Acta Scientiarum
http://www.periodicos.uem.br/ojs/
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v45i1.62390

Long-term effects of cover crops on physical-hydric properties of compacted soil

Deonir Secco[1], Doglas Bassegio[1*], Araceli Ciotti de Marins[2], Bruna de Villa[1], Luiz Antônio Zanão Júnior[3], Tiago Roque Benetoli da Silva[4] and Affonso Celso Gonçalves Junior[1]

[1]Universidade Estadual do Oeste do Paraná, Campus Cascavel, Rua Universitária, 1619, 85819-130, Universitário, Cascavel, Paraná, Brazil. [2]Universidade Estadual de Maringá, Campus Avançado de Umuarama, Umuarama, Paraná, Brazil. [3]Departamento de Solos, Instituto de Desenvolvimento Rural do Paraná, Santa Tereza do Oeste, Paraná, Brazil. [4]Universidade Tecnológica Federal do Paraná, Campus Toledo, Toledo, Paraná, Brazil. *Author for correspondence. E-mail: doglas.bassegio@unioeste.br

ABSTRACT. The screening of cover crops is essential for improving the physical-hydric properties of compacted soils. This study aimed to evaluate the effects of mixed or single cover crops on improving the physical-hydric properties of compacted Oxisol. Species with tap-rooted and fibrous-rooted rooting patterns were evaluated. The species included pearl millet (*Pennisetum americanum*), pigeon pea (*Cajanus cajan*), sunn hemp (*Crotalaria spectabilis*), velvet bean (*Mucuna pruriens*), white oat (*Avena sativa*), black oat (*Avena strigosa*), rye (*Secale cereale*), black oat + forage turnip (*Raphanus sativus*), black oat + white lupin (*Lupinus albus* L.), and black oat + group pea (*Pisum arvense* L.). Mixing cover crops did not improve the physical properties of the soil. The tap-rooted pigeon pea effectively reduces bulk density and increases porosity and saturated hydraulic conductivity (Ksat) in compact soils. The selection of cover crops with characteristics that improve soil physical-hydric properties is crucial for compacted areas.

Keywords: compaction; bulk density; no-till; cover crop.

Received on February 7, 2022.
Accepted on June 1, 2022.

Introduction

In Brazil, no-till (NT) farming is carried out with monocultures of maize (*Zea mays* L.), soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.) (Peixoto et al., 2019). On the one hand, simplifying production systems facilitates operational routines on rural properties (Garbelini et al., 2020). However, such rotations degrade the soil's physical, chemical, and biological properties (Ferreira, Tormena, Severiano, Zotarelli, & Betioli Júnior, 2021). These systems do not produce sufficient straw to adequately cover the soil throughout the year. This lack of ground cover causes soil compaction problems (Reichert et al., 2022). Soil compaction is caused by intense external pressures from agricultural equipment and the natural accommodation of soil particles (Hamza & Anderson, 2005; Tormena, Karlen, Logsdon, & Cherubin, 2017; Reichert et al., 2018; Ren, Nest, Ruysschaert, D'Hose, & Cornelis, 2019; Scarpare et al., 2019).

The predominance of crops with a nonaggressive root system combined with the absence of crop rotation in NT leads to soil compaction (Drescher et al., 2017; Fuentes-Llanillo et al., 2021). Compacted layers restrict root growth and affect crop yield (Reichert, Suzuki, Reinert, Horn, & Hakansson, 2009; Garbelini et al., 2020; Ramos, Almeida, Amaral, & Suzuki, 2022). Soil compaction costs farmers millions of dollars annually. The marked degradation of agricultural lands has generated annual losses of more than 600 million tons of soil due to erosion, at an estimated cost of 1.3 billion dollars per year (Dechen, Telles, Guimarães, & Maria, 2015).

Clay oxisols with compacted soil layers, as observed in numerous areas managed under NT in Brazil (Drescher et al., 2017), require practices that remedy soil compaction (Ferreira et al., 2021). For example, scarification is one of the most widely used mechanical methods in Brazil, and there is evidence that scarification produces short-term effects (Calonego & Rosolem, 2010; Calonego, Raphael, Rigon, Oliveira Neto, & Rosolem, 2017; Secco et al., 2021). Additionally, cover crops have been proposed as a sustainable way to avoid soil compaction (Rosolem, Foloni, & Tiritan, 2002; Hamza & Anderson, 2005; Calonego & Rosolem, 2010; Calonego et al., 2017; Secco et al., 2021).

Root growth is related to soil density and critical density for root growth (Reinert, Albuquerque, Reichert, Aita, & Andrada, 2008). There is a critical density for each soil type that can affect root growth (Reichert et al., 2009). This depends mainly on the textural class (Reinert et al., 2008). Reichert et al. (2009) proposed a critical soil density of 1.25–1.30 Mg m^{-3} for clayey soils. Soil density can affect the differences in root morphology among different cover plant species (Hudek, Putinica, Otten, & De Baets, 2022). Legume species have taproots with larger diameters and better penetration into the soil (Chen & Weil, 2010) and can create large-diameter pores in the soil for the growth of subsequent roots (Colombi, Braun, Keller, & Walter, 2017). In contrast, grasses are fibrous-rooted and have greater root lengths that grow in deeper soil layers (Hudek et al., 2022). Therefore, a mixture of legumes and grasses could be an alternative because of their positive effects (Vujić et al., 2021). Reinert et al. (2008) observed root deformation of cover crops such as *Raphanus sativus*, with increased root thickening, deviations in the vertical direction of root growth, and concentration of roots in the most superficial layer of soil with soil density above 1.85 Mg m^{-3}. Jabro, Allen, Rand, Dangi, and Campbell (2021) found that irrespective of rooting characteristics (tap- or fibrous roots), penetration resistance was reduced by 32.2% after three seasons.

