UNIVERSIDADE FEDERAL DE LAVRAS

DEVISON SOUZA PEIXOTO

SOIL COMPACTION IN NO-TILLAGE SYSTEM:

DIAGNOSIS, MONITORING AND ALLEVIATION

LAVRAS – MG

2021

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para obtenção do título de Doutor.

Prof. Dr. Bruno Montoani Silva
Orientador

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APROVADA em 28 de junho de 2021.

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2021

À minha família, mãe Elienalva, pai João e irmã Deise pelo apoio e dedicação em todas as etapas da minha vida acadêmica e por serem minhas inspirações e exemplos de vida.

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“A definição de insanidade é fazer a mesma coisa repetidamente e esperar resultados diferentes.”

(Albert Einstein)

“Uma pessoa que nunca cometeu um erro, nunca tentou nada de novo.”

(Albert Einstein)

“O que sabemos é uma gota; o que ignoramos é um oceano.”

(Isaac Newton)

RESUMO GERAL

Muitos desafios surgiram com a adoção do sistema plantio direto (SPD), por exemplo: compactação do solo, manejo de plantas daninhas e estratificação de matéria orgânica e nutrientes. Para superar estes desafios, proprietários rurais e pesquisadores têm empregado o preparo ocasional (PO), que consiste no uso de algum método de preparo do solo, como escarificação, subsolagem, aração e gradagem em SPD. Neste sentido, o objetivo geral foi contribuir para a melhoraria da acurácia do diagnóstico, monitoramento e alívio da compactação do solo em SPD. Os objetivos específicos foram: 1) realizar uma meta-análise global dos efeitos do PO na produtividade dos cultivos de grãos, nas propriedasdes físicas, químicas e biológicas do solo, na erosão do solo e controle de plantas daninhas; 2) identificar as propriedades físicas do solo mais relacionadas com a resposta dos cultivos às mudanças estruturais, e portanto, mais adequadas para o diagnóstico da compactação do solo; 3) testar a abordagem de aprendizagem de máquina na triagem de propriedades físicas do solo e sua relação com a produtividade das culturas; 4) propor uma metodologia de diagnóstico, monitoramento e alívio da compactação do solo em SPD usando a resistência à penetração como indicador; 5) unir o conhecimento de modelagem de pressões verticais aplicadas por máquinas agrícolas, capacidade de suporte de carga do solo (pressão de pré-consolidação) e qualidade física do solo (intervalo hídrico ótimo) para manejo preventivo da compactação do solo; 6) propor uma aplicação da aprendizagem de máquina para o diagnóstico da compactação do solo em SPD. O experimento foi implantado em outubro de 2015 na Fazenda Santa Helena, no município de Nazareno, Minas Gerais, em um Latossolo Vermelho Amarelo Distrófico típico, textura argilosa. Os tratamentos consistiram em manejos do solo para mitigação da compactação, combinando subsolagem e duas formas de aplicação de calcário, duas frequências de subsolagem (2 e 3 anos), escarificação, aplicação de gesso e um tratamento controle (SPD contínuo), totalizando 7 manejos. Os cultivos avaliados no período de 2015 a 2019 foram: soja (2015/2016 e 2017/2018), milho (2016/2017 e 2018/2019), feijão (2017) e trigo (2018). A meta-análise mostrou que o PO não afetou a produtividade dos cultivos, pH, fósforo disponível e a atividade microbiana; melhorou as propriedades físicas do solo e o controle de plantas daninhas; e reduziu a estabilidade dos agregados, carbono orgânico total do solo e a erosão do solo. Com o experimento verificou-se que o PO melhorou as propriedades físicas do solo e aumentou a produtividade dos cultivos subsequentes, especialmente a soja, trazendo benefícios econômicos. As propriedades físicas do solo mais sensíveis às práticas de PO e à resposta dos cultivos em produtividade foram resistência à penetração, capacidade de aeração, macroporosidade, capacidade de campo relativa e índice “S”. Para o diagnóstico e monitoramento da compactação do solo em SPD, os resultados mostraram maior acurácia quando a resistência à penetração é avaliada entre o potencial matricial de -0,03 e -0,50 MPa, preferencialmente -0,10 MPa, portanto, mais seco que a capacidade de campo como sugerido na literatura. Com base nestes resulados, uma proposta metodológica a partir da modelagem da resistência à penetração em laboratório como indicador de compactação do solo em áreas de SPD foi sugerida e testada. A união da modelagem de pressões verticais aplicadas por máquinas agrícolas, capacidade de suporte de carga do solo e qualidade física do solo foi eficiente para auxiliar no manejo preventivo da compactação do solo em sistemas de produção de culturas anuais. Por fim, a abordagem de classificação dos algoritmos de aprendizagem de máquina mostrou-se eficiente no diagnóstico e predição da compactação do solo em SPD, por combinar as respostas de um conjunto de propriedades físicas do solo e produtividade dos cultivos, melhorando a tomada de decisão quanto ao uso de PO.

Palavras-chave: Propriedades físicas do solo. Manejo do solo. Preparo ocasional. Resistência à penetração. Aprendizagem de máquina. Subsolagem.

GENERAL ABSTRACT

Many challenges have arisen with the adoption of no-tillage (NT), for example: soil compaction, weed management and stratification of soil organic matter and nutrients. To overcome these challenges, rural landowners and researchers have used occasional tillage (OT), which consists of using some method of soil tillage, such as chiseling, subsoiling, plowing and harrowing in consolidated NT. In this sense, the general objective was to improve the accuracy of the diagnosing, monitoring and alleviation of soil compaction in NT. The specific objectives were: 1) to perform a global meta-analysis of the effects of OT on annual crop yield, soil physical, chemical and biological properties, soil erosion and weed control; 2) to identify the soil physical properties that are more related to the crops response, and therefore, more suitable for the diagnosis of soil compaction; 3) to test the machine learning approach in sorting the soil physical properties and its relationship with crops yield; 4) to propose a methodology for diagnosing, monitoring and management of soil compaction in NT using the penetration resistance as an indicator; 5) linking knowledge of modeling vertical pressures applied by agricultural machines, soil load-bearing capacity (pre-consolidation pressure) and soil physical quality (least limiting water range) for preventive management of soil compaction; 6) to propose the use of machine learning for the diagnosis of soil compaction in NT. An experiment was implemented in October 2015 at Farm Santa Helena, in the municipality of Nazareno, Minas Gerais, in a Typic Hapludox, clay texture. The treatments consisted of soil management to mitigate compaction, combining subsoiling and two forms of lime application, two subsoiling frequencies (two and three years), chiseling, gypsum application and a control treatment (continuous NT), totaling seven managements. The crops evaluated in the period from 2015 to 2019 were: soybeans (2015/2016 and 2017/2018), maize (2016/2017 and 2018/2019), common beans (2017) and wheat (2018). The meta-analysis showed that OT did not affect crop yield, pH, available phosphorus and microbial activity; improved soil physical properties and weed control; and reduced aggregate stability, total organic carbon and soil erosion. It was found with the experiment that the OT improved the soil physical properties and increased the crops yield subsequent, especially soybeans, promoting economic benefits. The soil physical properties most sensitive of OT and the crops response were the penetration resistance, aeration capacity, macroporosity, relative field capacity and the “S” index. The penetration resistance should be evaluated between the matric potential of -0.03 and -0.50 MPa, preferably -0.10 MPa, for the diagnosing and monitoring of soil compaction in NT, therefore, drier than the field capacity suggested in the literature. From this, a methodological proposal using penetration resistance as an indicator of soil compaction in NT areas was suggested and tested. The link of modeling vertical pressures applied by agricultural machines, soil load-bearing capacity and soil physical quality was efficient to assist in the preventive management of soil compaction in annual crop production systems. Finally, the classification approach of machine learning algorithms proved to be efficient in the diagnosis of soil compaction in NT, by combining the responses of a set of soil physical properties and crop yield, improving decision making regarding the use of OT.

Keywords: Soil physical properties. Soil management. Occasional tillage. Penetration resistance. Machine learning. Subsoiling.

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SUMMARY

FIRST PART

INTRODUCTION

Brazil is one of the world's largest grain producers and exporters. The main cash crops cultivated in the country are soybean, corn, beans, wheat, rice, and seed cotton. In 2019/2020 season crop, some estimates showed that 65.9 million hectares were cultivated with cash crops. Soybean was the main crop (36.9 million hectares), followed by corn (18.5 million hectares), and lastly by beans (2.9 million hectares). The total production was 257 million tons, and average yields were: soybean (3,379 kg ha^{-1}), corn (5,537 kg ha^{-1}), beans (1,104 kg ha^{-1}), and wheat (2,663 kg ha^{-1}). The most important states to total production were: Mato Grosso (29.1%), Paraná (15.9%), Goiás (10.7%), Rio Grande do Sul (10.2%), Mato Grosso do Sul (8.0%), and Minas Gerais (6.0%), which together accounted for 80% of grain production in the country (COMPANHIA NACIONAL DE ABASTECIMENTO, 2021).

