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Correlation of the least limiting water range with soil physical attributes, nutrient levels and soybean yield

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In soils that are compacted or undergoing compaction, the interval of water available to the plants can decline to zero, which according to the least limiting water range (LLWR) method is called the critical soil bulk density ($Bd_{critical}$), when LLWR = 0. The aim of this study was to determine the LLWR of a highly clayey typic dystrophic Red Latosol (Oxisol) and to correlate it with the soil physical attributes, nutrient levels and soybean yield, because hypothetically if there is a negative correlation, the use of the LLWR associated with spatial variability maps can help reach decisions regarding intervention or modification of soil management. We observed that in no-till farming, limitation of plant development can occur as the soil dries out, mainly due to the higher resistance to mechanical penetration. Besides this, we found that the $LLWR_{0-0.10m}$ and $LLWR_{0.10-0.20m}$ values were correlated in greater numbers with macronutrients and micronutrients analyzed, and also with the land slope, compared the correlation with the soybean yield data. Therefore, nutritional analysis of the grains complemented by physical analysis of the soil can be used to identify nutritional imbalances that are not otherwise observable and thus, the LLWR can be useful for planning corrective actions regarding soil and crop management, based on measurement of the $Bd_{critical}$.

Key words: No-tillage system, no-till farming system, soil physical quality indicator, spatial variability of soil water content.

INTRODUCTION

Soybean growing is of great socioeconomic importance in Brazil and has been expanding particularly in the Cerrado (savanna) biome, where in 1990s farmers started shifting to no-till planting with precision techniques instead of traditional farming methods, to reduce the need for inputs. However, no-till farming can cause problems of subsurface soil compaction and erosion (Altmann, 2010). Although these problems have been ameliorated through improved techniques, other problems can also occur due to the rapid decomposition of crop residues and the relative lack of economically feasible options for crop rotation. These drawbacks can

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hamper efforts to mitigate excessive compaction of the surface layer, which is one of the main hindrances to water availability to plants (Hamza and Anderson, 2005).

To maximize crop yields, the water in the soil must be maintained within optimal parameters (Rejani and Yadukumar, 2010; Benjamin et al., 2014). However, in soils that are compacted or undergoing compaction, the interval of available water to plants can narrow to zero in function of low aeration under inefficient drainage conditions and increased mechanical resistance to penetration as the soil dries out (Araújo et al., 2013; Moreira et al., 2014). This interval is called the least limiting water range (LLWR) (Silva et al., 1994). Determination of this range involves calculation of the critical soil bulk density ($Bd_{critical}$), when LLWR = 0. This value can hypothetically be used with other information to monitor the physical quality of the soil, also considering the correlation with the particular parameters for each crop (Klein and Camara, 2007; Benjamin et al., 2014).

In this respect, the aim of this study was to determine the LLWR of a highly clayey typic dystrophic Red Latosol (Oxisol) and to correlate it with the soil physical attributes, nutrient levels and soybean yield.

MATERIALS AND METHODS

The study was conducted on a farm in the municipality of Diamantino, Mato Grosso, at 14°07'0" S latitude and 56°58'39" W longitude, at an altitude of 539 m. The region's climate is Aw according to the Köppen classification, with well-defined seasons: rainy (October to April) and dry (May to September). The average yearly rainfall is 1,816.9 mm and the average annual temperature varies from 16.2 to 25.5°C. The soil in the experimental field is classified as highly clayey typic dystrophic Red Latosol (Oxisol), "A" moderate horizon, developed under semideciduous tropical forest, with flat relief (Santos et al., 2013). The forest was cleared in 1987 and rice was planted that same year (for harvest in 1988). After this crop, soybeans and corn were grown in succession until the 1999-2000 growing season, with the soil being mobilized by harrowing to a depth of 0.20 m every three years plus fertilization in the furrow. From the 2000-01 to the 2003-04 growing seasons, cotton was cultivated, followed by soybeans and corn in succession again until 2013-2014, but now without tillage, during which period lime and fertilizers were applied as side dressing. For this study, we evaluated the 2013-2014 soybean crop (*Glycine max* L.), Monsoy 7639 RR cultivar, in an experimental plot covering approximately 12 ha (300 by 405 m) out of 56 ha field planted with spacing of 0.45 m between rows and an average of 15 plants per linear meter. The sowing occurred on October 23, 2013 and the plants were harvested on February 5, 2014.

