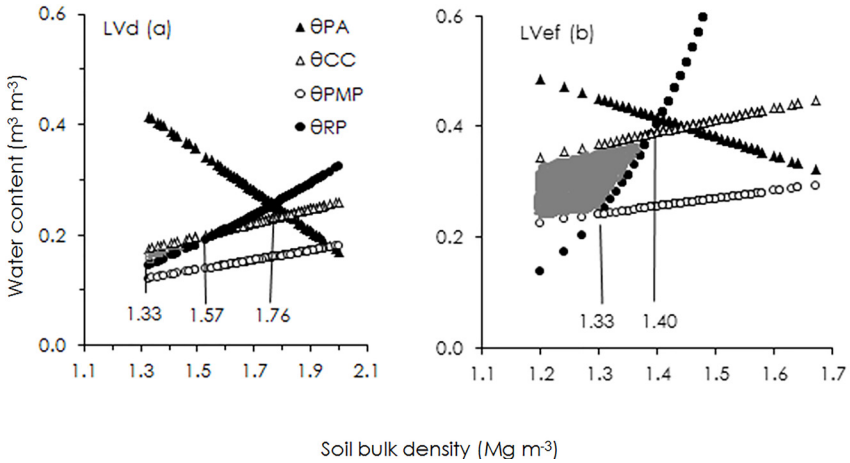

Figure 3. Soil water content (θ) as a function of soil bulk density in an LVd (a), and an LVef (b), for critical limits of aeration porosity (θ_{AP}), field capacity (θ_{FC}), permanent wilting point (θ_{PWP}) and soil penetration resistance (θ_{PR}). RPc of 2 MPa at the layer of 0-0.20m depth. The least limiting water range (LLWR) values corresponding to the gray-hatched area.

degradation since it starts to restrict the water range where the roots can grow and develop within the available water range (Cavalieri et al., 2011). Using the critical PR of 2 MPa in the LVd, the LLWR lower limit was the θ_{PR}. While in the LVef this limit showed the water content at the permanent wilting point (θ_{PWP}) only for BD values ≤ 1.33. Since, from values higher than these, the θ_{PR} has become the LLWR lower limit. Thus, in the LVef there is a more restricted amplitude of BD compared to the LVd. It indicates that the higher the BDc, the less chance the plant will remain under stress conditions.

The restriction of θ_{PR} in the LVd occurs in BD ranging from 1.33 to 1.57 Mg m^{-3} and coincides with the beginning of the LLWR limit in the condition of BD = 1.83 Mg m^{-3}. For the condition in the LVef, this impediment occurred in BD ranging from 1.33 to 1.40 Mg m^{-3}. While for the condition in the LVd only the T4 showed restriction.

Regardless of the soil class, the available water content (AWC = θ_{FC} - θ_{PWP}) was always higher than the LLWR, which characterizes the soils as physically degraded. Due to such behavior, Silva et al. (1994) point out the LLWR as a tool for analysis of soil structure more sensitive than the concept of available water. In general, in managed soils, LLWR is limited in the upper limit by the θ_{FC} and in the lower limit by the θ_{PR} as verified by Guimarães et al. (2013) in a sandy loam LVd. These authors affirmed that it was considered the LLWR lower limit for the entire range of BD, excepted for the native forest. In this study, this behavior did not occur in the LVef.

The LLWR amplitude in the LVd ranged from 0.01 to 0.04 m^3 m^{-3} and in the LVef ranged from 0.03 to 0.13 m^3 m^{-3}. The difference of this amplitude was 0.03 m^3 m^{-3} in the LVd and 0.10 m^3 m^{-3} in the LVef. The amplitude values of the LLWR were similar to those found by Blainski et al. (2012), who verified a variation of 0 to 0.11 m^3 m^{-3}, which is characteristic of the textural class of red Oxisols.