In this scenario, approximately half of the area cultivated with grains in Brazil is under no-tillage (NT), with more than 32 million hectares (KASSAM; FRIEDRICH; DERPSCH, 2018). In the world, the NT areas exceed 180 million hectares, corresponding to 12.5% of the agricultural area, and with an expansion of 10.5 million hectares per year (KASSAM; FRIEDRICH; DERPSCH, 2018). The NT consists of the adoption of three basic principles: minimal mechanical disturbance to the soil, permanent soil cover with crop residues, and crop diversification (LAL; REICOSKY; HANSON, 2007; DERPSCH et al., 2010; REICOSKY, 2015; KASSAM; FRIEDRICH; DERPSCH, 2018). NT is relevant for both the economy and conservation of soil and water resources (LAL; REICOSKY; HANSON, 2007; DERPSCH et al., 2010; KASSAM; FRIEDRICH; DERPSCH, 2018). Compared to conventional tillage, the benefits of NT include improved structure and stability of soil aggregates, increased water retention capacity, increased organic matter content in the topsoil, increased water infiltration rate in the soil, reduced water erosion, increased natural biodiversity, reduced energy consumption, higher or equal productivity compared to conventional systems, and higher profitability over time (LAL; REICOSKY; HANSON, 2007; ALVAREZ; STEINBACH, 2009; THIERFELDER; WALL, 2009; DERPSCH et al., 2010; DEVINE et al., 2014; KUROTHE et al., 2014; SINGH et al., 2014; SHRESTHA et al., 2015; BLANCO-CANQUI; RUIS, 2018; KASSAM; FRIEDRICH; DERPSCH, 2018).

The main challenges to the sustainability of grain production in Brazil are associated with the low production of straw to cover the soil, mainly due to the constant adoption of the soybean/corn successions and soybean/fallow in some regions; the management of weeds, primarily due to herbicide resistance; the incidence of pests and diseases due to the formation of a “green bridge” during most of the year; the deficient construction of soil fertility to establish production systems; and soil compaction problems, which lead to the use of soil tillage without a proper compaction diagnosis (MOREIRA, 2019). Thus, it is necessary to improve the management of soil and crops to achieve high yields and develop sustainable production systems.

Several studies have shown soil compaction problems in NT (REICHERT et al., 2009, 2017; SUZUKI; REICHERT; REINERT, 2013; NUNES et al., 2014, 2015a, 2015b; BLANCO-CANQUI; RUIS, 2018). Soil compaction reflects the other challenges for the sustainability of grain production systems in Brazil. Soil compaction in NT systems results from the intensification of the production system and and consequent increase in machine weight and traffic, often performed in inadequate soil moisture conditions. Besides, soil compaction is worsened by inefficient crop rotation, low use of cover crops and intercropping species, which reduce straw input and soil organic matter levels (DENARDIN; FAGANELLO; SANTI, 2008; DRESCHER et al., 2011; MOREIRA, 2019).

Globally, soil compaction is one of the main problems of degradation in agricultural soils and can reduce crop yields by up to 75% (HAMZA; ANDERSON, 2005; NAWAZ; BOURRIÉ; TROLARD, 2013; CORREA et al., 2019; KELLER et al., 2019). Soil compaction refers to the compression of unsaturated soil, which increases soil bulk density and simultaneously reduces soil porosity (macroporosity) owing to the application of mechanical stresses (DIAS JÚNIOR; PIERCE, 1996; SOIL SCIENCE GLOSSARY TERMS COMMITTEE, 2008; DIAS JUNIOR; TASSINARI; MARTINS, 2019). Crops have an optimal level of soil compaction, as the response of crops to the degree of soil compaction has parabolic behavior (HÅKANSSON, 1990; ARVIDSSON; HÅKANSSON, 1991, 2014). Therefore, not every increase in soil bulk density and reduction in soil porosity is harmful to plant development.

Soil compaction affects crop yields by impairing the physical factors that have a direct impact on crop growth, such as increased mechanical resistance, reduced aeration, and water availability (LETEY, 1985), restricting root growth, gases exchange, and water and nutrients uptake by plants' roots (LIPIEC; STĘPNIEWSKI, 1995; BENGOUGH et al., 2006; LIPIEC et al., 2012; SZATANIK-KLOC et al., 2018; CORREA et al., 2019).

To mitigate or alleviate the adverse effects of soil compaction on NT, farmers, consultants, and researchers have suggested the use of occasional or strategic soil tillage (OT), mostly with chisel plow and subsoiler (DRESCHER et al., 2011, 2016; NUNES et al., 2014, 2015b, 2015a; WANG et al., 2014; LOZANO et al., 2016). OT uses some soil tillage methods to mitigate possible problems arising from inadequate management practices in areas under long-term NT, such as weed control; soil compaction release; incorporation of crop residue; incorporation of lime, fertilizers, and organic compost; reduced stratification of organic matter, nutrients, and soil acidity; increased soil temperature in wet and cold areas; improved soil-seed contact; reduction of repellency between the soil surface and water (hydrophobicity); and breaking the cycles of pests and diseases in soils (BLANCO-CANQUI; WORTMANN, 2020).

OT can be harmful to NT by increasing soil and nutrient losses by erosion (MELLAND; ANTILLE; DANG, 2017; DEUSCHLE et al., 2019) and reducing the soil organic matter content (MELERO et al., 2011). These negative effects undermine the main benefits of NT in cropping systems of tropical regions (LAL; REICOSKY; HANSON, 2007). Therefore, the OT recommendation must be based on indicators that correlate with crop yield. If OT does not increase crop yield, its use would be questioned. Some studies have observed an increase in crop yield following OT (CALONEGO; ROSOLEM, 2010; NASCIMENTO et al., 2016; CALONEGO et al., 2017; BOTTA et al., 2019), whereas others found no effect (QUINCKE et al., 2007; GIRARDELLO et al., 2011; LÓPEZ-GARRIDO et al., 2011; DRESCHER et al., 2012). A recent literature review showed that, overall, OT could increase the risk of erosion, has a reduced effect on soil physical properties, and does not affect carbon stocks or crop yields. However, it reduces the vertical stratification of organic carbon and nutrients and decreases soil microbial biomass (BLANCO-CANQUI; WORTMANN, 2020).

These divergent results are likely due to differences in the sensitivity of crops to soil compaction (ARVIDSSON; ETANA; RYDBERG, 2014; ARVIDSSON; HÅKANSSON, 2014), water supply during the cultivation cycle (GIRARDELLO et al., 2011; HAKOJÄRVI et al., 2013), quality of the OT operations, soil recompaction by reducing the load-bearing capacity by tillage, breaking the continuity of pores and, perhaps most importantly, inaccurate compaction diagnosis for OT recommendation (DENARDIN; FAGANELLO; SANTI, 2008). A promising possibility to improving the accuracy of soil compaction diagnosis is the use of computational methods based on machine learning techniques. Some studies have already applied this approach to predict crop yields (MISHRA; MISHRA; SANTRA, 2016; CHLINGARYAN; SUKKARIEH; WHELAN, 2018; MAYA GOPAL; BHARGAVI, 2019), even using some soil properties as predictor covariates (PANTAZI et al., 2016; SMIDT et al., 2016).

In this context, this thesis intended to elucidate the following research problem: how to diagnose and monitor soil compaction status in an NT system and support the decision-making process that is economically and environmentally feasible towards the use of OT?

Hypothesis, objectives and thesis structure

Based on the problems presented, the hypotheses of this thesis are: 1) OT improves the physical conditions of soils, resulting in greater crop yield after mechanical intervention; 2) An accurate diagnosis of soil compaction in NT can be performed using quick, low-cost, and easy-to-measure soil physical properties, such as penetration resistance, soil bulk density, macroporosity; 3) OT effects on crop yield are maximized when associated with limestone application, superficial or in-depth; 4) Subsoiling is more effective as an OT method than chiseling; 5) Different subsoilers have distinct effects on soil physical properties and crop yields and 6) The persistence of OT effects in soil physical properties and crop yield is transitory and generally lasts for less than 24 months.