The authors have studied the effect of different cover crops under greenhouse conditions using compacted soils in pots (Rosolem et al., 2002; Calonego, Gomes, Santos, & Tiritan, 2011; Farias et al., 2013; Lima, Petter, & Leandro, 2015) and field conditions in non-mechanically compacted areas (Ren et al., 2019; Jabro et al., 2021; Hudek et al., 2022). Soil compacted under field conditions can create physical impediments to the soil surface, similar to the heavy traffic of machines and equipment in NT. To the best of our knowledge, there have been no studies on the of several cover crops under mechanical compaction. Thus, we hypothesized that some cover crops, either single or mixed, would be better adapted to grow in mechanically compacted soil, thereby affecting the physical-hydric properties of the soil. This study aimed to evaluate the effects of ten single or mixed cover crops on the physical properties of soil.

Material and methods

Site description

A long-term experiment (2015–2020) was conducted at the Rural Development Institute of Paraná – IAPAR – EMATER, Experimental Station of Santa Tereza do Oeste (53°29'37" W, 24°50'42" S, and 607 m a.s.l). According to the Koppen classification, the region presents a humid subtropical climate, with a mean annual rainfall of 1,840 mm.

The soil of the experimental area was classified as Oxisol (Soil Survey Staff, 2010). Table 1 shows the chemical and physical characteristics of the soil for the experimental area at a depth of 0.0–0.4 m. The following chemical attributes were analyzed: soil pH ($CaCl_2$); P and K^+ (Mehlich-1); exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} (KCl 1 mol L^{-1}); organic matter (Walkley Black); and base saturation (V%).

Table 1. Soil characteristics before the experiment start.

Depth	P (Mehlich−1)	SOC	pH	K^+	Ca^{2+}	Mg^{2+}	H+Al	Al^{3+}	BS
m	mg dm^{-3}	g kg^{-1}	$CaCl_2$		———————	$cmol_c$ dm^{-3}	———————		%
0.0–0.5	30.3	27.6	5.4	0.8	6.4	3.3	6.0	0.02	63.4
0.5–0.10	32.2	24.7	5.0	0.4	4.8	2.5	7.2	0.14	51.0
0.10–0.20	13.3	22.2	4.7	0.2	3.6	1.8	8.2	0.35	40.3
0.20–0.40	3.3	16.9	4.4	0.1	1.8	1.0	9.2	0.77	24.6

m	Sand	Clay	Silt
	—————————	g kg^{-1}	—————————
0.0–0.1	44.9	561.1	394.1
0.5–0.10	38.7	641.9	319.4
0.10–0.20	24.7	706.2	269.1

SOC: Soil organic carbon. BS: Base saturation.

Experimental design and treatments

Different cover crops were established in 2015 autumn-winter (March) under a NT system on soybean remains. The area was under a NT and crop rotation system, with maize grown in the winter and soybean in the summer.

The species included pearl millet (*Pennisetum americanum*), pigeon pea (*Cajanus cajan*), sunn hemp (*Crotalaria spectabilis*), velvet bean (*Mucuna pruriens*), white oat (*Avena sativa*), black oat (*Avena strigosa*), rye (*Secale cereale*), black oat + forage turnip (*Raphanus sativus*), black oat + white lupin (*Lupinus albus* L.), and black oat + group pea (*Pisum arvense* L.). Ten cover crops were evaluated mixed or single. Species with tap-rooted and fibrous-rooted rooting patterns were evaluated. The experiment was established in a completely randomized design with ten treatments and four replications. Each plot consisted of a 20 × 25 m area. The sowing of the cover species followed technical recommendations.

In 2017, a 16-t single drum roller (BOMAG BW 211D-40) was used to compact the soil in the plots with the cover crops. As a result, the soil moisture content was 38% and 37% in 0.0–0.1 and 0.1–0.2 m soil layers, respectively.

In October 2017, 2018, and 2019 soybeans were grown in the summer. In 2018 autumn-winter (March), the cover crops were established on soybean remains. In March 2019, maize was grown on soybean crop remains. Details on the treatments and crops are shown in Table 2.

Table 2. Crops development during the study period (2014–2015 to 2019–2020) and the treatment application scheme during the entire experimental period (2017–2018 to 2019–2020).

Season	Crops	Sowing date	Harvest date
2014–2015	Soybean	Nov. 11, 2014	Mar. 10, 2015
	Cover crops	Mar. 31, 2015	Oct. 19, 2015
2015–2016	Soybean	Oct. 20, 2015	Mar. 1, 2016
	Cover crops	Mar. 15, 2016	Sep. 27, 2016
2016–2017	Soybean	7 Oct. 2016	Mar. 8, 2017
	Crambe	May 11, 2017	Sep. 18, 2017
2017–2018 – Soil compaction	Soybean	Oct. 11, 2017	Mar. 6, 2018
	Cover crops	Mar. 8, 2018	Aug. 29, 2018
2018–2019	Soybean	Oct. 2, 2018	Feb. 14, 2019
	Maize	Feb. 21, 2019	Aug. 28, 2019
2019–2020	Soybean	Nov. 5, 2019	Feb. 25, 2020
	Maize	Mar. 30, 2020	Aug. 25, 2020

Sampling and analysis

Bulk density, macroporosity, microporosity, total porosity, and Ksat were determined. Using steel support, soil samples were taken at the center of the 0.0-0.3 m soil layer depths to force a volumetric ring into the soil. Collections of undisturbed samples were performed in 2017-2018 after soybean cultivation, in 2018-2019 before cover crops, in 2019 after soybean cultivation, and in 2019-2020 after maize harvest.

