Revista Ciência Agronômica, v. 53, e20207533, 2022
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Scientific Article
ISSN 1806-6690

Critical limits of soil physical attributes for corn and black oat in a Xanthic Hapludox[1]

Limites críticos dos atributos físicos do solo para milho e aveia preta em um Latossolo Bruno

Eloi Bareta Junior[2], Aline Marques Genú[3], Leandro Rampim[4], Renan Caldas Umburanas[2], Cristiano Andre Pott[4]*

ABSTRACT - Soil compaction can decrease potential crop yield and is frequently found in no-till cultivation systems, but there is little information on the critical limits of soil physical properties in these conditions, especially in subtropical soils. The objectives of this study were to evaluate the influence of tractor traffic on soil physical properties and identifies critical limits of soil bulk density, soil compaction degree, macro, and microporosity on crop yield of corn and black oat assessed in situ in a Xanthic Hapludox in Southern Brazil. Tractor machine traffic (0, 2, 5 and 20 passes) was established in no-till soil to create different soil compaction levels. Undisturbed soil samples were collected at depths of 0.00-0.05, 0.07-0.12 and 0.17-0.22 m just after tractor traffic in two moments: before corn cultivation, and then before black oat cultivation. Under the conditions of this experiment, the 10% higher yields of corn and black oats were obtained with macroporosity above 0.10 $m^3 m^{-3}$ and 0.13 $m^3 m^{-3}$, respectively. Similarly, the soil compactness degrees of 90% and 86% were considered critical for the corn and black oat, respectively. In addition, soil compaction by machine traffic reduced maize yield up to 33% and black oat biomass yield up to 44%. Our results demonstrate that growers should be aware of the consequences of machine traffic on soil properties, as it can severely compromise crop yields, especially of corn and black oats cultivated in very clayey soil like the one evaluated in this study.

Key words: Soil bulk density. Macroporosity. Microporosity. Soil degree of compactness.

RESUMO - A compactação do solo pode reduzir a produtividade potencial das culturas e é frequentemente encontrada no sistema plantio direto, mas há pouca informação sobre os limites críticos das propriedades físicas do solo nessas condições, especialmente em solos subtropicais. Os objetivos deste estudo foram avaliar a influência do tráfego de tratores nas propriedades físicas do solo e identificar limites críticos de densidade do solo, grau de compactação do solo, macro e microporosidade no rendimento das culturas de milho e aveia preta avaliados in situ em um Latossolo Bruno no Sul do Brasil. O tráfego de trator agrícola (0, 2, 5 e 20 passagens) foi estabelecido em sistema plantio direto para criar diferentes níveis de compactação do solo. Amostras indeformadas de solo foram coletadas em profundidades de 0,00-0,05; 0,07-0,12 e 0,17-0,22 m logo após o tráfego do trator em dois momentos: antes do cultivo de milho e, antes do cultivo de aveia preta. Nas condições deste experimento, os rendimentos 10% maiores de milho e aveia preta foram obtidos com macroporosidade acima de 0,10 $m^3 m^{-3}$ e 0,13 $m^3 m^{-3}$, respectivamente. Da mesma forma, o grau de compactação do solo de 90% e 86% foi considerado crítico para o milho e aveia-preta, respectivamente. Além disso, a compactação do solo pelo tráfego de máquinas reduziu o rendimento do milho em até 33% e o rendimento da biomassa de aveia preta em até 44%. Nossos resultados demonstram que os produtores devem estar atentos às consequências do tráfego de máquinas nas propriedades do solo, pois pode comprometer severamente o rendimento a produtividade das culturas, principalmente do milho e da aveia preta cultivados em solo muito argiloso como o avaliado neste estudo.

Palavras-chave: Densidade do solo. Macroporosidade. Microporosidade. Grau de compactação do solo.

DOI: 10.5935/1806-6690.20220003
Editor-in-Article: Prof. Tiago Osório Ferreira - toferreira@usp.br
*Author for correspondence
Received for publication on 06/08/2020; approved on 02/09/2021

[1]Part of the first author’s dissertation, presented to Postgraduate Program in Agronomy, Universidade Estadual do Centro-Oeste, Guarapuava, Paraná. This study was funded by Paraná State Araucária Foundation (Fundação Araucária, Brazil), Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil), and National Counsel of Technological and Scientific Development (CNPq)
[2]Postgraduate Program in Agronomy, Universidade Estadual do Centro-Oeste, Guarapuava-PR, Brazil, bareta.ebj@hotmail.com (ORCID ID 0000-0001-6339-6231), renan.umburanas@gmail.com (ORCID ID 0000-0002-4112-3598)
[3]Department of Agronomy, Universidade Estadual do Centro-Oeste, Guarapuava-PR, Brazil, agenu@unicentro.br (ORCID ID 0000-0002-7179-0244)
[4]Department of Agronomy, Postgraduate Program in Agronomy, Universidade Estadual do Centro-Oeste, Guarapuava-PR, Brazil, lrampim@unicentro.br (ORCID ID 0000-0001-8300-7424), cpott@unicentro.br (ORCID ID 0000-0002-4630-2659)

INTRODUCTION

Soil compaction especially occurs in no-till cultivation because there is intense traffic of agricultural machines (FERREIRA *et al*., 2020; TRENTIN *et al*., 2018) or inadequate cropping systems (SOMASUNDARAM *et al*., 2018), which affects soil structure and has a direct effect on crop yield (LIMA *et al*., 2018; MARINS *et al*., 2018; REICHERT *et al*., 2009).

The compacted soil impairs root growth, reduces hydraulic conductivity, especially the saturated one, and reduces air-filled porosity (REICHARDT; TIMM, 2020). Morphological and physiological plant attributes are affected by the aforementioned soil physical attributes, such as stunting growth, reducing plant height, and implementing a shallow root system (SHAH *et al*., 2017); it also decreases water and nutrient absorption, thus decreasing crop yields (COLOMBI; KELLER, 2019; MORAES *et al*., 2020; RIVERA *et al*., 2019).

Growers occasionally carry out mechanical chiseling of fields under a no-till system to mitigate soil compaction, which is not an indicated practice (MORAES *et al*., 2020), and some Brazilian farmers have been chiseling the soil under a no-till system every 2 to 5 years without considering soil physical attributes. However, it is prudent to be sure that the soil is compacted to chisel the soil, and the soil physical properties and critical limits should be assessed and established.