Thus, the overall objective of this thesis was to improve the diagnosis and monitoring of soil compaction in long-term NT to assist researchers, consultants, and farmers in the decision-making process towards the use of mitigation methods. The specific objectives were: 1) to summarize the effects of OT on soil physical, chemical and biological properties, crop yield, and soil erosion from studies worldwide 2) identify soil physical properties that are sensitive to changes promoted by OT in the soil and that relate to the yield of annual crops; 3) monitor the effects of OT on the soil physical properties and soybean, corn, wheat, and beans yields; 4) evaluate the effect of OT associated with limestone application in mitigating compaction problems in NT; 5) identify the most sensitive crops to OT; 6) evaluate the persistence of OT effects on soil physical properties and crop yield; 7) identify the most efficient mechanical method of OT (subsoiling or chisel plowing) to improve soil physical properties and crop yield; 8) propose new methods for diagnosing and monitoring soil compaction in a consolidated NT system, in order to assist in decision-making (management practices) towards the use of OT; 9) combine the knowledge of stresses applied by agricultural machinery, soil load-bearing capacity, and physical quality into one indicator that assists the preventive management of soil compaction in grain production systems.

To meet the objectives, the thesis was structured into five research articles. The chapter 1 is a global meta-analysis on the effects of OT on yields of annual crops, physical, chemical, and biological soil properties, erosion, and weed control. This article discusses the affecting factors of OT efficiency, the main aspects of NT management that optimize the use of OT, and the deficiencies in diagnosing soil compaction in NT (the main reason for the use of OT) that may mislead the decision-making processes towards the use of OT. The chapter 2 applied the Random Forest machine-learning algorithm to identify the soil physical properties most sensitive to soil changes caused by OT and the relationship between these physical properties with soybean yield after mechanical intervention. Fifteen soil physical properties were tested, and the most sensitive were: penetration resistance (PR), aeration capacity, macroporosity, relative field capacity, and the “S” index. In this article, we concluded that the Random Forest algorithm effectively screened the most effective indicators in diagnosing and monitoring soil compaction in NT systems. Besides, we showed that PR can guide the decision-making process towards the use of OT. The chapter 3 is a methodological proposal for diagnosing and monitoring soil compaction using PR as an indicator. We proposed an ideal range of soil water content for the proper diagnosis of soil compaction using PR. It was suggested a matric potential of -0.10 MPa, which is drier than the field capacity suggested in the literature. The chapter 4 sought to merge the knowledge of modeling vertical pressures applied by agricultural machines, soil load-bearing capacity (pre-consolidation pressure), and soil physical quality (optimal water range) to assist in the preventive management of soil compaction in annual crop production systems. Lastly, the chapter 5 applied the classification approach of four machine learning algorithms to diagnose soil compaction using eight soil physical properties together. The accuracy of the diagnosis using several soil physical properties is greater than using just one, such as PR in article 3. Thus, machine learning algorithms were tested, and the decision trees (CART and Random Forest) were the most efficient.

REFERENCES

ALVAREZ, R.; STEINBACH, H. S. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. **Soil and Tillage Research**, v. 104, n. 1, p. 1–15, jun. 2009. doi: 10.1016/j.still.2009.02.005.

ARVIDSSON, J.; ETANA, A.; RYDBERG, T. Crop yield in Swedish experiments with shallow tillage and no-tillage 1983-2012. **European Journal of Agronomy**, v. 52, p. 307–315, 2014. doi: 10.1016/j.eja.2013.08.002.

ARVIDSSON, J.; HÅKANSSON, I. A model for estimating crop yield losses caused by soil compaction. **Soil and Tillage Research**, v. 20, n. 2–4, p. 319–332, jun. 1991. doi: 10.1016/0167-1987(91)90046-Z.

ARVIDSSON, J.; HÅKANSSON, I. Response of different crops to soil compaction—Short-term effects in Swedish field experiments. **Soil and Tillage Research**, v. 138, p. 56–63, maio 2014. doi: 10.1016/j.still.2013.12.006.

BENGOUGH, A. G.; BRANSBY, M. F.; HANS, J.; MCKENNA, S. J.; ROBERTS, T. J.; VALENTINE, T. A. Root responses to soil physical conditions; growth dynamics from field to cell. **Journal of Experimental Botany**, v. 57, n. 2, p. 437–447, 1 jan. 2006. doi: 10.1093/jxb/erj003.

BLANCO-CANQUI, H.; RUIS, S. J. No-tillage and soil physical environment. **Geoderma**, v. 326, p. 164–200, set. 2018. doi: 10.1016/j.geoderma.2018.03.011.

BLANCO-CANQUI, H.; WORTMANN, C. S. Does occasional tillage undo the ecosystem services gained with no-till? A review. **Soil and Tillage Research**, v. 198, p. 104534, 2020. doi: 10.1016/j.still.2019.104534.

BOTTA, G. F.; ANTILLE, D. L.; BIENVENIDO, F.; RIVERO, D.; CONTESSOTTO, E. E. Energy requirements for alleviation of subsoil compaction and the effect of deep tillage on sunflower (Helianthus annus L.) yield in the western region of Argentina’s rolling pampa. **Engineering for Rural Development**, v. 18, p. 174–178, 2019. doi: 10.22616/ERDev2019.18.N216.

CALONEGO, J. C.; RAPHAEL, J. P. A.; RIGON, J. P. G.; OLIVEIRA NETO, L. de; ROSOLEM, C. A. Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. **European Journal of Agronomy**, v. 85, p. 31–37, 2017. doi: 10.1016/j.eja.2017.02.001.

CALONEGO, J. C.; ROSOLEM, C. A. Soybean root growth and yield in rotation with cover crops under chiseling and no-till. **European Journal of Agronomy**, v. 33, n. 3, p. 242–249, 2010. doi: 10.1016/j.eja.2010.06.002.

CHLINGARYAN, A.; SUKKARIEH, S.; WHELAN, B. **Machine learning approaches for crop yield prediction and nitrogen status estimation in precision agriculture: A reviewComputers and Electronics in Agriculture**Elsevier, , 2018. . doi: 10.1016/j.compag.2018.05.012.

COMPANHIA NACIONAL DE ABASTECIMENTO. **Boletim da Safra de Grãos: Acompanhamento da safra 2020/21 brasileira de grãos - 8º levantamento**. Brasília, DF: CONAB, 2021.

CORREA, J.; POSTMA, J. A.; WATT, M.; WOJCIECHOWSKI, T. Soil compaction and the architectural plasticity of root systems. **Journal of Experimental Botany**, v. 70, n. 21, p. 6019–6034, 2019. doi: 10.1093/jxb/erz383.

DENARDIN, J. E.; FAGANELLO, A.; SANTI, A. Falhas na implementação do sistema plantio direto levam à degradação do solo. **Revista Plantio Direto**, v. 18, p. 3–4, 2008.

DERPSCH, R.; FRIEDRICH, T.; KASSAM, A.; HONGWEN, L. Current status of adoption of no-till farming in the world and some of its main benefits. **International Journal of Agricultural and Biological Engineering**, v. 3, n. 1, p. 1–25, 2010. doi: 10.3965/j.issn.1934-6344.2010.01.001-025.

DEUSCHLE, D.; MINELLA, J. P. G.; HÖRBE, T. de A. N.; LONDERO, A. L.; SCHNEIDER, F. J. A. Erosion and hydrological response in no-tillage subjected to crop rotation intensification in southern Brazil. **Geoderma**, v. 340, p. 157–163, abr. 2019. doi: 10.1016/j.geoderma.2019.01.010.

DEVINE, S.; MARKEWITZ, D.; HENDRIX, P.; COLEMAN, D. Soil Aggregates and Associated Organic Matter under Conventional Tillage, No-Tillage, and Forest Succession after Three Decades. **PLoS ONE**, v. 9, n. 1, p. e84988, 20 jan. 2014. doi: 10.1371/journal.pone.0084988.

DIAS JUNIOR, M. de S.; TASSINARI, D.; MARTINS, P. C. C. Compactação do solo: atualização. In: SEVERIANO, E. DA C.; MORAES, M. F. DE; PAULA, A. M. DE (Ed.). **Tópicos em Ciência do Solo**. 10. ed. [s.l.] Sociedade Brasileira de Ciência do Solo, 2019. p. 7–69.

DIAS JÚNIOR, M. S.; PIERCE, F. J. Revisão de literatura: o processo de compactação do solo e sua modelagem. **Revista Brasileira de Ciencia do Solo**, v. 20, p. 175–182, 1996.