Undeformed soil samples were obtained at the end of the phenological stage of the crop (R7.2), using an Uhland auger to bore holes in the 0-0.10 m and 0.10-0.20 m layers for insertion of stainless steel cylinders (50 mm in diameter by 50 mm in height), to include the profile exploited by soy roots. The sampling layout was in an irregular mesh due to deviations of the level curves, oriented between the crop rows, with a total of 117 collection points for each layer. These points were georeferenced with maximum vertical and horizontal error of 5 mm using a Topcon HiPer® Pro GPS device. In the laboratory these samples were saturated with distilled water and submitted to different matrix potentials, using 14 repetitions: 2, 6 and 10 kPa, using a sandbox (Eijkelkamp Agrisearch Equipment, model 08.01), and pressures of 33, 66, 100, 300 and 1500 kPa, using a pressure plate extractor (Soilmoisture Equipment Corp. model 1500F1®), to determine the curves of water retention and penetration resistance, and consequently the LLWR (Moreira et al., 2014). After reaching the water balance at each potential, the samples were weighed on a scale with accuracy of 0.01 g and then transferred to an electronic bench penetograph operating at constant penetration velocity of 10 mm min^{-1} (0.1667 mm s^{-1}), with a load cell having nominal capacity of 196.13 N (20 kgf), shaft with cone of 3.7407 mm in diameter and semiangle of 30º. The device was connected to a computer to record the readings (Bianchini et al., 2013). Then, the samples were dried at 105°C for 48 h to calculate the bulk density (Donagema et al., 2011).

To determine the soil water retention curves and soil resistance to penetration, and consequently the LLWR followed the procedures described in Moreira et al. (2014). The lower limit of the LLWR was defined by considering the moisture corresponding to the permanent wilting point based on water tension of 1500 kPa (Silva et al., 1994) and the soil penetration resistance at a limiting value of 2.0 MPa (Silva et al., 1994). In turn, the upper limit was determined by the water content value related to the field capacity at tension of 10 kPa (Silva et al., 1994) and by aeration porosity of 10% (Silva et al., 1994).

The microporosity values were determined by the difference between the moist mass of the sample at tension equivalent to a 60 cm water column and the dry mass after the sample was dried in an oven at 105°C for 48 h. This difference was then multiplied by the soil bulk density. Next we determined the total soil porosity of the samples based on the respective particle density values of each sampling point. Finally, we measured the macroporosity by the difference between the total porosity and microporosity. From the deformed samples, we determined the percentages of sand, silt and clay by the pipette method, using a shaker table for 16 h to accelerate dispersion of the particles, and also measured the quantity of organic matter by the oxidation method with potassium dichromate and colorimetric measurement (Donagema et al., 2011).

The soybean yield (kg ha^{-1}) was estimated by harvesting plants along 4 linear meters at each sampling point, with the bean moisture corrected to 14%. Then we determined the levels of N of grains by acid digestion, distillation and titration – Kjeldahl method, as well as P, k, Ca, Mg, S, Zn, Cu, Fe, Mn and B by simultaneous multi-element measurement by inductively coupled plasma atomic emission spectrometry, or ICP-AES (Silva, 2009).

All the data were normally distributed according to the Shapiro-Wilk test ($P > 0.05$). We then calculated the pairwise bivariate correlations between the LLWR, soil bulk density, land slope and levels of macronutrients, micronutrients and the soybean grain yield by the Pearson and t-tests ($\alpha = 0.05$), utilizing the Sigma Plot Version 12.5 software, considering the 117 data pairs from each soil layer. Besides this, we analyzed and modeled the spatial structure of the LLWR by the method of ordinary kriging, in 2 × 2 m blocks (Yamamoto and Landim, 2013). The semivariogram model was fitted using the Gamma Design GS^{+TM} software: Geostatistics for the Environmental Sciences, version 10.0.