A similar condition of the LLWR variation in the LVd found in the present study was also verified by Lima et al. (2015) in an Oxisol

(607 g kg^{-1} clay content) with 0-0.04 m^3 m^{-3} water content in the PRc of 2 MPa at the layer of 0-0.20 m depth. According to the results, tractors-induced pressures on the soils led to a soil structure degradation process. Narrower LLWR range found in the LVd compared to that found in the LVef in this present study reaffirms the comment by Neves Jr. (2013) that the range in which the soil water content can vary without any restrictions related to the availability of water, aeration porosity and soil resistance to root penetration is narrow.

BDc is influenced by soil management and has an inverse relationship with soil clay content (Reichert et al., 2009), as evidenced in this study. In an integrated crop–livestock systems, Fidalski et al. (2013) observed in a sandy/medium texture LVd with PRc equal to 2.5 MPa, that the BDc values were 1.66, 1.64 and 1.62 Mg m^{-3} at the layers of 0-0.10; 0.10-0.20, and 0.20-0.30 m depth, respectively. In a medium texture LVd submitted to different compaction conditions at the 0.30 m depth, Freddi et al. (2009) found 1.46 Mg m^{-3} BDc after using PRc of 2.15 MPa. A similar situation was observed by Pereira et al. (2010), who verified BDc values of 1.43 Mg m^{-3} for conventional tillage and values higher and lower than 1.43 Mg^{-3} for different no-tillage systems, in a medium texture LVd at the 0.20 m depth with 2 MPa PRc. The difference in BDc can also be attributed to the soil class, according to Romero et al. (2014) who found BDc of 1.62 to 1.38 Mg m^{-3} in a clayey LVd and in a very clayey Oxisol ("Latossolo Vermelho Amarelo" - LVA), respectively, at the layer of 0.40-0.60 m depth with PRc of 1 MPa.

The restriction for the penetration resistance in the LVd occurred from 1.33 Mg m^{-3} BD value and coincides with the starting of the LLWR limit. In the LVd, all treatments with additional compaction showed limitations imposed by field capacity, since their BD values were higher than 1.57 Mg m^{-3}. In the LVd, all treatments with additional compaction showed limitations imposed by field capacity since their BD values were higher than 1.57 Mg m^{-3}. In the T0 for the LVef, there would be a restriction for the PR, independently of the water content that remained in the field capacity, since the BD values were lower than 1.40 Mg m^{-3}.

Therefore, the management of the machines during the implementation of the treatments in the LVd resulted in severe restrictions to the LLWR, added to the low rainfall, resulting in low corn yield. Thus, the choice of the application of the treatments submitted to the LVd provided physical degradation in this soil by increasing its BD and PR. The LLWR in the LVd is small, on the other hand, the BD values already start at 1.30 Mg m-3 and increase to extreme values. Thus, in most samples the LLWR was zero, that is, the condition is not ideal for plant growth. The treatments T0 and T1 in the LVef are considered tolerable, according to the LLWR values (Table 3). The use of less favorable managements to the growth and development of the corn crop in the LVd and LVef areas should be avoided in order not to compromise the soil structure. Since, the practice of subsoiling for the soil decompaction has a high operational cost and high energy demand (Cortez, 2013). In summary, reducing soil compaction is vital to ensure high LLWR values in agricultural management systems, because an increase in soil bulk density requires high soil water content to maintain soil resistance under non-limiting cultivation conditions (Souza et al., 2015).

Thus, the results of this study indicate that the LLWR is efficient in detecting unfavorable conditions to crop development and corroborates the recommendations of Blainski et al. (2012). These authors state that the LLWR is a robust indicator of the physical quality of agricultural soils. In addition to this, the LLWR is considered a well-established index to assess the quality of cultivated soils (Cavalieri et al., 2011). Therefore, the results of this study agree with the results of several authors who emphasize that the LLWR is a more sensitive parameter than the soil water retention curve to evaluate changes in soil structure (Roque et al., 2011; Silva et al., 2011 e Guedes Filho et al., 2013).

Conclusions

The treatments submitted to the LVd provided physical degradation by increasing BD and PR, added to lower clay and organic matter content of this soil comparing to the LVef.

The determination of the LLWR was efficient and complementary for identifying more favorable or more impeditive conditions to the compaction in the LVef for the corn crop development in relation to the LVd.

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