The machine traffic affects the soil degree of compactness, which in turn affects the total porosity, size, and dynamics of soil pores. Larger pores are represented by macroporosity and are the most important for soil aeration and the speed of water flow, while smaller pores, represented by microporosity, represent water which is strongly retained in the soil (REICHARDT; TIMM, 2020). Soil physical properties which are influenced by soil management and can be used as indicators of soil compaction include soil bulk density (BD) (MORAES *et al*., 2016; REICHERT *et al*., 2009; TRENTIN *et al*., 2018) and soil porosity (macroporosity and microporosity) (BARBOSA *et al*., 2019; MORAES *et al*., 2016). Despite the importance of these topics, the relationship between porosity, especially microporosity, and plant growth is little reported (MORAES *et al*., 2020). Although BD is one of the attributes more used to evaluate soil compaction (GUBIANI; REINERT; REICHERT, 2014), their values are dependent on particle size and organic matter content (MARCOLIN; KLEIN, 2011).

Accordingly, the use of soil degree of compactness (DC) represents the relationship between BD and the reference bulk density (BD_{ref}) obtained by Proctor test (MARCOLIN; KLEIN, 2011; OLIVEIRA *et al*., 2016), and is considered a useful indicator of soil physical condition as it is a way of normalizing soil density in relation to texture (KOUREH *et al*., 2020; OLIVEIRA *et al*., 2016; ROSSETTI; CENTURION, 2015; SUZUKI *et al*., 2007). Root growth is restricted when BD exceeds BD_{ref} (KELLER; HÅKANSSON, 2010). The degree of compactness, like matric water tension, is related to the air-filled porosity and limits of penetration resistance, in addition to being similar in different soils, which makes it a useful parameter in studying the biological effects of soil compaction (HÅKANSSON; LIPIEC, 2000).

Critical values of DC and macroporosity depend on the soil texture (SUZUKI *et al*., 2007). The macroporosity reference values found in literature vary from 0.08 to 0.14 m^3 m^{-3} (CARTER, 1990) and minimum values in subtropical highly weathered soils are reported as 0.10 m^3 m^{-3} to avoid compromising root growth (REICHERT; SUZUKI; REINERT, 2007); even though soil aeration is a dynamic process, root depth, soil type and soil respiration rate determine the air-filled porosity requirements (BARTHOLOMEUS *et al*., 2008). The lower limit of macroporosity varies according to crop root growth capacity; as the compaction impairs root growth, the soil area available for plant exploitation and root respiration impairs water relationships and nutrient availability (REICHARDT; TIMM, 2020). The macropore continuity in very clayey soils is greater and the reference value less than 0.10 m^3 m^{-3} would be enough to ensure aeration for the root system (REICHERT *et al*., 2009). The optimum DC for soybean cultivated in Oxisol was 86% (SUZUKI *et al*., 2007), while the maximum yield for barley was found with DC between 77 and 84% (CARTER, 1990), indicating that it is considered a non-compacted range.

In view of the above, the objectives of this study were to evaluate the influence of tractor traffic on the soil physical properties of an oxisol and identify critical limits of soil bulk density, soil degree of compactness, macro and microporosity on crop yield of corn and black oat assessed in situ in a no-till system in Southern Brazil.

MATERIAL AND METHODS

Site description, experimental design, and treatments

The experiment was carried out in Guarapuava, Parana, Brazil (25º 23'S and 51º 27' W, 1041 m above sea level), under humid subtropical mesothermic climate (Cfb) and the topography is smooth to gently undulated. The soil of the experimental site is a Xanthic Hapludox with a very clayey texture. The soil granulometric analysis indicated 748, 215, and 37 g kg^{-1} of clay, silt, and sand, respectively.

The experimental design was of randomized blocks arrangement, with 4 treatments and 6 replications, and the plot size was 80 m^2 (5 m × 16 m). The treatments consisted of the following soil compaction by tractor traffic throughout the plot: control (without machine traffic), 2 passes, 5 passes and 20 passes. Soil compaction in the experimental area was carried out on October 27, 2016, two days after a precipitation period of around 70 mm. The average soil moisture was 0.43 m^3 m^{-3} at that moment, close to the humidity that the micropores were filled with water and the macropores were drained (Table 2). The tractor used to generate different levels of soil compaction was a John Deere 7515 model with 140 hp power, weighted with ¾ of the tire volume with water, plus six front weights of 50 kg each and four rear weights of 75 kg each, with a total weight of 6 Mg.

Sampling and evaluation of soil physical properties

First, undisturbed soil samples were collected at depths of 0.00-0.05, 0.07-0.12 and 0.17-0.22 m in two moments: before corn cultivation on November 7, 2016 (10 days after soil compaction), and before black oat cultivation on June 22, 2017 (238 days after soil compaction), in order to determine the critical limits of soil physical properties. Thus, the soil bulk density (BD), as well as the macro and microporosity (EMBRAPA, 2011) were determined using undisturbed soil samples. The undisturbed soil samples were subsequently subjected to the tension table at -6 kPa after being saturated for 48 hours to determine macro and microporosity. Soil total porosity was the sum of macro and microporosity. Afterward, the soil samples were oven-dried at 105 ºC until constant weight to determine the BD.

Next, a normal Proctor test was used (MARCOLIN; KLEIN, 2011) to determine the reference bulk density (BD_{ref}). The test consisted of using an impact resulting from a fixed load in soil samples submitted to different humidity, resulting in a density curve achieved as a function of humidity. A 2.5 kg socket, a cylindrical metallic mold (10 cm in diameter and 12.73 cm in height) and a complementary metal ring were used to simulate the impact load. The BD_{ref} was determined in the same layers as the undisturbed samples (0.00-0.05, 0.07-0.12, and 0.17-0.22 m). The BD values of each layer and treatment were divided by the BD_{ref} of each studied layer to determine soil degree of compactness (DC).