RESULTS AND DISCUSSION

At 5% probability, the adjustments explained over 90% of the soil volumetric moisture (θ) and more than 76% of the penetration resistance (PR), with mean residual standard error of at most 3.63% for θ, considering the mean total porosity value of each soil layer (0.51 for 0-0.10 and 0.47 m^3 m^{-3} for 0.10-0.20 m), and at most of 17.60%, considering the PR value of 1 MPa (Table 1). Besides this, the signs of the coefficients (negative or positive)

Table 1. Equations for fitting the water retention and mechanical penetration resistance curves.

Layers (m)	Equations [1]	F-test	R^2	SER
	Soil water retention curves			
0-0.10	θ = 0.452484***. │Ψ│-0.091415***. Bd0.367267***	P < 0.0001	0.9262	0.0186
0.10-0.20	θ = 0.359406***. │Ψ│-0.073829***. Bd0.709454***	P < 0.0001	0.9400	0.0131
	Soil penetration resistance curves			
0-0.10	$PR = 0.021079^{*}. \theta^{-3.411566^{***}}. Bd^{5.497318^{***}}$	P < 0.0001	0.7944	0.1760
0.10-0.20	$PR = 0.0011860^{*}. \theta^{-5.3030664^{***}}. Bd^{6.4934087^{***}}$	P < 0.0001	0.8418	0.1510

[1] ***(P < 0.0001), *(P < 0.05) = significant at 5% probability by the t-test; θ = volumetric moisture (m^3 m^{-3}); |Ψ| = matrix potential (kPa); Bd = soil bulk density (Mg m^{-3}); PR = soil penetration resistance (MPa); R^2 = coefficient of determination; SER = standard error of residuals for 109 degrees of freedom.

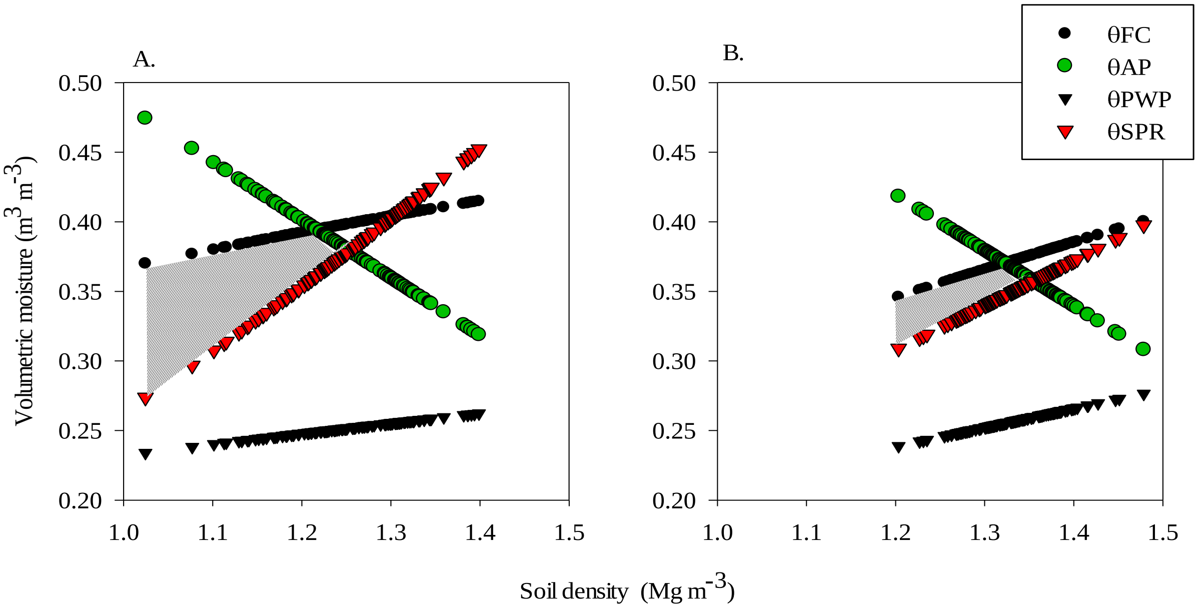

Figure 1. Volumetric moisture in function of soil bulk density at depths of 0-0.10 (A) and 0.10-0.20 m (B), with the gray shaded area representing the LLWR, considering the limits of field capacity (θFC), aeration porosity (θAP), permanent wilting point (θPWP) and mechanical penetration resistance (θSPR).

were in agreement with the theoretical signs (Araújo et al., 2013).