DRESCHER, M. S.; ELTZ, F. L. F.; DENARDIN, J. E.; FAGANELLO, A. Persistência do efeito de intervenções mecânicas para a descompactação de solos sob plantio direto. **Revista Brasileira de Ciência do Solo**, v. 35, n. 5, p. 1713–1722, out. 2011. doi: 10.1590/S0100-06832011000500026.

DRESCHER, M. S.; ELTZ, F. L. F.; DENARDIN, J. E.; FAGANELLO, A.; DRESCHER, G. L. Resistência à penetração e rendimento da soja após intervenção mecânica em latossolo vermelho sob plantio direto. **Revista Brasileira de Ciencia do Solo**, v. 36, n. 6, p. 1836–1844, 2012. doi: 10.1590/S0100-06832012000600018.

DRESCHER, M. S.; REINERT, D. J.; DENARDIN, J. E.; GUBIANI, P. I.; FAGANELLO, A.; DRESCHER, G. L. Duração das alterações em propriedades físico-hídricas de Latossolo argiloso decorrentes da escarificação mecânica. **Pesquisa Agropecuária Brasileira**, v. 51, n. 2, p. 159–168, fev. 2016. doi: 10.1590/S0100-204X2016000200008.

GIRARDELLO, V. C.; AMADO, T. J. C.; NICOLOSO, R. da S.; HÖRBE, T. de A. N.; FERREIRA, A. de O.; TABALDI, F. M.; LANZANOVA, M. E. Alterações nos atributos físicos de um latossolo vermelho sob plantio direto induzidas por diferentes tipos de escarificadores e o rendimento da soja. **Revista Brasileira de Ciencia do Solo**, v. 35, n. 6, p. 2115–2126, 2011. doi: 10.1590/S0100-06832011000600026.

HÅKANSSON, I. A method for characterizing the state of compactness of the plough layer. **Soil and Tillage Research**, v. 16, n. 1–2, p. 105–120, abr. 1990. doi: 10.1016/0167-1987(90)90024-8.

HAKOJÄRVI, M.; HAUTALA, M.; RISTOLAINEN, A.; ALAKUKKU, L. Yield variation of spring cereals in relation to selected soil physical properties on three clay soil fields.

European Journal of Agronomy, v. 49, p. 1–11, 2013. doi: 10.1016/j.eja.2013.03.003.

HAMZA, M. A.; ANDERSON, W. K. Soil compaction in cropping systems. **Soil and Tillage Research**, v. 82, n. 2, p. 121–145, jun. 2005. doi: 10.1016/j.still.2004.08.009.

KASSAM, A.; FRIEDRICH, T.; DERPSCH, R. Global spread of Conservation Agriculture. **International Journal of Environmental Studies**, v. 76, n. 1, p. 29–51, 2 jan. 2018. doi: 10.1080/00207233.2018.1494927.

KELLER, T.; SANDIN, M.; COLOMBI, T.; HORN, R.; OR, D. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. **Soil and Tillage Research**, v. 194, p. 104293, nov. 2019. doi: 10.1016/j.still.2019.104293.

KUROTHE, R. S.; KUMAR, G.; SINGH, R.; SINGH, H. B.; TIWARI, S. P.; VISHWAKARMA, A. K.; SENA, D. R.; PANDE, V. C. Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India. **Soil and Tillage Research**, v. 140, p. 126–134, jul. 2014. doi: 10.1016/j.still.2014.03.005.

LAL, R.; REICOSKY, D. C.; HANSON, J. D. Evolution of the plow over 10,000 years and the rationale for no-till farming. **Soil and Tillage Research**, v. 93, n. 1, p. 1–12, mar. 2007. doi: 10.1016/j.still.2006.11.004.

LETEY, J. Relationship between Soil Physical Properties and Crop Production. In: STEWART, B. A. (Ed.). **Advances in Soil Science**. Advances in Soil Science. New York, NY: Springer New York, 1985. 1 p. 277–294.

LIPIEC, J.; HORN, R.; PIETRUSIEWICZ, J.; SICZEK, A. Effects of soil compaction on root elongation and anatomy of different cereal plant species. **Soil and Tillage Research**, v. 121, p. 74–81, maio 2012. doi: 10.1016/j.still.2012.01.013.

LIPIEC, J.; STĘPNIEWSKI, W. Effects of soil compaction and tillage systems on uptake and losses of nutrients. **Soil and Tillage Research**, v. 35, n. 1–2, p. 37–52, ago. 1995. doi: 10.1016/0167-1987(95)00474-7.

LÓPEZ-GARRIDO, R.; MADEJÓN, E.; MURILLO, J. M.; MORENO, F. Soil quality alteration by mouldboard ploughing in a commercial farm devoted to no-tillage under Mediterranean conditions. **Agriculture, Ecosystems and Environment**, v. 140, n. 1–2, p. 182–190, 2011. doi: 10.1016/j.agee.2010.12.001.

LOZANO, L. A.; SORACCO, C. G.; VILLARREAL, R.; RESSIA, J. M.; SARLI, G. O.; FILGUEIRA, R. R. Soil Physical Quality and Soybean Yield as Affected by Chiseling and Subsoiling of a No-Till Soil. **Revista Brasileira de Ciência do Solo**, v. 40, p. 1–12, 2016. doi: 10.1590/18069657rbcs20150160.

MAYA GOPAL, P. S.; BHARGAVI, R. Performance Evaluation of Best Feature Subsets for Crop Yield Prediction Using Machine Learning Algorithms. **Applied Artificial Intelligence**, v. 33, n. 7, p. 621–642, 7 jun. 2019. doi: 10.1080/08839514.2019.1592343.

MELERO, S.; PANETTIERI, M.; MADEJÓN, E.; MACPHERSON, H. G.; MORENO, F.; MURILLO, J. M. Implementation of chiselling and mouldboard ploughing in soil after 8 years of no-till management in SW, Spain: Effect on soil quality. **Soil and Tillage Research**, v. 112, n. 2, p. 107–113, abr. 2011. doi: 10.1016/j.still.2010.12.001.

MELLAND, A. R.; ANTILLE, D. L.; DANG, Y. P. Effects of strategic tillage on short-term erosion, nutrient loss in runoff and greenhouse gas emissions. **Soil Research**, v. 55, n. 3, p. 201, 2017. doi: 10.1071/SR16136.

MISHRA, S.; MISHRA, D.; SANTRA, G. H. Applications of machine learning techniques in agricultural crop production: A review paper. **Indian Journal of Science and Technology**, v. 9, n. 38, 2016. doi: 10.17485/ijst/2016/v9i38/95032.

MOREIRA, S. G. Desafios para a sustentabilidade dos sistemas de produção com culturas anuais. **Informações Agronômicas**, v. 4, p. 1–12, 2019.

NASCIMENTO, V.; ARF, O.; TARSITANO, M. A. A.; GARCIA, N. F. S.; PENTEADO, M. S.; SABUNDJIAN, M. T. Economic analysis of rice and common bean production in succession to green manure crops and mecahnical soil decompression in Brazilian Savannah. **Revista Ceres**, v. 63, n. 3, p. 315–322, jun. 2016. doi: 10.1590/0034-737X201663030006.

NAWAZ, M. F.; BOURRIÉ, G.; TROLARD, F. Soil compaction impact and modelling. A review. **Agronomy for Sustainable Development**, v. 33, n. 2, p. 291–309, abr. 2013. doi: 10.1007/s13593-011-0071-8.

NUNES, M. R.; DENARDIN, J. E.; PAULETTO, E. A.; FAGANELLO, A.; PINTO, L. F. S. Mitigation of clayey soil compaction managed under no-tillage. **Soil and Tillage Research**, v. 148, p. 119–126, maio 2015a. doi: 10.1016/j.still.2014.12.007.

NUNES, M. R.; DENARDIN, J. E.; PAULETTO, E. A.; FAGANELLO, A.; PINTO, L. F. S. Effect of soil chiseling on soil structure and root growth for a clayey soil under no-tillage. **Geoderma**, v. 259–260, p. 149–155, dez. 2015b. doi: 10.1016/j.geoderma.2015.06.003.

NUNES, M. R.; PAULETTO, E. A.; DENARDIN, J. E.; FAGANELLO, A.; SPINELLI PINTO, L. F.; SCHEUNEMANN, T. Persistência dos efeitos da escarificação sobre a compactação de Nitossolo sob plantio direto em região subtropical úmida. **Pesquisa Agropecuária Brasileira**, v. 49, n. 7, p. 531–539, jul. 2014. doi: 10.1590/S0100-204X2014000700005.