Management and evaluations of corn and black oat

After the soil compaction process, corn was sown on November 8, 2016, using a conventional hybrid DKB 290 with a seeding rate of 7.5 seeds m^{-2} and a row spacing of 0.90 m. Basic fertilization consisted of 26 kg ha^{-1} of N (urea), 90 kg ha^{-1} of P_2O_5 (triple superphosphate), and 51 kg ha^{-1} of K_2O (potassium chloride) and a top-dress fertilization with 100 kg ha^{-1} of N (urea) was carried out 20 days after sowing. Preventive management of pests, diseases and weeds was properly carried out. Then, an area of 10 m^2 per plot was harvested at full maturity to determine corn grain yield and grain moisture was adjusted to 130 g kg^{-1}.

Black oat (*Avena strigosa* Schreb.) cv IAPAR 61 was sown on July 22, 2017 in the winter, with a seeding rate of 360 seeds m^{-2} and a row spacing of 0.17 m. Top-dress fertilization was carried out after 20 days with 100 kg ha^{-1} of N (urea). Then, an area of 0.5 m^{-2} per plot was cut at its full bloom stage at 0.01 m from soil surface and oven-dried at 60 ºC to evaluate black oat dry matter.

Statistical analysis

The data were subjected to the normality and homogeneity test of the residuals. The data were subjected to analysis of variance (ANOVA) under a factorial scheme (4 × 3) to relate machine traffic and soil depths, and each sampling moment was independently evaluated. Corn grain yield and black oat dry matter yield were submitted to one-way ANOVA. The data were classified by the Tukey test at the 5% significance level when ANOVA showed a significant difference (α = 0.05).

A regression study was carried out among the soil properties, relative corn yield and relative dry matter of black oat to determine the critical limits of soil physical properties. The relative crop yield was defined as the relationship between the crop yield and the average of the best crop yield among soil compaction treatments. The ideal limit of the physical properties was delimited at 90% of the relative corn crop yield and black oat dry matter using equations of first or second degree, and using the coefficient of determination as criteria. The critical limit criteria adopted in this study is estimated within the transition zone, associated with a reduction in growth or yield in 10%, which is also used in soil fertility (NÚCLEO ESTADUAL PARANÁ – SOCIEDADE BRASILEIRA DE CIÊNCIA DO SOLO, 2017).

RESULTS AND DISCUSSION

The reference bulk density (BD_{ref}) obtained by Proctor test was 1.19, 1.20 and 1.21 Mg m^{-3} for the layers of 0.00-0.05, 0.07-0.12 and 0.17-0.22 m, respectively. The soil moisture content in BD_{max} ranged from 0.32 to 0.36 kg kg^{-1}. There was a significant difference between the soil compaction treatments by machine traffic for the BD, DC, macro, and microporosity soil properties (Table 1). Total porosity was not different between the treatments.

The soil compaction was verified at 0.00 until 0.22 m depth at the highest soil compaction level (20 passes of tractor traffic), as evidenced in the BD and DC values.

Thus, BD values of 1.18, 1.10 and 1.09 Mg m^{-3} were found for this treatment in soil layers of 0.00-0.05, 0.07-0.12 and 0.17-0.22 m, respectively. It was also verified that DC can reach 99%, 92%, and 90% for this treatment in soil layers of 0.00-0.05, 0.07-0.12 and 0.17-0.22 m, respectively (Table 1).

The corn yield was lower with 20 passes of the machine traffic, while there was no difference among the other treatments (Table 2). The corn yields in the treatment with 20 passes were 34%, 28% and 34% lower than 0, 2, and 5 passes of the machine traffic, respectively. The black oat dry matter was higher without soil compaction (0 passes) compared to the other treatments, which did not differ from each other. The black oat dry matter in the treatment with 0 passes were 33%, 50% and 78% higher than 2, 5, and 20 passes of the machine traffic, respectively (Table 2).

Table 1 - Bulk density, degree of compactness, macroporosity, microporosity and total porosity in a Xanthic Hapludox under different machine traffic compaction treatments evaluated in different soil depths before corn and black oat crop seasons carried out in 2016 and 2017 growing seasons at Guarapuava, Paraná, Brazil

Soil physical properties	Machine traffic (nº passes)	Before corn			Before black oat		
		Soil depth (m)					
		0.00-0.05	0.07-0.12	0.17-0.22	0.00-0.05	0.07-0.12	0.17-0.22
Bulk Density (Mg m^{-3})	0	1.00 bAB*	0.96 bB	1.01 bA	1.10 aA	1.04bB	1.04bB
	2	1.13 aA	1.05 aB	1.03 bB	1.12 aA	1.06 bB	1.04 bB
	5	1.15 aA	1.07 aB	1.03 bB	1.13 aA	1.11 aA	1.05 abB
	20	1.18 aA	1.10 aB	1.09 aB	1.11 aA	1.11 aA	1.08 aA
Degree of compactness (%)	0	84 bAB	80 bB	84 bA	92 aA	86 bB	86 bB
	2	95 aA	87 aB	85 bB	94 aA	88 bB	86 bB
	5	96 aA	89 aB	85 bB	95 aA	92 aA	87 abB
	20	99 aA	92 aB	90 aB	93 aA	92 aA	89 aA
Macroporosity (m^3 m^{-3})	0	0.15 aB	0.20 aA	0.14 aB	0.07 abB	0.13 aA	0.12 aA
	2	0.08 bB	0.12 bA	0.11 aA	0.07 abB	0.13 aA	0.12 aA
	5	0.09 bB	0.11 bA	0.11 aA	0.06 bB	0.11 abA	0.12 aA
	20	0.07 bB	0.10 bA	0.07 bB	0.08 aB	0.10 bA	0.10 bAB
Microporosity (m^3 m^{-3})	0	0.47 bA	0.43 bB	0.48 cA	0.50 abA	0.48 aA	0.49 aA
	2	0.51 aA	0.48 aB	0.50 bAB	0.53 aA	0.47 aB	0.49 aB
	5	0.50 aAB	0.47 aB	0.51 bA	0.50 abA	0.48 aA	0.49 aA
	20	0.50 aB	0.49 aB	0.53 aA	0.48 bB	0.49 aAB	0.52 aA
Total porosity (m^3 m^{-3})	0	0.62^{ns}	0.63^{ns}	0.62^{ns}	0.57^{ns}	0.61^{ns}	0.61^{ns}
	2	0.59	0.61	0.62	0.60	0.59	0.61
	5	0.58	0.59	0.62	0.56	0.59	0.61
	20	0.58	0.59	0.60	0.56	0.59	0.61