Based on the fitted data, we plotted graphs and observed that with increasing soil bulk density, the volumetric moisture equivalent to the critical levels of penetration resistance (θPR = 2.0 MPa) determined the largest portions of the lower limits of the LLWR (Figures 1A and B).

However, the impact of the θPR on reducing the LLWR was greater. This finding is in line with the hypothesis that as soils that are compacted or undergoing compaction dry out, this can limit plants' development, mainly due to the higher soil resistance to penetration (Collares et al., 2006; Safadousta et al., 2014). This greater influence of the θPR_{limit} in determining the LLWR has been reported for different soil classes (Collares et al., 2006; Klein and Camara, 2007; Araújo et al., 2013; Moreira et al., 2014; Safadousta et al., 2014).

In this respect, to check for a possible relation between the LLWR and the soil attributes and plant parameters, we carried out a correlation analysis (Table 2). Although the soybean yield was only correlated with the level of phosphorous and manganese in the beans, the $LLWR_{0-0.10\ m}$ and $LLWR_{0.10-0.20\ m}$ values were correlated in greater numbers with macronutrients and micronutrients analyzed.

During the growing cycle, events can occur, such as excess or deficit of water in the layer exploited by the roots, even for short periods, that can upset the balance of mobility, absorption and transport of nutrients in the soil-plant system (Gregory, 2006), as well as increase the availability of iron (Becker and Asch, 2005) and

Table 2. Pearson correlation coefficients between the variables.

Variables	Yield	LLWR_10	LLWR_20	Bd_10	Bd_20	Slope
Yield of grains()kg ha^{-1}	1					
LLWR _10 (m^3 m^{-3})	0.01	1				
LLWR _20 (m^3 m^{-3})	0.04	0.22*	1			
Bd _10 (Mg m^{-3})	-0.11	-0.79***	-0.15	1		
Bd _20 (Mg m^{-3})	-0.03	-0.18	-0.94***	0.16	1	
Slope (m)	-0.04	-0.23*	-0.26**	0.03	0.25*	1
N (g kg^{-1})	0.14	-0.09	0.02	-0.03	0.02	0.09
P (g kg^{-1})	0.28**	-0.29**	-0.03	0.04	0.05	0.28**
K (g kg^{-1})	0.04	0.25**	0.27**	-0.09	-0.20*	-0.42***
Ca (g kg^{-1})	0.06	0.04	0.28**	0.03	-0.22*	-0.35**
Mg (g kg^{-1})	0.08	-0.19	0.24*	0.05	-0.16	-0.11
S (g kg^{-1})	0.08	-0.22*	-0.17	0.08	0.17	0.33**
Zn (mg kg^{-1})	-0.06	-0.32**	-0.13	0.14	0.18	0.42***
Cu (mg kg^{-1})	-0.06	0.06	0.26**	0.03	-0.29**	-0.31**
Fe (mg kg^{-1})	0.05	0.15	-0.05	-0.13	0.06	-0.06
Mn (mg kg^{-1})	-0.24*	0.23*	0.00	-0.06	0.03	-0.10
B (mg kg^{-1})	0.10	-0.11	-0.01	0.03	0.01	0.19*

(1) *** ($P < 0.0001$), ** ($P < 0.01$), * ($P < 0.05$) = significant at 5% probability by the t-test.