Then, the soil samples were placed to saturate in plastic trays with water up to 2/3 of the cylinder height. The bottom of the cylinder was wrapped in polyester fabric to prevent soil loss. The samples were weighed after 48 h of immersion to determine the saturated weight. Then, the cylinders were set on a sand column (Reinert & Reichert, 2006), submitted to a tension of 0.6-m, and recorded the wet weight. After this, samples were dried in a forced-air oven at 105°C for 48h, and the dry soil mass was determined. First, bulk density was calculated by dividing the dry soil by the volume of the volumetric cylinder. Considering that the water in the macropores was removed at 0.6-m, the volume of micropores was determined. Next, total soil porosity was calculated based on the difference between the saturated and dry soil masses, plus the sample volume. Finally, Macroporosity was obtained by calculating the difference between the total porosity and microporosity. Subsequently, soil samples were re-saturated for 24h, and Ksat was measured using a falling-head permeameter (Gubiani, Reinert, Reichert, Gelain, & Minella, 2010).

Statistical analysis

The data were tested for the assumptions of analysis of variance (normality). When these requirements were met, the data were subjected to an analysis of variance ($p < 0.05$) using the statistical software Sisvar® (Statistical Analysis Software, UFLa, Lavras, Minas Gerais State, Brazil). The means were compared using the LSD test, and statistical significance was tested at $p < 0.05$.

Results and discussion

Cover crops did not differ concerning bulk density values in the first seasons before mechanical compaction (2017–2018) (Figure 1A). Density values in the first year were not affected by the residual effect of NT used before the start of the experiment. The lack of difference between cover crops in soil physical properties in this study in the early years was expected, as physical properties generally change slowly (Blanco-Canqui & Ruis, 2020; Secco et al., 2021). These results are related to the slow decomposition of the root system. Jabro et al. (2021) observed that the roots of cover crops took four years to decompose and produce root canals and porous spaces in compacted soil. Furthermore, differences between cover crops may be more evident when the soil is compacted, possibly because root growth changes under these conditions (Grzesiak, Grzesiak, Hura, Marcińska, & Rzepka, 2013).

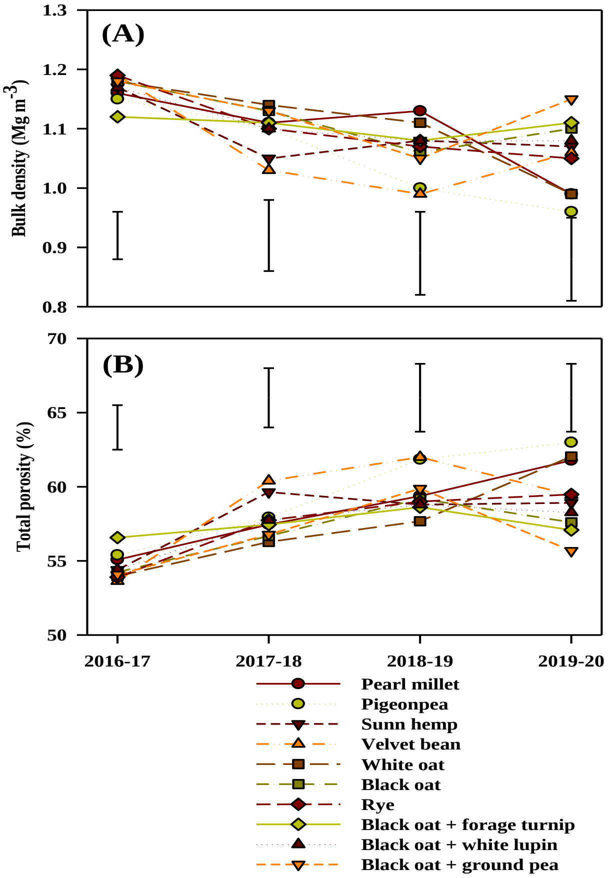

Figure 1. Cover crops affecting bulk density (A) and total porosity (B). The bar indicates the LSD (0.05) significant differences between cover crops.

After four seasons, pigeon pea (0.96 Mg m^{-3}) was more efficient in reducing bulk density than velvet bean (1.15 Mg m^{-3}) and black oat + forage turnip (1.11 Mg m^{-3}) in 2019-2020. Pigeon pea has tap roots that can develop in compacted soils and form biopores (Lynch & Wojciechowski, 2015). In addition, pigeon peas promote an increase in organic carbon (Soares et al., 2021), improving soil physical quality and allowing greater soil conservation. According to Bengough (2012), root diameter is an important characteristic for the formation of pores induced by roots, particularly in soils with high mechanical strength and compaction. However, according to Farias et al. (2013), pigeon pea roots showed little growth in an oxisol under controlled conditions in compacted pots. Chen and Weil (2011) argued that taproots have a low tendency for soil laterality. Thick root systems predominantly increase soil macroporosity (Bodner, Leitner, & Kaul, 2014). Blanco-Canqui and Jasa (2019) observed that grass had a greater effect on soil properties than legumes after 12 years. Our findings showed that pigeon pea roots have the potential to reduce density in the compacted layer. The results possibly indicate that the roots decomposed and formed voids and biological channels after four seasons.