*Uppercase letter on the line and lowercase letter in the column classify the means by Tukey's test (p < 0.05). ns: not significant. The statistical comparison is within each crop

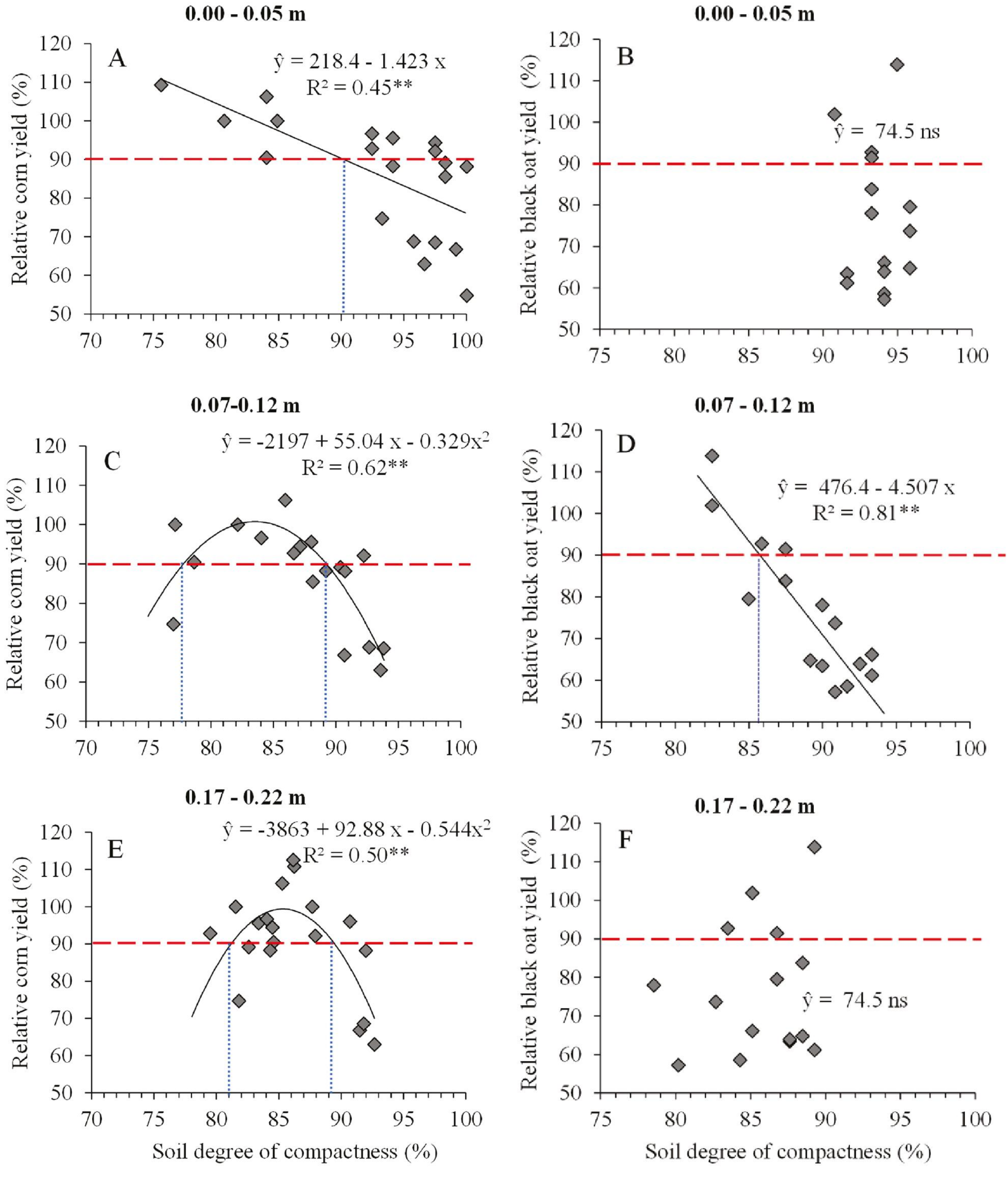
Table 2 - Corn grain yield (kg ha^{-1}) and black oat dry matter yield (kg ha^{-1}) in response to soil compaction by machine traffic treatments at Guarapuava, Paraná, Brazil, 2017

Machine traffic (no. of passes)	Corn grain yield (Mg ha^{-1})	Black oat dry matter (Mg ha^{-1})
0	11.7 a*	6.1 a
2	10.8 a	4.6 b
5	11.8 a	4.1 b
20	7.8 b	3.4 b

* Lowercase letter in the column classify the averages by Tukey's test (p < 0.05)

The relationship between DC with corn yield presented distinct behavior in the three layers, in which the 0.00-0.05 m layer obtained the critical DC limit of 90% (Figure 1A), equivalent to BD limit of 1.07 Mg m^{-3}. There was a quadratic fit in the 0.07-0.12 m layers between the relative corn yield with DC, which was between 77 to 90% (Figure 1C), equivalent to BD between 0.93 to 1.08 Mg m^{-3}. The ideal DC range in the 0.17-0.22 m layer