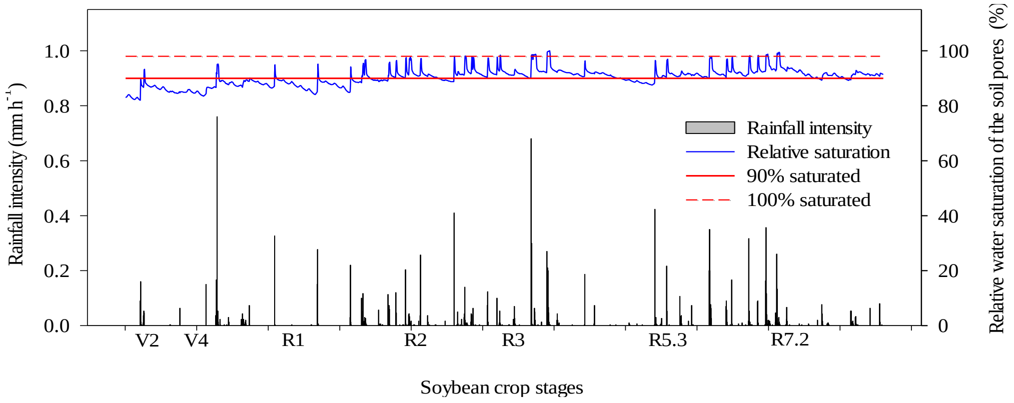

Figure 2. Rainfall intensity versus relative water saturation of the soil pores in the 0 to 0.20 m layer. Remark: The data were obtained every 5 min by sensors and recorded at an automatic weather station (HOBO® U30), located in the center of the experimental unit.

manganese (Millaleo et al., 2010). These elements can accumulate in the plant biomass, reaching toxic levels. In this study, we found that approximately 60% of the soil moisture measurements in the layer exploited by the root system were at below the critical limit of under 10% of free porosity for gas exchange, especially in the grain-filling phenological stage (Figure 2). This is a possible explanation for the negative correlation between the manganese level and soybean yield, not least because the Mn and Fe levels in the grains correlated positively (r = 0.32; P < 0.01) (Table 2).

With respect to the positive correlation between the level of phosphorus and the soybean yield, since the phosphate fertilization was applied as side dressing instead of incorporated in the layer used by the root system, latent deficiency in the uptake of this element by the plants might have occurred, without visible symptoms yet (Table 2). It is known that oxisols contain large amounts of more weathered minerals, such as kaolinite and iron and aluminum oxides, and also that phosphorus forms chemical bonds in the form of orthophosphate ions, especially $H_2PO_4^-$, with iron, aluminum and calcium. These bonds increase the adsorption and reduce the solubility of the phosphorus applied as fertilizer as time passes (Raij, 2011). Besides this, since the adsorption of phosphorus occurs by diffusion, resulting from the depletion of the element around the root system, the greater the extent and area of the root system (if the soil properties are adequate), the higher will be probability of phosphorus uptake (Raij, 2011). In light of this, the mentioned correlation might be due to the fact that most of the phosphate from fertilization was not available to the roots, or losses might have occurred due to surface runoff. Approximately 3% of the soil moisture measurements were above 100% of the total porosity, even during the grain-filling phenological stage (Figure 2). This result together with the negative correlation between phosphorous level and land slope can indicate loss of phosphorus by surface runoff, although the land slope is 2% only, (Table 2). Therefore, nutritional analysis of soybeans can be used to plan corrective actions.

Each nutrient has a unique mobility, uptake and transport pattern in the soil-plant system. These parameters are affected by the particular farming practices and edaphoclimatic factors (Kerbauy, 2012). Among the variables that influence the uptake of nutrients by plants, adequate water content in the soil is the most important. This factor, along with the atmospheric demand for water vapor, is the main cause of nutrient transfer from the soil to the roots (Gregory, 2006; Kerbauy, 2012). Besides this, since the LLWR is modeled with other parameters besides soil bulk density that also affect the development of plants, the LLWR is more sensitive to identify the variability of water readily available to plants. This explains the larger number of correlations found with the levels of nutrients in the soybeans (Table 2).