PANTAZI, X. E.; MOSHOU, D.; ALEXANDRIDIS, T.; WHETTON, R. L.; MOUAZEN, A. M. Wheat yield prediction using machine learning and advanced sensing techniques. **Computers and Electronics in Agriculture**, v. 121, p. 57–65, 2016. doi: 10.1016/j.compag.2015.11.018.

QUINCKE, J. A.; WORTMANN, C. S.; MAMO, M.; FRANTI, T.; DRIJBER, R. A.; GARCÍA, J. P. One-time tillage of no-till systems: Soil physical properties, phosphorus runoff, and crop yield. **Agronomy Journal**, v. 99, n. 4, p. 1104–1110, 2007. doi: 10.2134/agronj2006.0321.

REICHERT, J. M.; BRANDT, A. A.; RODRIGUES, M. F.; DA VEIGA, M.; REINERT, D. J. Is chiseling or inverting tillage required to improve mechanical and hydraulic properties of sandy clay loam soil under long-term no-tillage? **Geoderma**, v. 301, n. May, p. 72–79, set. 2017. doi: 10.1016/j.geoderma.2017.04.012.

REICHERT, J. M.; SUZUKI, L. E. A. S.; REINERT, D. J.; HORN, R.; HÅKANSSON, I. 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, mar. 2009. doi: 10.1016/j.still.2008.07.002.

REICOSKY, D. C. Conservation tillage is not conservation agriculture. **Journal of Soil and Water Conservation**, v. 70, n. 5, p. 103A-108A, 1 set. 2015. doi: 10.2489/jswc.70.5.103A.

SHRESTHA, B. M.; SINGH, B. R.; FORTE, C.; CERTINI, G. Long-term effects of tillage, nutrient application and crop rotation on soil organic matter quality assessed by NMR spectroscopy. **Soil Use and Management**, v. 31, n. 3, p. 358–366, set. 2015. doi:

10.1111/sum.12198.

SINGH, A.; PHOGAT, V. K.; DAHIYA, R.; BATRA, S. D. Impact of long-term zero till wheat on soil physical properties and wheat productivity under rice–wheat cropping system. **Soil and Tillage Research**, v. 140, p. 98–105, jul. 2014. doi: 10.1016/j.still.2014.03.002.

SMIDT, E. R.; CONLEY, S. P.; ZHU, J.; ARRIAGA, F. J. Identifying Field Attributes that Predict Soybean Yield Using Random Forest Analysis. **Agronomy Journal**, v. 108, n. 2, p. 637, 2016. doi: 10.2134/agronj2015.0222.

SOIL SCIENCE GLOSSARY TERMS COMMITTEE. **Glossary of soil science terms**. Madison, WI: Soil Science Society of America, 2008.

SUZUKI, L. E. A. S.; REICHERT, J. M.; REINERT, D. J. Degree of compactness, soil physical properties and yield of soybean in six soils under no-tillage. **Soil Research**, v. 51, n. 4, p. 311, 2013. doi: 10.1071/SR12306.

SZATANIK-KLOC, A.; HORN, R.; LIPIEC, J.; SICZEK, A.; SZEREMENT, J. Soil compaction-induced changes of physicochemical properties of cereal roots. **Soil and Tillage Research**, v. 175, n. May 2017, p. 226–233, jan. 2018. doi: 10.1016/j.still.2017.08.016.

THIERFELDER, C.; WALL, P. C. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. **Soil and Tillage Research**, v. 105, n. 2, p. 217–227, nov. 2009. doi: 10.1016/j.still.2009.07.007.

WANG, Q.; LU, C.; LI, H.; HE, J.; SARKER, K. K.; RASAILY, R. G.; LIANG, Z.; QIAO, X.; LI, H.; MCHUGH, A. D. J. The effects of no-tillage with subsoiling on soil properties and maize yield: 12-Year experiment on alkaline soils of Northeast China. **Soil and Tillage Research**, v. 137, p. 43–49, abr. 2014. doi: 10.1016/j.still.2013.11.006.

SECOND PART - PAPERS

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PAPER 1 – OCCASIONAL TILLAGE IN NO-TILLAGE SYSTEMS: A GLOBAL META-ANALYSIS

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Highlights

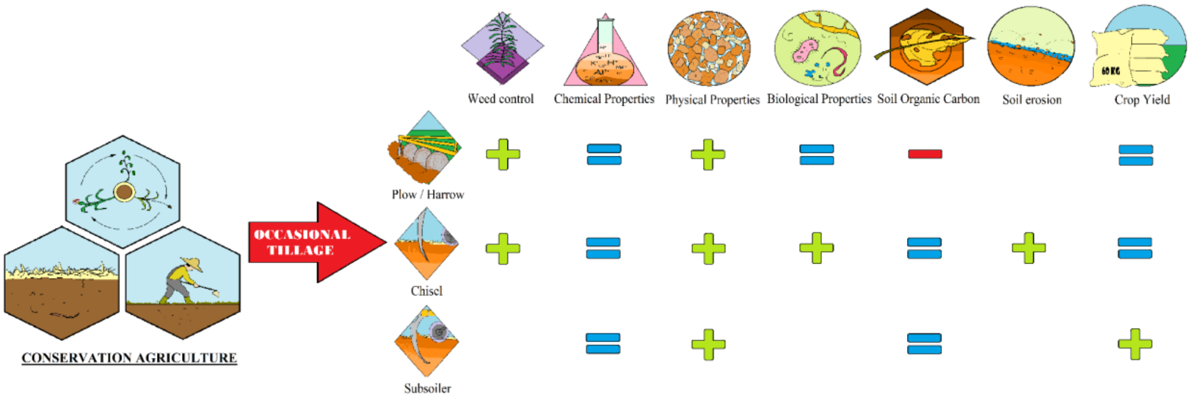
- Overall, occasional tillage (OT) has limited effect on crop yields.
- Impacts of OT were measured as a function of climate, texture, equipment and duration of no-tillage (NT).
- OT reduced soil compaction and improved erosion resistance and weed control.
- OT reduced organic C and did not affect pH, P and microbial activity.
- In general, beneficial OT occurs in 5–10 yr NT and depends on equipment.

Abstract

No-tillage (NT) is a major component of conservation agricultural systems. Challenges that have arisen with the adoption of NT include soil compaction, weed management, and stratification of organic matter and nutrients. As an attempt to overcome these challenges, occasional tillage (OT) has been used as a soil management practice in NT systems. However, little is known about the impacts of OT on agronomic and environmental factors. For this reason, the objectives of this meta-analysis were: 1) to summarize the effects of OT on crop productivity, soil physical, chemical and biological properties, soil erosion and weed control; 2) to discuss the main aspects of NT management to optimize the use of OT; 3) to point out shortcomings in the diagnosis of soil compaction in NT systems, which may lead to erroneous decision-making processes regarding the use of OT. Overall, OT did not affect crops yields, although increased crop yields were observed in regions under water restriction and in soils with low retention capacity and water availability; OT improved soil physical properties (penetration resistance, soil bulk density, macroporosity, and total porosity), with persistence, generally, greater than 24 months, and decreased the soil aggregates stability; total organic carbon was reduced, particularly when plow/harrow was used and NT was already consolidated, and there was no effect on pH and available P; OT increased microbial biomass carbon, but had no effect on total microbial activity; soil erosion was reduced due to increased soil-water infiltration and reduced runoff, and finally, weed management was also improved by OT. It is suggested that suitable NT implementation and management, with the correct application of NT principles, will overcome problems associated with NT. As soil compaction is the main justification for the use of OT, methods of diagnosis and monitoring of soil compaction should be improved to assist in decision-making.

Keywords: chiseling, subsoiling, one-time tillage, strategic tillage, conservation agriculture.

Graphical abstract



1. Introduction

No-tillage (NT) is a key component of conservation agricultural systems, defined by the application of three interconnected principles: no or minimum mechanical soil disturbance, biomass mulch soil cover and crop species diversification (crop rotation/succession/intercropping) (Derpsch et al., 2010; Kassam et al., 2019; Reicosky, 2015). As it is a more sustainable agricultural management than conventional tillage, its adoption has been growing every year. It is estimated that in 2015/2016 the global area under NT was approximately 180 million hectares, corresponding to about 12.5% of the total agricultural areas, and an annual expansion rate of 10.5 million hectares (Kassam et al., 2019). Kassam et al. (2019) listed the main reasons for the widespread adoption of NT: 1) reduced production costs and time savings; 2) technical flexibility in sowing, application of fertilizers, and weed control; 3) equal or greater productivity and more stability over time; 4) greater protection of the soil against water and wind erosion; 5) greater efficiency in the nutrients uptake by plants; 6) lower costs and reduced pest and disease control problems; and 7) greater efficiency in water storage and uptake by plants. However, NT may present some agronomic and environmental drawbacks (Dang et al., 2015a; López-Garrido et al., 2014; Pittelkow et al., 2015b).