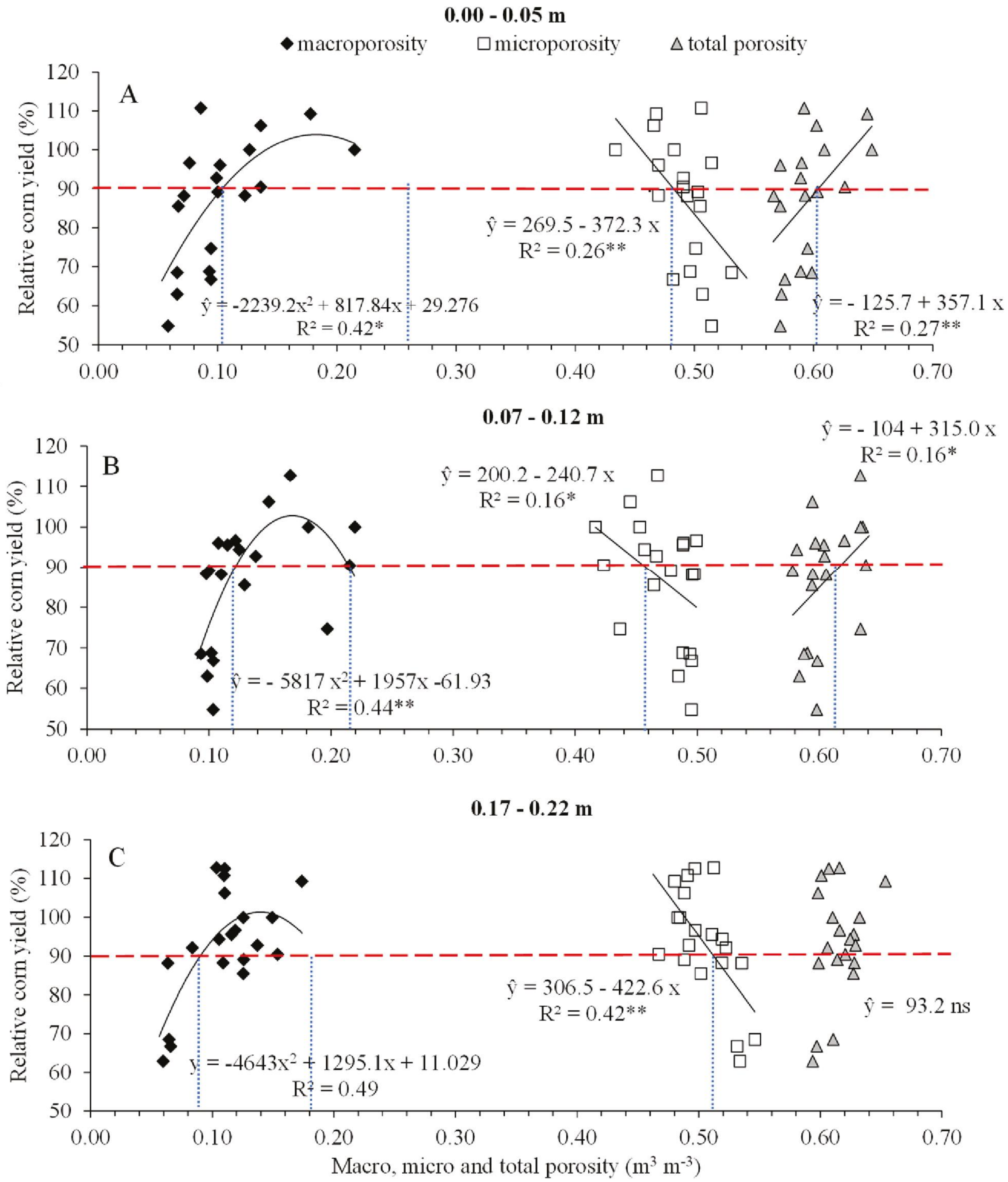
Figure 1 - Corn and black oat relative crop yield as a function of soil degree of compactness from layers 0.00-0.05 m (A and B), 0.07-0.12 m (C and D), and 0.17-0.22 m (E and F). The red line (dash and dot) represents 90% of relative corn yield from average of treatment, and the blue dashed line represents the intersection point. * Significant at $p < 0.05$; ** Significant at $p < 0.01$



was between 81 to 90% (Figure 1E), equivalent to BD between 0.98 to 1.08 Mg m^{-3}. The most favorable crop performance of around 85% of degree of compactness was also reported by Håkansson and Lipiec (2000).

There is quadratic fit in deep soil layers because if the soil degree of compactness is high (critical superior boundary), there is higher water infiltration, which increases the susceptibility of water deficit by plants. If

Figure 2 - Corn relative crop yield as a function of macroporosity, microporosity, and total porosity in layers from 0.00-0.05 m (A), 0.07-0.12 m (B), and 0.17-0.22 m (C) evaluated in 2016/2017 growing season at Guarapuava, Paraná, Brazil. The red line (dash and dot) represents 90% of relative corn yield from average of treatment, and the blue dashed line represents the intersection point. *Significant at $p < 0.05$; ** Significant at $p < 0.01$



the soil degree of compactness is low (critical inferior boundary), it is evidence of low macroporosity and higher microporosity at a level which impairs root growth, with similar observations being reported by Carter (1990).

The external forces responsible for soil compaction (i.e. machine traffic) mainly affect macroporosity, which in turn affects water infiltration into the soil by reducing hydraulic conductivity, as well as reducing aeration (REICHARDT; TIMM, 2020).

Macroporosity and total porosity in the 0.00-0.05 m layer had a positive linear fit compared with relative corn yield, while microporosity had a negative linear fit with relative corn yield. Based on the 90% of relative corn yield, the ideal macroporosity in the 0.00-0.05 m layer ranged between 0.104 and 0.261 m^3 m^{-3}, the ideal microporosity was below 0.482 m^3 m^{-3} and the ideal total porosity was above 0.604 m^3 m^{-3} (Figure 2A).

Microporosity in the 0.07 to 0.12 m layer had a quadratic fit compared with relative corn yield, while microporosity had a negative linear fit and total porosity had a positive linear fit. Based on the 90% of relative corn yield, the ideal macroporosity in the 0.07 to 0.12 m layer ranged between 0.122 and 0.215 m^3 m^{-3}, the ideal microporosity was below 0.458 m^3 m^{-3} and the ideal total porosity was above 0.616 m^3 m^{-3} (Figure 2B).

Macroporosity in the 0.17-0.22 m layer had a positive linear fit compared with relative corn yield, microporosity had a negative linear fit and total porosity had no significant linear nor quadratic fit. Based on the 90% of relative corn yield, the ideal macroporosity in the 0.17-0.22 m layer ranged between 0.090 and 0.189 m^3 m^{-3} and the ideal microporosity was below 0.512 m^3 m^{-3} (Figure 2C).

The relationship between BD or DC with relative black oat dry matter yield presented not significant relationship in the 0.00-0.05 m (Figure 1B) and 0.17-0.22 m layers (Figure 1F), while there was a negative linear fit in the 0.07-0.17 m layer (Figure 1D). The 0.07-0.17 m layer presented a critical BD limit of 1.02 Mg m^{-3} and a critical DC of 86% (Figure 1D).