It was observed that the LLWR of each layer simultaneously correlated only with the level of potassium (K) of the grain and the land slope. In addition to this result, while the LLWR$_{0\text{-}0.10\ \text{m}}$ was positively correlated with manganese (Mn) and negatively with phosphorus (P), sulfur (S), zinc (Zn); the LLWR$_{0.10\text{-}0.20\ \text{m}}$ correlated positively with only calcium (Ca), magnesium (Mg) and copper (Cu) of the grains (Table 2). According to a nutrient's mobility in the soil, its uptake occurs preferentially by mass flux, root interception or diffusion. The ions K^+ and Cu^{2+} are preferentially absorbed by the roots via the diffusion process while the ions Ca^{2+} and Mg^{2+} are preferentially absorbed by mass flux. Therefore, it is not enough for these elements to be present in adequate concentrations in the soil. For good plant nutrition, it is essential for the flow of water in the soil to be sufficient to dissolve these nutrients so they can be carried to the roots (Kerbauy, 2012). Therefore, as broadcast application of lime and fertilizer began to be applied was 10 years, the expansion of the LLWR$_{0.10\text{-}\ 0.20\text{m}}$ based on its positive correlation with Ca, Mg and Cu of grains can benefit a greater absorption of these nutrients by plants. Already the proportional ratio of k of grains with the LLWR the evaluated layers can be explained by the probability of k suffer leaching in the soil profile (Raij, 2011).

On the negative correlations with LLWR$_{0\text{-}\ 0.10\text{m}}$, in the case of sulfur (S) in the form of the anion SO_4^{2-}, the same is susceptible to leaching under conditions of greater water availability, because, in Oxisols, may predominate negative charges at pH 6 to 6.5. Knowing this, it is important to highlight the positive correlations between grain nutrient levels between P and S (r = 0.29; $P < 0.01$), P and Zn (r = 0.47; $P < 0.0001$), and Zn (r = 0.39; $P < 0.0001$). It is also important to report that, while the LLWR$_{0\text{-}\ 0.10\text{m}}$ was negatively correlated with the P of grains, unlike the P was positively correlated with grain yield; while the LLWR$_{0\text{-}\ 0.10\text{m}}$ was positively correlated with Mn of grains, unlike the Mn was negatively correlated with grain yield (Table 2).

Furthermore, there was no correlation of boron grains with grain yield and the LLWR, but there was a positive correlation between the levels of B and P in grain (r = 0.21; $P < 0.05$), B and Zn (r = 0.22; $P < 0.05$). As the absorption of phosphorus plant in $H_2PO_4^-$ or $H_2PO_4^{2-}$ and Zn^{2+} depends on the boron level available in the soil solution, there may be an imbalance in this sense (Raij, 2011). In addition, there was a positive correlation of P, S, Zn and B of the grains with the terrain slope, but the reverse with the LLWR (Table 2). Therefore, the negative correlation of P and Zn may be related to deficiency of B, since P and Zn are most adsorbed on the soil (Raij, 2011). Hence, it is important to complement analyses of the plants with soil analyses, to provide more information to plan corrective actions when there are undesirable correlations that can cause declining yield with time, such as the pairwise correlations between the LLWR, land slope and nutrient levels in the soybeans, as phosphorus and manganese levels of the soybeans.

A reasonable portion of the samples had bulk density values above Bd$_{\text{critical}}$, namely 50 and 34% at depths of 0-0.10 m (Bd$_{\text{critical}}$ = 1.26 Mg m^{-3}) and 0.10-0.20 m (Bd$_{\text{critical}}$ = 1.36 Mg m^{-3}), respectively. In light of these aspects, visualization of this variability in space can support decisions to intervene of modify the soil management. Therefore, we fitted the semivariograms of the unitary data from the LLWR$_{0\text{-}0.10\ \text{m}}$ and LLWR$_{0.10\text{-}0.20\ \text{m}}$ values and obtained the following results: (i) Lower semivariogram range values in the surface layer, indicating less heterogeneity of the 0-0.10 m layer; and (ii) High degree of spatial dependence, that is, the LLWR presented strong spatial continuity with almost no nugget effect, referring to the percentage of unexplained variance (Table 3).