Cover crop mixtures may have bigger effects on soil properties than single species because of species diversity (Ruis et al., 2020), which was not observed in the present study. Higher root diversity, such as the presence of both taproots and fibrous roots, can use resources more effectively (Smith, Atwood, & Warren, 2014). For example, mixing a fibrous-rooted species with a tap-rooted species can reduce soil density compared to a single tap-rooted plant. This is because the roots of fibrous-rooted species may have better contact with the soil matrix, possibly promoting better aggregation (Stavi, Lal, Jones, & Reeder, 2012), which was not verified in this study. Ruis et al. (2020) showed that the effects of cover crop mixtures on soil properties are unclear.

In 2019–2020, it was found that pigeon pea growth provided higher values of soil porosity (59%) than velvet bean species (54%) (Figure 1B). Among the various cover crops used, pigeon pea species (14%) were more efficient in increasing soil macroporosity than black oat + forage turnip (14%) in the same season (Figure 2B). Macroporosity followed the soil density trend. Some studies have reported that macropores are reduced in compacted soils (Colombi et al., 2017; Feng, Wang, Liu, Bai, & Reading, 2019). Cover crops can influence the soil pore size distribution in several ways. Pores are created when the decaying organic components of roots and residues are less dense than the mineral constituents, decreasing the soil density (Silva et al., 2021; Reichert et al., 2022). Additionally, increasing organic matter (OM) increases straw aggregation and soil stability, resulting in greater root growth (Haruna et al., 2020). A higher soil macroporosity indicates a better structural condition of the soil for plant growth, as it has large pores that facilitate water and air transport and improve root proliferation (Reichert, Rodrigues, Bervald, & Kato, 2016; Calonego et al., 2017; Panziera et al., 2022). Consequently, root canals are left in the soil for subsequent crops, reducing the negative effects of soil compaction (Chen, Weil, & Hill, 2014; Ajayi, Horn, Rostek, Uteau, & Peth, 2019).

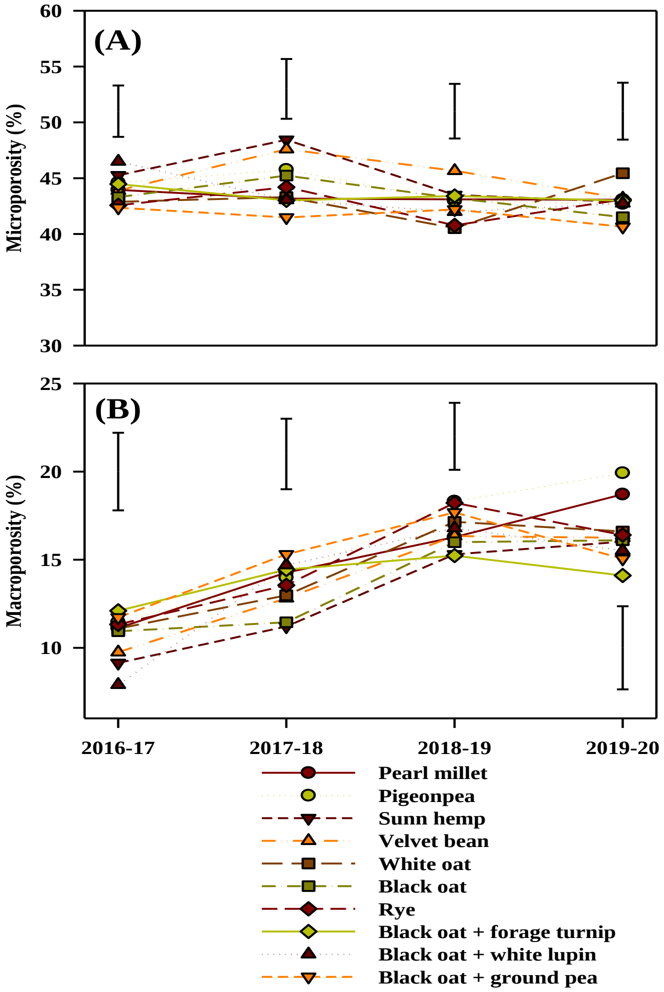

Figure 2. Cover crops affecting soil microporosity (A) and Macroporosity (B). The bar indicates the LSD (0.05) significant differences between cover crops.

The increase in total porosity can be attributed to increased macroporosity because the microporosity showed little change (Figure 2A). More evident differences were observed in macroporosity than in microporosity, which is in agreement with Awe, Reichert, and Fontanela (2020) and Lima et al. (2020). According to these authors, microporosity is not expected to change after subsequent harvests because of soil use and management. According to Lima et al. (2022), micropores predominate in soils with a high silt and clay content and have low dependence on the degree of compactness. According to the authors, the total porosity and larger pores depend more on the compaction state than the micropores.