The relationship between porosity with relative black oat dry matter yield presented no significant relationship in the 0.00-0.05 m (Figure 3A and B) and 0.17-0.22 m layers (Figure 3E and F), while there was a negative linear fit in the 0.07-0.17 m layer (Figure 3C and D).

Based on the 90% of relative black oat dry matter, the ideal macroporosity in the 0.07-0.17 m layer is above 0.13 m^3 m^{-3} and the ideal total porosity is above 0.61 m^3 m^{-3}.

The soil compaction carried out by machine traffic modified soil physical properties, increased BD, DC and microporosity, and decreased the macroporosity to a depth of 0.22 m. The increase in BD and decrease macroporosity in compacted soils is commonly reported in different soil types (CARTER, 1990; LIMA *et al.*, 2018; POTT *et al.*, 2019; REICHERT *et al.*, 2009). The critical BD to consider the Xanthic Hapludox evaluated in our study as a compacted soil ranged from 1.07 to 1.09 Mg m^{-3} for corn and 1.03 Mg m^{-3} for black oat. Another study on this same soil type considered non-compacted soil with BD greater than 1.30 Mg m^{-3} (ANDREOLLA *et al.*, 2015) taking into account the references of Reichert *et al.* (2009). The lower BD values found in our study reinforce the need to assess BD_{ref}, in which they ranged from 1.19 to 1.21 Mg m^{-3}. These low BD values indicate the importance of using DC to determine whether the soil is compacted or not (KOUREH *et al.*, 2020; MARCOLIN; KLEIN, 2011; OLIVEIRA *et al.*, 2016; ROSSETTI; CENTURION, 2015).

The DC of 90% resulted in a potential relative yield below 90% for corn (Figure 1A, C, and E). Oliveira *et al.* (2016) verified a reduction by 50% of root length when the soil reached a DC of 98%. Suzuki *et al.* (2007) found that the optimum DC for soybean cultivation in Oxisol was 86%. Carter (1990) obtained a maximum yield of barley in DC with values between 77 and 84%, indicating that it was considered a non-compacted range. Sá *et al.* (2016) considered a DC value of 88% as critical for the growth of sugarcane roots. Silva, Albuquerque and Costa (2014) studying soybean growth in mini-lysimeter, found that a critical value of BD occurs when it was above 1.14 Mg m^{-3}, which corresponds to 95% of DC.

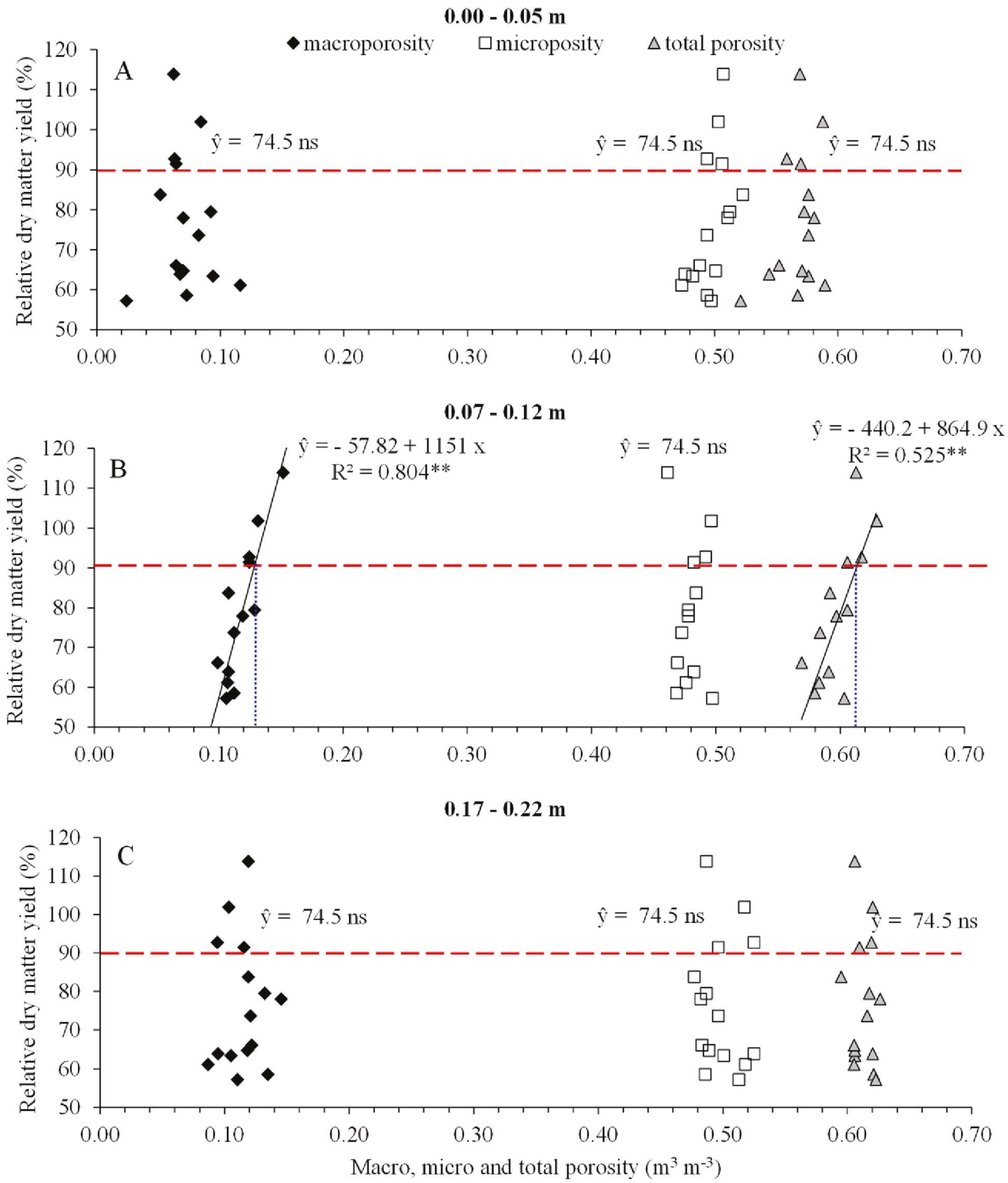
Black oat roots penetrate the compacted soil with no apparent deviation (BURR-HERSEY *et al.*, 2017). In our study, black oat presented 90% of dry matter yield when the DC was greater than 86%. Pott *et al.* (2019) also verified the response of dry matter of black oat due to different soil physical properties.