We then interpolated and cross-validated the data. It is important to note that very few studies have been published providing cross-validation results of interpolation by Kriging. Here we obtained satisfactory linearity ($r \approx 0.50$), low explanation ($R^2 \approx 0.25$), but estimated error acceptable, and the models were significant for both soil layers ($P < 0.05$ by the F-test) (Table 4).

Therefore, as the linear regressions were significant at

Table 3. Parameters obtained by fitting the semivariogram to the LLWR in the soil layers.

Layer (m)	Parameters [1]						R^2	N
	Model	C_o	$C_o + C$	$C/ C_o + C$	*A*	SDD		
0-0.10	Esférico	0.000010	0.003920	0.997	28.00	High	0.51	112
0.10-0.20	Exponencial	0.000001	0.000437	0.998	63.90	High	0.89	113

[1] C_O = nugget effect, C = level, A = range (m), SDD = spatial dependence degree, N = number of data points used in the adjustment, with exclusion of biased points from the 0.10-0.20 m layer.

Table 4. Cross-validation of the interpolation of the LLWR in the soil layers.

Layer (m)	Intercept	Coeficient	N [1]	r	R^2	P Teste F	EPE	TVC[2]
	y0	*a*						
0- 0.10	0.006^{ns}	0.344***	108	0.558	0.311	< 0.0001	0.033	0.5030
0.10- 0.20	0.006^{ns}	0.244***	113	0.475	0.226	< 0.0001	0.010	0.0509

[1] N = number of pairs of data points used to fit the model; [2] CVT = constant variance test by Spearman correlation (P > 0.05). *** (P < 0.0001), ^{ns} = not significant (P > 0.05) by the t-test.

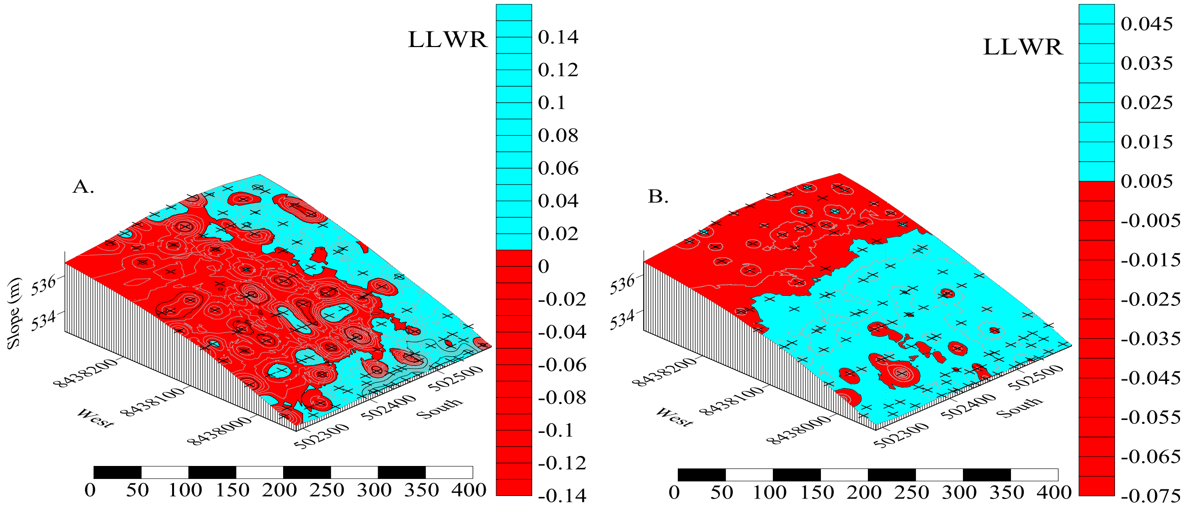

Figure 3. Two-dimensional maps obtained by ordinary kriging, in 2 × 2 m blocks, for the $LLWR_{0-\ 0.10m}$ (A) and $LLWR_{0.10-\ 0.20m}$ (B). note the crosses on the maps indicate the sampling points.

the 5% level of probability by F test, the statistical models were accepted. Then, it was generated maps of the spatial variability of the LLWR for the layers evaluated based on data interpolation by kriging at regular intervals of 0.5 by 0.5 m, considering the separation limit of the bulk density, when the LLWR = 0. Thus, it was found that the spatial correlation analysis was important because it allows to view the area ratio of those values LLWR, wherein Bd > $Bd_{crtical}$, where we observed greater range of LLWR values in topsoil (Figure 3).