Ksat was affected ($p < 0.05$) by cover crops during the entire period of the experiment (2016–2017 to 2019–2020). Ksat increased as cover crops improved the soil's physical characteristics (Figure 3). Pigeon peas with taproots increased Ksat to 260 mm h^{-1}, possibly due to improved soil porosity and bulk density. Yu et al. (2016) observed that taproots with a predominance of thick root shafts had the strongest effect on soil hydraulic conductivity, increasing thick pore channels. Owing to the increase in macroporosity generated by cover crops, Haruna, Anderson, Nkongolo, and Zaibon (2018) reported that cover crops improved Ksat by approximately 32% in the 0-20 cm layer.

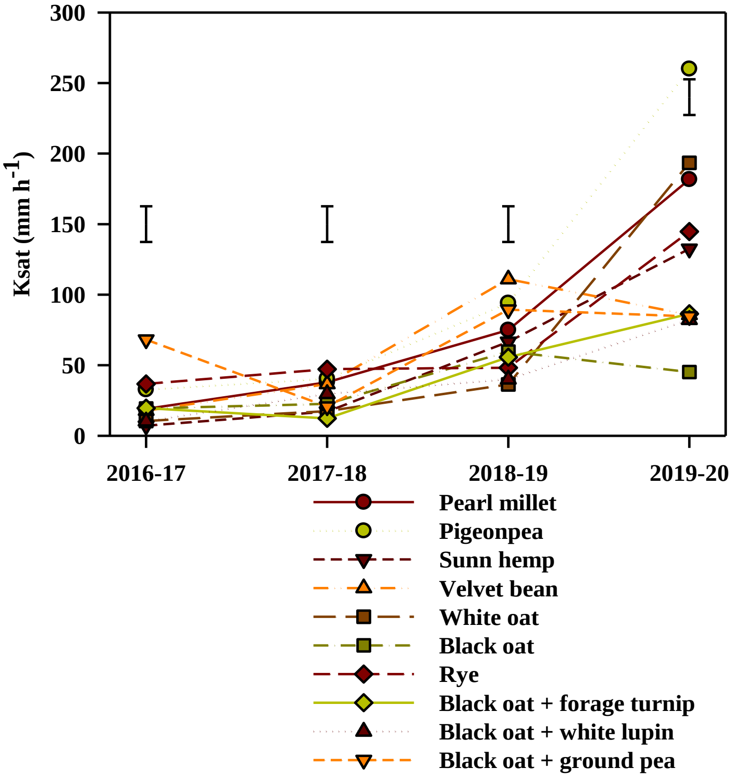

Figure 3. Cover crops affecting Ksat. The bar indicates the LSD (0.05) significant differences between cover crops.

The root canals made by cover crops increase the connectivity between pores (Soracco et al., 2019), which may explain Ksat changes. Soil Ksat is a vital physical property that determines the rate of water infiltration, internal drainage, and other hydrological processes (Jafari, Sheikh, Hossein-Alizadeh, & Rezaii-Moghadam, 2017). Cover crop roots promote changes in soil pore space, which affects Ksat (Carminati et al., 2016). Çerçioğlu, Anderson, Udawatta, and Alagele (2019) also noted that the highest Ksat values were observed five seasons after establishing cover crops, compared to soil samples from the first and second seasons. These differences may be due to better soil structure, lower bulk density, and the proportion of macropores and large mesopores that help water move quickly through the soil (Çerçioğlu et al., 2019). In addition, macropores and fissures were responsible for rapid water transport through the soil profile. In addition to the effects of root growth on improving density and porosity, the biomass remaining in the soil is important for alleviating soil compaction and improving Ksat. OM and straw exert a traffic dampening effect by partially dissipating the impact energy applied to the ground by machines (Reichert et al., 2018).

Conclusion

In this study, ten single or mixed cover crops were cultivated in mechanically compacted soils. Pigeon pea could reduce bulk density and increase porosity and Ksat in compacted soils. Ksat increased as cover crops improved soil physical characteristics. Mixing cover crops did not improve the physical properties of the soil. The selection of cover crops with characteristics that improve the physical properties of soil is crucial for compacted areas.

References

Ajayi, A. E., Horn, R., Rostek, J., Uteau, D., & Peth, S. (2019). Evaluation of temporal changes in hydrostructural properties of regenerating permanent grassland soils based on shrinkage properties and µCT analysis. *Soil and Tillage Research*, *185*, 102–112. DOI: https://doi.org/10.1016/j.still.2018.09.005

Awe, G. O., Reichert, J. M., & Fontanela, E. (2020). Sugarcane production in the subtropics: Seasonal changes in soil properties and crop yield in no-tillage, inverting and minimum tillage. *Soil and Tillage Research*, *196*, 1-7. DOI: https://doi.org/10.1016/j.still.2019.104447

Blanco-Canqui, H., & Jasa, P. J. (2019). Do grass and legume cover crops improve soil properties in the long term?. *Soil Science Society of America Journal*, *83*(4), 1181-1187. DOI: https://doi.org/10.2136/sssaj2019.02.0055

Blanco-Canqui, H., & Ruis, S. J. (2020). Cover crop impacts on soil physical properties: A review. *Soil Science Society of America Journal*, *84*(5), 1527-1576. DOI: https://doi.org/10.1002/saj2.20129

Bengough, A. G. (2012). Water dynamics of the root zone: rhizosphere biophysics and its control on soil hydrology. *Vadose Zone Journal*, *11*(2). DOI: https://doi.org/10.2136/vzj2011.0111

Bodner, G., Leitner, D., & Kaul, H. P. (2014). Coarse and fine root plants affect pore size distributions differently. *Plant and Soil*, *380*(1), 133-151. DOI: https://doi.org/10.1007/s11104-014-2079-8

Calonego, J. C., & Rosolem, C. A. (2010). Soybean root growth and yield in rotation with cover crops under chiseling and no-till. *European Journal of Agronomy*, *33*(3), 242-249. DOI: http://doi.org/10.1016/j.eja.2010.06.002

Calonego, J. C., Gomes, T. C., Santos, C. H., & Tiritan, C. S. (2011). Cover crops growth in compacted soil. *Bioscience Journal*, *27*(2), 289-296.