The increased tolerance of crops to compacted soils can be mitigated through genetic improvement and with management practices that recovery soil properties, such as porosity (COLOMBI; KELLER, 2019).

The soil macroporosity in our study was a good indicator of soil physical quality of black oat yield. Although significant, this is a static soil property, which may not represent the temporal variability of factors which directly affect crop growth and development. According to Colombi and Keller (2019), root growth is decreased in compacted soil due to high soil penetration resistance and due to low oxygen concentration in soil air caused by reduced fluid transport capability.

In this study, increasing the intensity of the machine traffic reduced the macroporosity, which consequently increased the microporosity. It was observed that the increase in microporosity occurred in a small range, and that there was a negative relationship with yield in the largest microporosities (Figure 3). This negative relationship evidences that the greater microporosity may be related to the physical impediment of root growth provided by greater soil compaction.

Figure 3 - Relative crop dry matter of black oat as a function of macroporosity, microporosity, and total porosity in layers from 0.00-0.05 m (A), 0.07-0.12 m (B), and 0.17-0.22 m (C) at Guarapuava, Paraná, Brazil, 2016-2017. The red line (dash and dot) represents 90% of dry matter yield of black oat, and the blue dashed line represents the intersection point. *Significant at $p < 0.05$; ** Significant at $p < 0.01$



The compaction treatments from machine traffic were installed before sowing the corn. The soil physical attributes were evaluated and then the corn was sown; the physical attributes of the soil were evaluated again, and the black oats were sown. The soil disturbance caused by sowing corn possibly caused the non-effect of the machine traffic treatments on the macroporosity in the 0.00-0.05 m surface layer (Figure 3a). The non-effect of macroporosity in the lower subsurface layer evaluated (0.17-0.22 m) also evidences that the root growth of corn mitigated the compaction effects in the layers (Figure 3c), which can be an effect of “biological decompression” by corn roots. This information was also evidenced by bulk density (Table 1), where the amplitude of bulk density between machine traffic treatments within the 0.17-0.22 m layer were clearly reduced when evaluated before black oat when compared to the evaluation before corn.

In order to reach at least 90% of maximum relative crop yield in the Xanthic Hapludox evaluated in the 0.00 to 0.22 m layers, a minimum macroporosity from 0.10 to 0.12 m^3 m^{-3} was necessary for corn cultivation, and at least 0.13 m^3 m^{-3} for black oat cultivation (Figures 2 and 3). It was reported that the macroporosity of 0.10 m^3 m^{-3} in some very clayey soils from subtropical environments will not necessarily be limiting for root growth in no-tillage (REICHERT; SUZUKI; REINERT, 2007; REICHERT *et al*., 2009), but would probably reduce yield potential of corn and black oats as evidenced in our results. The definition of a critical limit is important to carry out the soil physical characteristics diagnosis and decision-making in soil or crop management.

In addition to the decrease in the macroporosity, we found an increase in microporosity, without changing the total pore volume in both evaluations. For this study with very clayey soil, the microporosity greater than the range from 0.46 to 0.51 m^3 m^{-3} decreased the corn yield. The machine traffic in our study caused an imbalance between macro and microporosity, which possibly affected hydraulic conductivity, despite maintaining total soil porosity. Hydraulic conductivity in soil is dynamic and usually expressed in terms of volumetric moisture without considering the pore size, as macro and micro porosity continuously varies in the soil without abrupt transition (REICHARDT; TIMM, 2020). There is possibly a plateau of micropores, and when soil compaction overcomes this limit at the expense of the macropore volume, it can increase water retained in the soil, or pores became unavailable for water retention, which in turn reduces the water availability and aeration to the roots. This is a hypothesis to explain the reduction in the corn and black oat yields in these aforementioned conditions; however, further studies with water availability approaches should be carried out to test this.

An increase in microporosity was caused by the soil compaction by the machine traffic treatments, which consequently decreased the macroporosity. This relationship of decreased macroporosity and increased microporosity agree with other studies (MARINS *et al.*, 2018; MORAES *et al*., 2020), but most of them had no microporosity reference value.

CONCLUSIONS

This study has advanced in knowledge by identifying critical porosity, bulk density and degree of compactness values in a Xanthic Hapludox for developing corn and black oat crops under a no-till system. The 10% higher yields under the conditions of this experiment were obtained with macroporosity above 0.10 m^3 m^{-3} and 0.13 m^3 m^{-3} for corn and black oats, respectively. Similarly, the soil degrees of compactness of 90% and 86% were considered critical for the corn and black oat, respectively. In addition, soil compaction by machine traffic reduced maize yield up to 33% and black oat biomass yield up to 44%. Our results demonstrate that growers should be aware of the consequences of machine traffic on soil properties, as it can severely compromise crop yields, especially of corn and black oats cultivated in very clayey soil like the one evaluated in this study.

ACKNOWLEDGEMENTS

We acknowledge the *Universidade Estadual do Centro-Oeste (Paraná)* for the structure made available to conduct this study, especially the staff of the *Departamento de Agronomia* and the *Programa de Pós-graduação em Agronomia*.

The authors would like to thank the funding from Paraná State Araucária Foundation (Fundação Araucária, Brazil), Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil - Finance Code 001) and from National Counsel of Technological and Scientific Development (CNPq, Brazil).

REFERENCES

ANDREOLLA, V. R. M. *et al.* Pastejo e adubação nitrogenada sobre os atributos físicos do solo em sistema de integração lavoura-pecuária. **Engenharia Agricola**, v. 35, n. 6, p. 1019-1031, 2015.

BARBOSA, L. C. *et al.* Soil physical quality associated with tillage practices during sugarcane planting in south-central Brazil. **Soil and Tillage Research**, v. 195, p. 104383, 2019.