The main challenges with the adoption of NT include soil compaction (Blanco-Canqui and Ruis, 2018; Peixoto et al., 2019a; Reichert et al., 2009), weed management (Bajwa, 2014; Dang et al., 2015b, 2015a; Nichols et al., 2015), and stratification of soil organic carbon (SOC) and nutrients (Barth et al., 2018; Blanco-Canqui and Wortmann, 2020; Cade-Menun et al., 2010). The main causes of soil compaction in NT are associated with the intensification of agricultural systems and, consequently, increased machine traffic, inefficiency in crop rotation, intercropping, and use of cover crops, low residue input and organic matter, and machine traffic under inadequate soil moisture conditions (Denardin et al., 2008; Drescher et al., 2011; Moreira, 2019).

Weed management is regarded to be one of the greatest challenges of NT systems, as the ecology and dynamics of weeds are different from that in conventional tillage systems. Associated with this, problems of resistance to herbicides are more frequent, and the inefficiency in crop rotation and production of crop residues reduces the allelopathic and physical effects on weeds (Bajwa, 2014; Chauhan et al., 2012; Lee and Thierfelder, 2017; Nichols et al., 2015). The stratification of SOC and nutrients, in turn, is caused by the maintenance of crop residues and application of liming and fertilizers on soil surface, without incorporation. However, with proper management of soil fertility, the surface application has been enough to correct acidity problems and increase crop yields (Auler et al., 2019; Caires, 2013; Caires et al., 2015, 2006).

In order to mitigate these problems, landowners and researchers have used occasional tillage (OT) in NT (Blanco-Canqui and Wortmann, 2020; Dang et al., 2015a, 2015b). The OT consists of using some method of soil tillage, such as chiseling, subsoiling, plowing and harrowing, in NT, aiming to mitigate potential problems with the adoption of this management system (Blanco-Canqui and Wortmann, 2020). A growing concern in Brazil is that some farmers have adopted rotational tillage in NT areas, that is, soil tillage at predefined times, often without making a diagnosis about the need of performing such management practice (Denardin et al., 2008; Moreira, 2019).

In a literature review, Blanco-Canqui and Wortmann (2020) observed that OT can increase the risk of soil erosion; it has little effect on soil physical properties, and it does not affect water content and SOC stocks; but it reduces the vertical stratification of SOC and nutrients, decreases microbial biomass and does not affect crop yield. Although some results have already led to some inferences and conclusions, few studies have evaluated the effects of OT on soil properties, erosion, weed control, and crop responses. In addition, a meta-analysis aggregates information and discussions using a statistical method that provides greater support for the conclusions.

In this sense, the objectives of this meta-analysis were: 1) to summarize the effect of OT on crops yield, soil physical, chemical and biological properties in the arable layer and subsurface, soil erosion and weed control; 2) to discuss the main aspects of NT management to avoid and minimize the use of OT; 3) to point out deficiencies in the diagnosis of soil compaction in NT, which may culminate in erroneous decision-making processes regarding the use of OT.

2. Material and Methods

2.1. Data collection

An extensive literature search was carried out on peer-reviewed articles that investigated the effects of OT on annual crops yields, soil physical, chemical, and biological properties, soil erosion (soil-water infiltration, runoff and soil cover) and weed control relative to NT systems. This survey used ISI Web of Science ((http://apps.webofknowledge.com/), Scopus (http://www.scopus.com) and Google Scholar (http://www.scholar.google.com), and covered papers published between January 1987 and December 2019. The search terms included ‘no-till*’, ‘conservation till*’, ‘conservation agriculture’, ‘occasional till*’, ‘strategic till*’, ‘one-time till*’, ‘chisel*’, ‘plow*’, ‘harrow*’, ‘subsoiling’. This research resulted in a total of 68 publications (Fig. 1), which were screened based on the following criteria:

(1) The studies had to contain field experiments with side-by-side comparisons between OT and NT. It was considered that in NT the cultivation practices caused minimal mechanical soil disturbance, only occurring in sowing operations that created a furrow to place seed and fertilizer (Kassam et al., 2019), and excluded practices of reduced tillage as well as minimum tillage. It was considered OT any type of soil tillage in areas under NT with varied objectives, such as weed control; alleviation of soil compaction; incorporation of crop residues excess; incorporation of limestone, fertilizers and organic compost; reduction of stratification of organic matter, nutrients and soil acidity; increasing soil heating in wet and cold areas; improving soil-seed contact; reducing the repellency between the soil surface and water; and disruption of cycles of pests and diseases in soils (Blanco-Canqui and Wortmann, 2020).

(2) Articles with results from single soil tillage were selected, excluding those that used rotational tillage (for example, OT at predefined time intervals), except when sampling/evaluation occurred when only the first soil tillage had been carried out.

(3) Agronomic practices such as intensity of cultivation, fertilizer management, crop rotations and succession, and irrigation had to be similar between the OT and NT plots, ensuring that the treatments were affected only by soil tillage.

(4) All soil properties and variables related to soil erosion, crop productivity, soil cover and weeds presented in the articles were initially selected. In the end, only the variables that best represented each category (soil physical, chemical and biological properties, soil erosion, crop response, and weed management), and which had the greatest number of studies and observations were used in the meta-analysis.

Based on the abovementioned criteria, the following variables were selected within each of the six categories: 1) crops productivity: yield; 2) soil physical properties: soil bulk density (BD), penetration resistance (PR), macroporosity (Mac), total porosity (TP), degree of compactness (DC), soil moisture, percentage of aggregates > 2 mm (AG > 2) and mean weighted diameter of aggregates (MWD); 3) soil chemical properties: soil organic carbon (SOC), pH and available P; 4) soil biological properties: microbial biomass carbon (MBC) and total microbial activity (TMA); 5) soil erosion: soil-water infiltration (SI), runoff, and soil mulch cover; 6) weeds: number of weeds. When data were presented in figures, the values were extracted using Plot Digitizer (http://plotdigitizer.sourceforge.net/).

Information on soil properties was extracted within all depths available in the studies. In the end, it was performed an average corresponding to the depths between 0-0.20 m and below 0.20 m (0.20+ m) for each study. This procedure was done when the study evaluated two or more layers within 0-0.20 m or 0.20+ m. More than 98% of the observations of the 0.20+ m depth corresponded to the 0.20-0.30 m layer.

From the information that was available for all studies, the following factors that could affect the effectiveness of OT were tested: aridity index - average annual rainfall divided by potential evapotranspiration [using latitude and longitude data through the Climate Database v2 (Trabucco and Zomer, 2019)]; climate zone; clay content; OT equipment used for soil tillage; duration of no-tillage; and duration of OT until sampling/evaluation. The effect of OT on crop yield was also tested through distinctive types of cultivation.