Calonego, J. C., Raphael, J. P., Rigon, J. P., Oliveira Neto, L., & Rosolem, C. A. (2017). Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. *European Journal of Agronomy*, *85*, 31-37. DOI: https://doi.org/10.1016/j.eja.2017.02.001

Carminati, A., Zarebanadkouki, M., Kroener, E., Ahmed, M. A., & Holz, M. (2016). Biophysical rhizosphere processes affecting root water uptake. *Annals of Botany*, *118*(4), 561-571. DOI: https://doi.org/10.1093/aob/mcw113

Çerçioğlu, M., Anderson, S. H., Udawatta, R. P., & Alagele, S. (2019). Effect of cover crop management on soil hydraulic properties. *Geoderma*, *343*, 247-253. DOI: https://doi.org/10.1016/j.geoderma.2019.02.027

Chen, G., & Weil, R. R. (2010). Penetration of cover crop roots through compacted soils. *Plant and Soil*, *331*(1), 31-43. DOI: https://doi.org/10.1007/s11104-009-0223-7

Chen, G., & Weil, R. R. (2011). Root growth and yield of maize as affected by soil compaction and cover crops. *Soil and Tillage Research*, *117*, 17-27. DOI: https://doi.org/10.1016/j.still.2011.08.001

Chen, G., Weil, R. R., & Hill, R. L. (2014). Effects of compaction and cover crops on soil least limiting water range and air permeability. *Soil and Tillage Research*, *136*, 61-69. DOI: https://doi.org/10.1016/j.still.2013.09.004

Colombi, T., Braun, S., Keller, T., & Walter, A. (2017). Artificial macropores attract crop roots and enhance plant productivity on compacted soils. *Science of the Total Environment*, *574*, 1283-1293. DOI: https://doi.org/10.1016/j.scitotenv.2016.07.194

Dechen, S. C. F., Telles, T. S., Guimarães, M. D. F., & Maria, I. C. D. (2015). Losses and costs associated with water erosion according to soil cover rate. *Bragantia*, *74*(2), 224-233. DOI: https://doi.org/10.1590/1678-4499.0363

Drescher, M. S., Reinert, D. J., Denardin, J. E., Gubiani, P. I., Faganello, A., Silva, B. R. D., & Zardin, M. C. (2017). Fertilizer shanks to promote soil decompaction in the seeding operation. *Ciência Rural*, *47*(3), 1-8. DOI: https://doi.org/10.1590/0103-8478cr20160026

Farias, L. D. N., Bonfim-Silva, E. M., Pietro-Souza, W., Vilarinho, M. K., Silva, T. J., & Guimarães, S. L. (2013). Características morfológicas e produtivas de feijão guandu anão cultivado em solo compactado. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *17*(5), 497-503. DOI: https://doi.org/10.1590/S1415-43662013000500005

Feng, Y., Wang, J., Liu, T., Bai, Z., & Reading, L. (2019). Using computed tomography images to characterize the effects of soil compaction resulting from large machinery on three-dimensional pore characteristics in an opencast coal mine dump. *Journal of Soils and Sediments*, *19*(3), 1467-1478. DOI: https://doi.org/10.1007/s11368-018-2130-0

Ferreira, C. J. B., Tormena, C. A., Severiano, E. D. C., Zotarelli, L., & Betioli Júnior, E. (2021). Soil compaction influences soil physical quality and soybean yield under long-term no-tillage. *Archives of Agronomy and Soil Science*, *67*(3), 383-396. DOI: https://doi.org/10.1080/03650340.2020.1733535

Fuentes-Llanillo, R., Telles, T. S., Junior, D. S., Melo, T. R., Friedrich, T., & Kassam, A. (2021). Expansion of no-tillage practice in conservation agriculture in Brazil. *Soil and Tillage Research*, *208*, 1-28. DOI: https://doi.org/10.1016/j.still.2020.104877

Garbelini, L. G., Franchini, J. C., Debiasi, H., Balbinot Junior, A. A., Betioli Junior, E., & Telles, T. S. (2020). Profitability of soybean production models with diversified crops in the autumn winter. *Agronomy Journal*, *112*(5), 4092-4103. DOI: https://doi.org/10.1002/agj2.20308

Grzesiak, S., Grzesiak, M. T., Hura, T., Marcińska, I., & Rzepka, A. (2013). Changes in root system structure, leaf water potential and gas exchange of maize and triticale seedlings affected by soil compaction. *Environmental and Experimental Botany*, *88*, 2-10. DOI: https://doi.org/10.1016/j.envexpbot.2012.01.010

Gubiani, P. I., Reinert, D. J., Reichert, J. M., Gelain, N. S., & Minella, J. P. G. (2010). Permeâmetro de carga decrescente associado a programa computacional para a determinação da condutividade hidráulica do solo saturado. *Revista Brasileira de Ciência do Solo*, *34*(3), 993-997. DOI: https://doi.org/10.1590/S0100-06832010000300041