BARTHOLOMEUS, R. P. *et al*. Critical soil conditions for oxygen stress to plant roots: substituting the Feddes-function by a process-based model. **Journal of Hydrology**, v. 360, p. 147-165, 2008.

BURR-HERSEY, J. E. *et al.* Developmental morphology of cover crop species exhibit contrasting behaviour to changes in soil bulk density, revealed by X-ray computed tomography. **Plos One**, v. 12, n. 7, p. 1-18, 2017.

CARTER, M. R. Relationship of strength properties to bulk density and macroporosity in cultivated loamy sand to loam soils. **Soil and Tillage Research**, v. 15, n. 3, p. 257-268, 1990.

COLOMBI, T.; KELLER, T. Developing strategies to recover crop productivity after soil compaction—A plant eco-physiological perspective. **Soil and Tillage Research**, v. 191, p. 156-161, 2019.

EMBRAPA. **Manual de métodos de análise de solo**. Rio de Janeiro: Embrapa Solos, 2011. 230 p. (Documentos 132).

FERREIRA, C. J. B. *et al.* Soil compaction influences soil physical quality and soybean yield under long-term no-tillage. **Archives of Agronomy and Soil Science**, p. 1-14, 21 fev. 2020.

GUBIANI, P. I.; REINERT, D. J.; REICHERT, J. M. Valores críticos de densidade do solo avaliados por condições de contorno. **Ciencia Rural**, v. 44, n. 6, p. 994-1000, 2014.

HÅKANSSON, I.; LIPIEC, J. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. **Soil and Tillage Research**, v. 53, n. 2, p. 71-85, 2000.

KELLER, T.; HÅKANSSON, I. Estimation of reference bulk density from soil particle size distribution and soil organic matter content. **Geoderma**, v. 154, n. 3/4, p. 398-406, 2010.

KOUREH, H. K. *et al.* Critical values of soil physical quality indicators based on vegetative growth characteristics of spring wheat (*Triticum aestivum* L.). **Journal of Soil Science and Plant Nutrition**, v. 20, n. 2, p. 493-506, 2020.

LIMA, C. L. R. de *et al.* Critical values of physical attributes of an Ultisol under uses in South of Brazil. **Revista Brasileira de Ciencias Agrarias**, v. 13, n. 2, p. 1-9, 2018.

MARCOLIN, C. D.; KLEIN, V. A. Determinação da densidade relativa do solo por uma função de pedotransferência para a densidade do solo máxima. **Acta Scientiarum. Agronomy**, v. 33, n. 2, p. 349-354, 2011.

MARINS, A. C. de *et al.* Crambe grain yield and oil content affected by spatial variability in soil physical properties. **Renewable and Sustainable Energy Reviews**, v. 81, p. 464-472, 2018.

MORAES, M. T. de *et al.* Soil compaction impacts soybean root growth in an Oxisol from subtropical Brazil. **Soil and Tillage Research**, v. 200, p. 104611, 2020.

MORAES, M. T. de *et al*. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. **Soil and Tillage Research**, v. 155, p. 351-362, 2016.

OLIVEIRA, P. D. de *et al*. Critical limits of the degree of compactness and soil penetration resistance for the soybean crop in N Brazil. **Journal of Plant Nutrition and Soil Science**, v. 179, n. 1, p. 78-87, 2016.

POTT, L. P. *et al*. Mitigation of soil compaction for boosting crop productivity at varying yield environments in southern Brazil. **European Journal of Soil Science**, p. 1-16, 2019.

REICHARDT, K.; TIMM, L. C. **Soil, plant and atmosphere**: concepts, processes and applications. [*S. l.*]: Springer International Publishing, 2020. *E-book* (456 p.).

REICHERT, J. M. *et al*. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. **Soil and Tillage Research**, v. 102, n. 2, p. 242-254, 2009.

REICHERT, J. M.; SUZUKI, L. E. A. S.; REINERT, D. J. Compactação do solo em sistemas agropecuários e florestais: identificação, efeitos, limites críticos e mitigação. **Tópicos em Ciência do Solo**, p. 49-134, 2007.

RIVERA, M. *et al.* Soil compaction induced changes in morpho-physiological characteristics of common bean. **Journal of Soil Science and Plant Nutrition**, v. 19, n. 1, p. 217-227, 2019.

ROSSETTI, K. D. V.; CENTURION, J. F. Ensaio de compactação em Latossolo cultivado com milho sob diferentes períodos de adoção de tipos de manejo. **Revista Brasileira de Ciencias Agrarias**, v. 10, n. 4, p. 499-505, 2015.

SÁ, M. A. C. de *et al.* Qualidade física do solo e produtividade da cana-de-açúcar com uso da escarificação entre linhas de plantio. **Pesquisa Agropecuaria Brasileira**, v. 51, n. 9, p. 16101622, 2016.

SHAH, A. N. *et al*. Soil compaction effects on soil health and cropproductivity: an overview. **Environmental Science and Pollution Research**, v. 24, n. 11, p. 10056-10067, 2017.

SILVA, F. D. R.; ALBUQUERQUE, J. A.; COSTA, A. da. Crescimento inicial da cultura da soja em latossolo bruno com diferentes graus de compactação. **Revista Brasileira de Ciencia do Solo**, v. 38, n. 6, p. 1731-1739, 2014.

SOCIEDADE BRASILEIRA DE CIÊNCIA DO SOLO. **Manual de adubação e calagem para o estado do Paraná**. Curitiba: SBCS/NEPAR, 2017. 482 p.

SOMASUNDARAM, J. *et al*. Effect of contrasting tillage and cropping systems on soil aggregation, carbon pools and aggregate-associated carbon in rainfed Vertisols. **European Journal of Soil Science**, v. 69, n. 5, p. 879-891, 2018.

SUZUKI, L. E. A. S. *et al.* Grau de compactação, propriedades físicas e rendimento de culturas em Latossolo e Argissolo. **Pesquisa Agropecuaria Brasileira**, v. 42, n. 8, p. 1159-1167, 2007.

TRENTIN, R. G. *et al*. Soybean productivity in Rhodic Hapludox compacted by the action of furrow openers. **Acta Scientiarum. Agronomy**, v. 40, n. 1, p. 1-9, 2018.