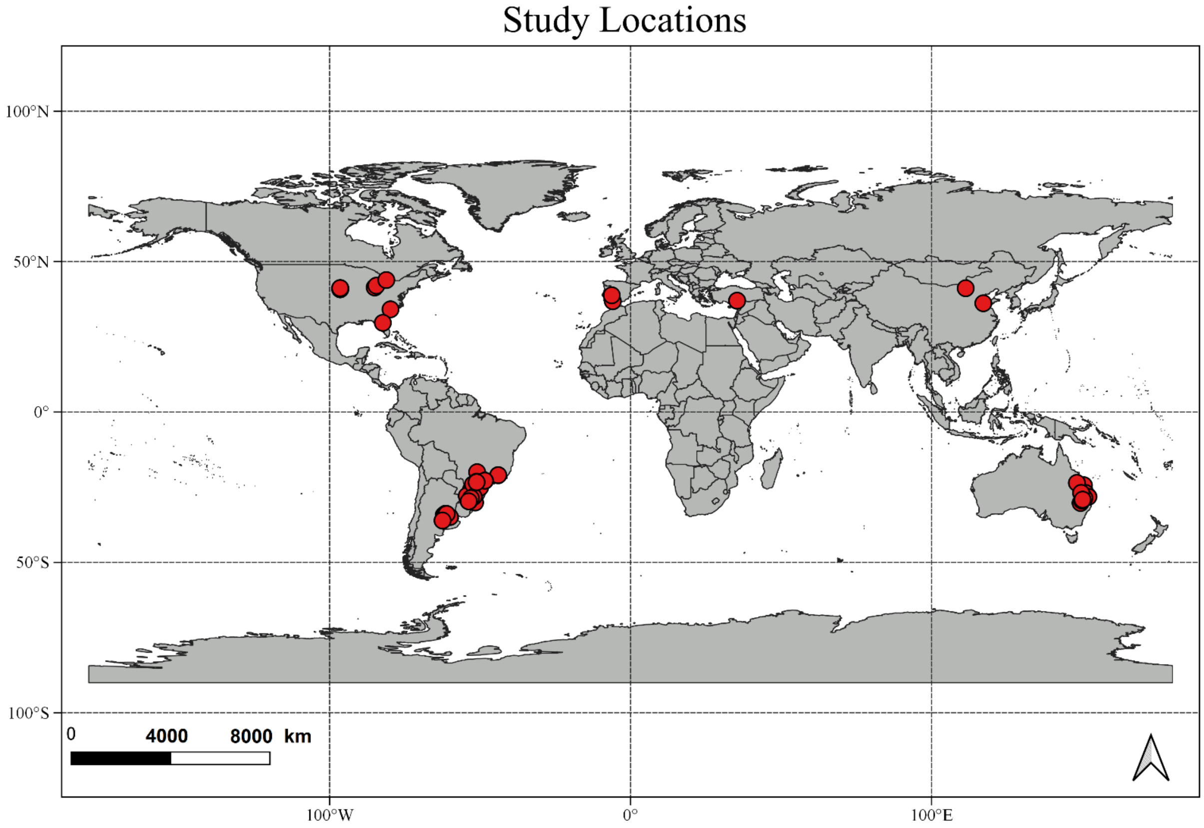


Fig. 1. Studies location with comparisons between occasional tillage and no-tillage used in the meta-analysis. Total (68); Argentina (3); Australia (8); Brazil (42); Canada (1); China (2); Spain (2); United States of America (8); Turkey (2).

The aridity index was categorized as dry (≤0.65) and wet (>0.65); the climate zone in subtropical (20-30º) and temperate (30-66º) [studies were not found in the tropical zone (0-20º)]; the clay content ≤35% and >35%; the OT equipment in chisel, subsoiler and plow and/or harrow; the duration of no-tillage in initial/intermediate (0-5 years), transitional (5-10 years) and stabilized (>10 years) (Derpsch, 2008; Reichert et al., 2016); the duration of OT up until the time of sampling/evaluation at 0-12, 12-24 and >24 months; and the crop type in maize, soybean, sorghum, and wheat. Other crops were found within the studies, namely: barley, beans, chickpeas, oats, rice, and sunflower; however, due to the reduced number of studies and observations, they were not included in this meta-analysis.

2.2. Data analysis

The meta-analysis was conducted following procedures previously consolidated in the literature (Adams et al., 1997; Hedges et al., 1999; Pittelkow et al., 2015b, 2015a). Data were analyzed by calculating the natural logarithm of the response ratio (lnRR) for each variable to compare OT and NT means. As the measures of variation were available for few studies, individual observations were weighted by the number of observations, with weights (n_{ot} x n_{nt})/(n_{ot} + n_{nt}), where n_{ot} and n_{nt} represent the number of repetitions for OT and NT, respectively (Adams et al., 1997; Pittelkow et al., 2015a). Observations with more than five standard deviations from the lnRR (up to 2% of the observations for some variables) were excluded (Pittelkow et al., 2015a). This procedure was important to eliminate abnormal observations in the data set, which would greatly affect the estimation of the confidence interval due to the small number of studies.

The 95% bootstrap confidence intervals were generated for lnRR using 5000 bootstrap interactions with the 'boot' package. Resampling was stratified at each level of the studied factors, allowing those observations of all levels of a factor were present in each resampling. The results were considered significant when the bootstrap confidence intervals did not overlap zero. To facilitate the interpretation, all the results of the variables were reported as percentage variation of the OT relatively to NT, using the following equation: RR% = (exp (lnRR) – 1) * 100. All statistical analyses were performed with R, version 3.6.1 (R Development Core Team, 2019).

3. Results and discussion

3.1. Overview

A total of 68 articles were selected in this meta-analysis (Fig. 1). Most studies are concentrated in Brazil (61.7%), followed by Australia (11.8%) and the United States of America (11.8%). In Europe, only two studies (Spain), and no studies were found in Africa. In the tropical climate region (0 - 20 º latitude), no studies evaluating OT were found (Fig. 1). All studies were without irrigation and only three studies did not perform crop rotation.

According to a literature review by Blanco-Canqui and Wortmann (2020), OT can promote numerous benefits in long-term NT when correctly targeted to agroecosystems with problems, among them: weed control; alleviate soil compaction; incorporate excess crop residues, limestone, fertilizers and organic compost application; reduced stratification of organic matter, nutrients and soil acidity, etc. In 66% of the total articles analyzed (Fig. 2), OT was carried out to improve soil physical conditions, especially due to soil compaction in the NT; 17% for weed control; 12% to reduce the stratification of nutrients and organic matter; and 5% to improve soil fertility, by applying limestone in depth. The objectives pursued with the OT varied by country. All studies carried out in Australia aimed to control weeds, however, they also evaluated the effects on soil properties, erosion and crop yield. Conversely, in more than 95% of studies carried out in Brazil, the OT objective was to improve soil physical conditions by alleviation of soil compaction, and less than 5% aimed to improve soil fertility by applying limestone in depth.

The equipment or mechanical methods used in the OT were mainly four, organized in three groups: plow/harrow, chisel and subsoiler. Most studies used chisel (68%) as the OT method, followed by plow/harrow (24%) and subsoiler (8%). The subsoiler has the potential to cause disturbance to a greater depth (>0.40 m), while chisel (≤0.40 m) and plow/harrow (<0.30 m) disturb to a shallower depth (Soil Science Glossary Terms Committee, 2008).

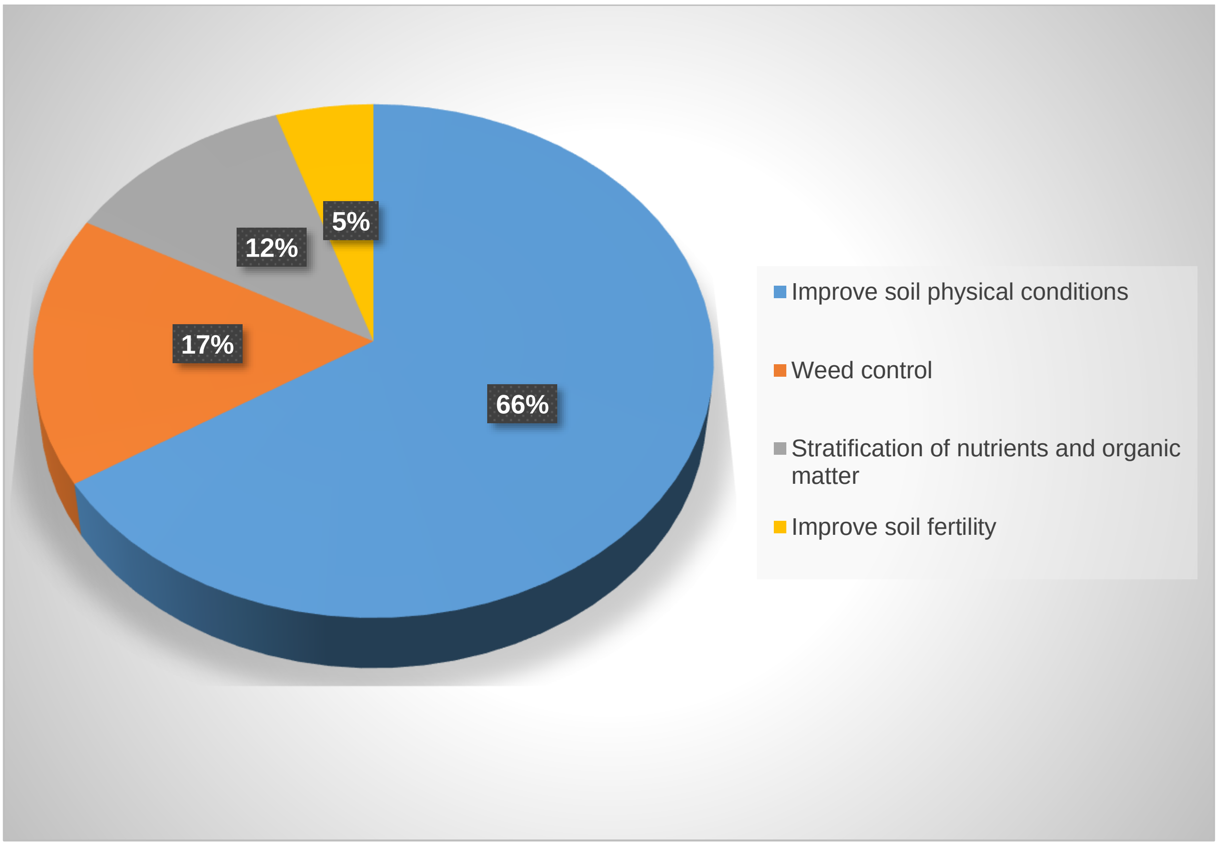


Fig. 2. Reasons for performing occasional tillage in no-tillage system (n = 68 articles).