Hamza, M. A., & Anderson, W. K. (2005). Soil compaction in cropping systems: a review of the nature, causes and possible solutions. *Soil and Tillage Research*, *82*(2), 121-145. DOI: http://dx.doi.org/10.1016/j.still.2004.08.009

Haruna, S. I., Anderson, S. H., Nkongolo, N. V., & Zaibon, S. (2018). Soil hydraulic properties: Influence of tillage and cover crops. *Pedosphere*, *28*(3), 430-442. DOI: https://doi.org/10.1016/S1002-0160(17)60387-4

Haruna, S. I., Anderson, S. H., Udawatta, R. P., Gantzer, C. J., Phillips, N. C., Cui, S., & Gao, Y. (2020). Improving soil physical properties through the use of cover crops: A review. *Agrosystems, Geosciences & Environment*, *3*(1), 1-18. DOI: https://doi.org/10.1002/agg2.20105

Hudek, C., Putinica, C., Otten, W., & De Baets, S. (2022). Functional root trait-based classification of cover crops to improve soil physical properties. *European Journal of Soil Science*, *73*(1), 1-16. DOI: https://doi.org/10.1111/ejss.13147

Jabro, J. D., Allen, B. L., Rand, T., Dangi, S. R., & Campbell, J. W. (2021). Effect of previous crop roots on soil compaction in 2 yr rotations under a no-tillage system. *Land*, *10*(202), 1-10. DOI: https://doi.org/10.3390/land10020202

Jafari, R., Sheikh, V., Hossein-Alizadeh, M., & Rezaii-Moghadam, H. (2017). Effect of soil sample size on saturated soil hydraulic conductivity. *Communications in Soil Science and Plant Analysis*, *48*(8), 908-919. DOI: https://doi.org/10.1080/00103624.2017.1323086

Lima, R. P., Keller, T., Giarola, N. B., Tormena, C. A., da Silva, A. R., & Rolim, M. M. (2020). Measurements and simulations of compaction effects on the least limiting water range of a no-till Oxisol. *Soil Research*, *58*, 62-72. DOI: https://doi.org/10.1071/SR19074

Lima, L. B., Petter, F. A. & Leandro, W. M. (2015). Desempenho de plantas de cobertura sob níveis de compactação em Latossolo Vermelho de Cerrado. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *19*(11), 1064-1071. DOI: http://dx.doi.org/10.1590/18071929/agriambi.v19n11p1064-1071

Lima, R. P., Rolim, M. M., Toledo, M. P., Tormena, C. A., da Silva, A. R., Silva, I. A. C., & Pedrosa, E. M. (2022). Texture and degree of compactness effect on the pore size distribution in weathered tropical soils. *Soil and Tillage Research*, *215*. DOI: https://doi.org/10.1016/j.still.2021.105215

Lynch, J. P., & Wojciechowski, T. (2015). Opportunities and challenges in the subsoil: pathways to deeper rooted crops. *Journal of Experimental Botany*, *66*(8), 2199-2210. DOI: https://doi.org/10.1093/jxb/eru508

Panziera, W., Lima, C. L. R., Timm, L. C., Aquino, L. S., Barros, W. S., Stumpf, L., ... Pauletto, E. A. (2022). Investigating the relationships between soil and sugarcane attributes under different row spacing configurations and crop cycles using the state-space approach. *Soil and Tillage Research*, *217*, 1-6. DOI: https://doi.org/10.1016/j.still.2021.105270

Peixoto, D. S., Silva, B. M., Oliveira, G. C., Moreira, S. G., Silva, F., & Curi, N. (2019). A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. *Soil and Tillage Research*, *194*, 1-7. DOI: https://doi.org/10.1016/j.still.2019.104307

Ramos, M. F., Silva Almeida, W. R., Amaral, R. D. L., & Suzuki, L. E. A. S. (2022). Degree of compactness and soil quality of peach orchards with different production ages. *Soil and Tillage Research*, *219*, 1-7. DOI: https://doi.org/10.1016/j.still.2022.105324

Reichert, J. M., Suzuki, L. E. A. S., Reinert, D. J., Horn, R., & Hakansson, I. (2009). Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. *Soil and Tillage Research*, *102*(2), 242-254. DOI: https://doi.org/10.1016/j.still.2008.07.002

Reichert, J. M., Rodrigues, M. F., Bervald, C. M. P., & Kato, O. R. (2016). Fire-free fallow management by mechanized chopping of biomass for sustainable agriculture in Eastern Amazon: Effects on soil compactness, porosity, and water retention and availability. *Land Degradation & Development*, *27*(5), 1403-1412. DOI: https://doi.org/10.1002/ldr.2395

Reichert, J. M., Corcini, A. L., Awe, G. O., Reinert, D. J., Albuquerque, J. A., Gallarreta, C. C. G., & Docampo, R. (2022). Onion-forage cropping systems on a Vertic Argiudoll in Uruguay: Onion yield and soil organic matter, aggregation, porosity and permeability. *Soil and Tillage Research*, *216*, 1-7. DOI: https://doi.org/10.1016/j.still.2021.105229

Reichert, J. M., Mentges, M. I., Rodrigues, M. F., Cavalli, J. P., Awe, G. O., & Mentges, L. R. (2018). Compressibility and elasticity of subtropical no-till soils varying in granulometry organic matter, bulk density and moisture. *Catena*, *165*, 345-357. DOI: https://doi.org/10.1016/j.catena.2018.02.014