The reasons for the appearance of these areas less favorable to plant water availability can be associated with the past traffic or more frequent maneuvering of farm machinery in this region, possibly causing leftover compacted subsurface layers not eliminated with implementation of the no-tillage system. This hypothesis is supported by the positive correlation of the soil bulk density in the 0.10-0.20 cm layer with higher land slope (Table 2). Another possible explanation is the inherent variations of the surface layer, or variations induced by farming practices in past years, such as the pore size or granulometry (Table 5).

We observed that while the $LLWR_{0-0.10m}$ and $LLWR_{0.10-0.20m}$ values were positively correlated with the content of sand and macropores in the soil, the land slope was negatively correlated with these attributes. Furthermore,

Table 5. Pearson correlation coefficients between the variables.

Variable	LLWR_10	LLWR_20	Slope
LLWR_10 (m^3 m^{-3})	1		
LLWR_20 (m^3 m^{-3})	0.22*	1	
Slope (m)	-0.23*	-0.26**	1
Organic matter (g dm^{-3})	-0.06	0.00	0.16
Sand content, 0 to 0.10 m, g kg^{-1})	0.10	0.20*	-0.26**
Clay content, 0 to 0.10 m, g kg^{-1})	-0.07	-0.15	0.24*
Silt content, 0 to 0.10 m (g kg^{-1})	-0.08	-0.11	0.06
Sand content, 0.10 to 0.20 m(g kg^{-1})	0.23*	0.17	-0.31**
Clay content, 0.10 to 0.20 m (g kg^{-1})	-0.15	-0.16	0.30**
Silt content, 0.10 to 0.20 m (g kg^{-1})	-0.13	-0.02	0.04
Macropores, 0 to 0.10 m (m^3 m^{-3})	0.63***	0.07	-0.08
Macropores, 0.10 to 0.20 m (m^3 m^{-3})	0.08	0.70***	-0.37***
Micropores, 0 to 0.10 m (m^3 m^{-3})	-0.32**	0.01	0.21**
Micropores, 0.10 to 0.20 m (m^3 m^{-3})	0.08	-0.42***	0.35**

(1) *** ($P < 0.0001$), ** ($P < 0.01$), * ($P < 0.05$) = significant at 5% probability by the t-test.

while the $LLWR_{0-0.10m}$ and $LLWR_{0.10-0.20m}$ values were negatively correlated with the content of clay and micropores in the soil, the land slope was positively correlated with these attributes (Table 5). Therefore, the reason for the increase in the LLWR values inversely with land slope is best explained by the soil porosity and granulometry. Since it is not possible to change the soil texture, corrective actions or changes in the production system should be carried out to balance the macro and micropores in the soil as well as the nutritional equilibrium of the soybeans, especially phosphorus and manganese of grains because both correlated with grain yield (Tabela 2). Therefore, it is possible to use the critical soil bulk density ($Bd_{critical}$) value, when LLWR = 0, as a limit for monitoring soil physical quality.

Conclusions

1. There was greater mechanical penetration resistance of the soil (θPR = 2.0 MPa), and thus a narrower least limiting water range (LLWR), in drier soil. Therefore, in no-till farming the main limiting factor to plant development as soil dries out is resistance to penetration.
2. Although the soybean yield was only correlated with the level of phosphorus and manganese in the grains, the $LLWR_{0-0.10m}$ and $LLWR_{0.10-0.20m}$ values were correlated in greater numbers with of the macronutrients and micronutrients analyzed, and also with the land slope. In light of this, nutritional analysis of the grains complemented by physical analysis of the soil can be used to identify imbalances not otherwise spatially apparent and to plan corrective actions in soil and crop management, based on the critical bulk density value ($Bd_{critical}$), when LLWR = 0.

Conflict of Interest

The authors have not declared any conflict of interest.

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