Reinert, D. J., Albuquerque, J. A., Reichert, J. M., Aita, C., & Andrada, M. M. C. (2008). Limites críticos de densidade do solo para o crescimento de raízes de plantas de cobertura em Argissolo Vermelho. *Revista Brasileira de Ciência do Solo*, *32*(5), 1805-1816. DOI: https://doi.org/10.1590/S0100-06832008000500002

Reinert, D. J., & Reichert, J. M. (2006). Coluna de areia para medir a retenção de água no solo: protótipos e teste. *Ciência Rural*, *36*(6), 1931-1935. DOI: https://doi.org/10.1590/S0103-84782006000600044

Ren, L., Nest, T. V., Ruysschaert, G., D'Hose, T., & Cornelis, W. M. (2019). Short-term effects of cover crops and tillage methods on soil physical properties and maize growth in a sandy loam soil. *Soil and Tillage Research*, *192*, 76-86. DOI: https://doi.org/10.1016/j.still.2019.04.026

Rosolem, C. A., Foloni, J. S. S., & Tiritan, C. S. (2002). Root growth and nutrient accumulation in cover crops as affected by soil compaction. *Soil and Tillage Research*, *65*(1), 109-115. DOI: http://dx.doi.org/10.1016/S0167-1987(01)00286-0

Ruis, S. J., Blanco-Canqui, H., Elmore, R. W., Proctor, C., Koehler-Cole, K., Ferguson, R. B., ... Shapiro, C. A. (2020). Impacts of cover crop planting dates on soils after four years. *Agronomy Journal*, *112*(3), 1649-1665. DOI: https://doi.org/10.1002/agj2.20143

Scarpare, F. V., van Lier, Q. D. J., Camargo, L., Pires, R. C. M., Ruiz-Correa, S. T., Bezerra, A. H. F., ... Dias, C. T. D. S. (2019). Tillage effects on soil physical condition and root growth associated with sugarcane water availability. *Soil and Tillage Research*, *187*, 110-118. DOI: https://doi.org/10.1016/j.still.2018.12.005

Secco, D., Bassegio, D., Villa, B., Marins, A. C., Junior, L. A. Z., Silva, T. R. B., & Souza, S. N. M. (2021). Crambe oil yield and soil physical properties responses to no-tillage, cover crops and chiseling. *Industrial Crops and Products*, *161*, 1-6. DOI: https://doi.org/10.1016/j.indcrop.2020.113174

Silva, R. F., Costa Severiano, E., Oliveira, G. C., Barbosa, S. M., Peixoto, D. S., Tassinari, D., ... Figueiredo, T. D. A. F. R. (2021). Changes in soil profile hydraulic properties and porosity as affected by deep tillage soil preparation and Brachiaria grass intercropping in a recent coffee plantation on a naturally dense Inceptisol. *Soil and Tillage Research*, *213*, 1-8. DOI: https://doi.org/10.1016/j.still.2021.105127

Soares, M. D. R., Souza, Z. M., Campos, M. C. C., Silva, R. B., Esteban, D. A. A., Noronha, R. L., ... Cunha, J. M. (2021). Land-use change and its impact on physical and mechanical properties of Archaeological Black Earth in the Amazon rainforest. *Catena*, *202*, 1-7. DOI: https://doi.org/10.1016/j.catena.2021.105266

Soil Survey Staff. (2010). *Keys to soil taxonomy* (11th ed.). Washingthon, DC: USDA-Natural Resources Conservation Service.

Soracco, C. G., Villarreal, R., Melani, E. M., Oderiz, J. A., Salazar, M. P., Otero, M. F., ... Lozano, L. A. (2019). Hydraulic conductivity and pore connectivity. Effects of conventional and no-till systems determined using a simple laboratory device. *Geoderma*, *337*, 1236-1244. DOI: https://doi.org/10.1016/j.geoderma.2018.10.045

Smith, R. G., Atwood, L. W., & Warren, N. D. (2014). Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. *PLoS ONE*, *9*(5), 1-8. DOI: https://doi.org/10.1371/journal.pone.0097351

Stavi, I., Lal, R., Jones, S., & Reeder, R. C. (2012). Implications of cover crops for soil quality and geodiversity in a humid-temperate region in the Midwestern USA. *Land Degradation & Development*, *23*(4), 322-330. DOI: https://doi.org/10.1002/ldr.2148

Tormena, C. A., Karlen, D. L., Logsdon, S., & Cherubin, M. R. (2017). Corn stover harvest and tillage impacts on near-surface soil physical quality. *Soil and Tillage Research*, *166*, 122-130. DOI: https://doi.org/10.1016/j.still.2016.09.015

Yu, Y., Loiskand, W., Kaul, H. P., M, Himmelbauer, Wei, W., Chen, L., & Bodner, G. (2016). Estimation of runoff mitigation by morphologically different cover crop root systems. *Journal of Hydrology*, *538*, 667-676. DOI: https://doi.org/10.1016/j.jhydrol.2016.04.060

Vujić, S., Krstić, D., Mačkić, K., Čabilovski, R., Radanović, Z., Zhan, A., & Ćupina, B. (2021). Effect of winter cover crops on water soil storage, total forage production, and quality of silage maize. *European Journal of Agronomy*, *130*, 1-7. DOI: https://doi.org/10.1016/j.eja.2021.126366