The variables with more studies and observations decreased in the following order: crop yields, soil bulk density, penetration resistance, macroporosity, total porosity, and soil organic carbon. The remaining variables ranged from 10 to 40 observations. Only two studies evaluated the effects of OT on greenhouse gases emissions, as also reported by Blanco-Canqui and Wortmann (2020). Four studies were found on soil nutrients losses by water erosion.

3.2. Crop yields

In general, OT did not increase the yields of annual crops (Fig. 3). However, there was effectiveness depending on some factors studied, such as: OT equipment, duration of no-tillage, duration of OT until sampling, clay content, climatic zone and aridity index (Fig. 3). In a recent literature review, Blanco-Canqui and Wortmann (2020) showed that many factors can influence the effectiveness of OT, among them, method of tillage, frequency of tillage, soil texture, soil organic carbon, soil type, climate, soil management system, depth of tillage, etc. Some of these factors do not apply to our study (e.g. frequency of tillage) and others did not have available information for most studies (e.g. soil organic carbon).

OT increased the yields of annual crops when cultivation took place in a temperate zone (7.4%), dry weather (7.4%), using subsoiler (35.9%), no-tillage in transitional phase (11.2%), sampling ≥24 months after OT (6.1%), and soil with clay content ≤ 35% (7.8%). Approximately 70% of the studies have mainly focused on mitigation of soil compaction by improving soil physical conditions. Studies have shown that under proper conditions of water supply, there is no correlation between soil physical properties and crop yields (Calonego et al., 2017; Calonego and Rosolem, 2010; Cecagno et al., 2016; Hakojärvi et al., 2013). Hence, under water stress conditions (temperate zone and dry weather), OT increased crop yields. Most studies in the temperate zone occurred under dry weather and had soils with ≤35% clay. Therefore, in climate conditions with water restriction and soils with low water retention and availability, OT promotes an increase in yields of annual crops.

Subsoiling promotes soil loosening in greater depths (>0.40 m), compared to chiseling and/or plowing/harrowing (Soil Science Glossary Terms Committee, 2008). Therefore, it improves soil physical conditions in depth, promoting greater root development and optimizing water and nutrients use by plants, leading to increased crops yield (Schneider et al., 2017) (Fig. 3). Despite the sharp increase in crop yields (35.9%) using subsoiling, most studies used chiseling and plowing and/or harrowing as OT methods. Further studies using subsoiler are encouraged to consolidate the results observed in the present study.

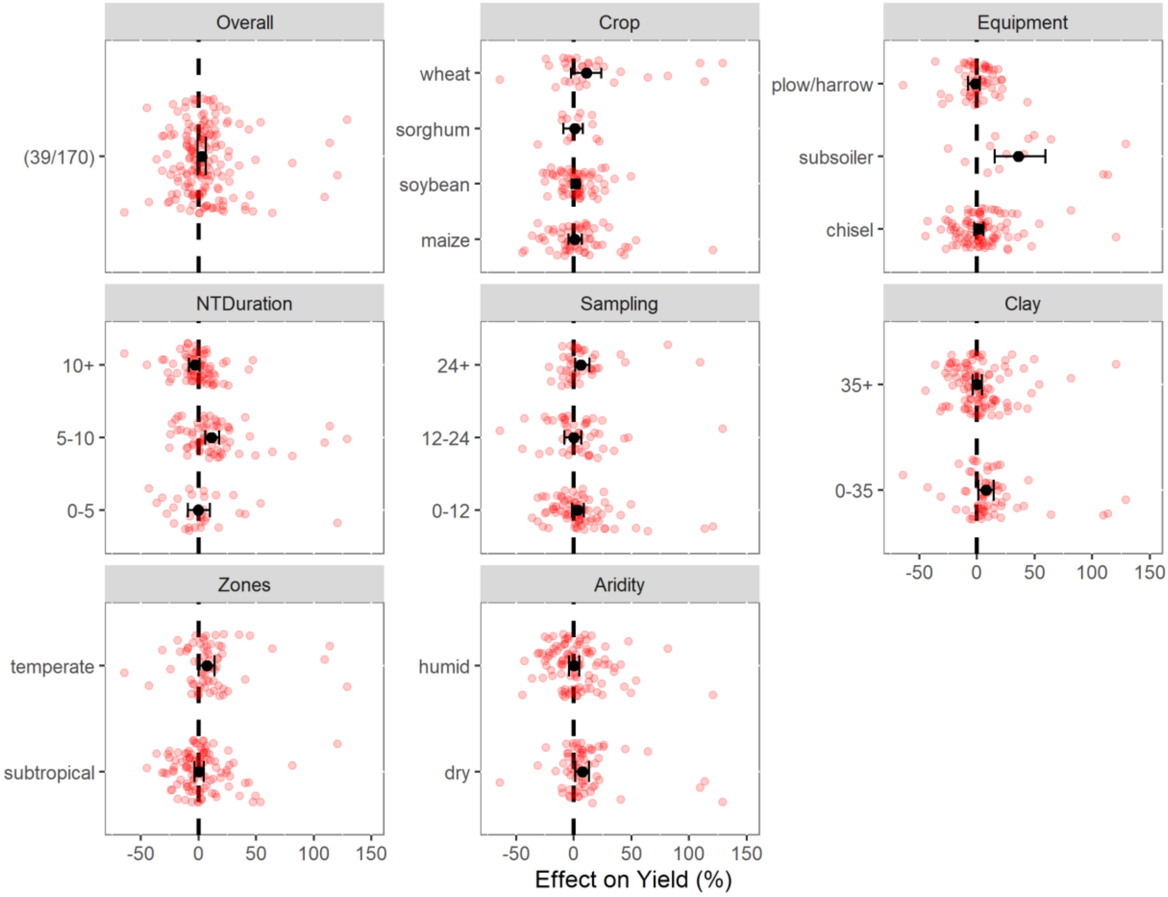


Fig. 3. Effect of occasional tillage relative to no-tillage on yield of annual crops as a function of crop type, OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), climate zone and aridity index. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

OT in transitional NT (5-10 years) promoted an increase in the yield of annual crops. Soil tillage for implementation of NT causes disturbance in soil structure; it is generally observed in the initial phases of NT an increase in TP and Mac, and lower BD (Reichert et al., 2016; Veiga et al., 2007). With increased time of NT, there is a trend to increase BD until reaching a stable value around 5 years of adoption (Derpsch, 2008; Reichert et al., 2016). This process results from the rearrangement of soil particles and aggregates (Moraes et al., 2019, 2017) and the loads exerted by the traffic of agricultural machinery and implements, especially under inadequate soil moisture conditions (Botta et al., 2012). In stabilized/consolidated NT, BD may decrease over time, following the increase in soil organic carbon in the top layer, which improves the soil aggregation and structural stability (Derpsch, 2008; Lal, 2009; Reichert et al., 2016). Therefore, the transitional NT presents more restrictive soil physical conditions to the growth and development of crops. OT promotes greater benefits in terms of structural alleviation, increasing the yield of annual crops. This result can be important to compose the OT diagnosis and decision-making strategies.

The effect of OT on the yield of annual crops only occurred ≥24 months after OT (Fig. 3). It is admitted that 52 factors are responsible for the growth and development of crops (Tisdale et al., 1985), among them, the conditions of plantability and seed germination. OT can impair land leveling, soil cover and water content on soil surface layers (Camara and Klein, 2005; Salton et al., 1998; Seki et al., 2015), making sowing more difficult (plantability), and consequently, seed germination and adequate plant stand (Gesch and Cermak, 2011), with a possible reduction in the crop yields. The effect is more expressive right after OT and decreases over time, as the soil has a natural rearrangement, and also due to the traffic of machines and implements. According to a study by Mahl et al. (2004), there was no effect of chiseling on sowing quality 18 months after the operation.

The ineffectiveness of the OT, in general, in the yield of annual crops may be related to the deficient diagnosis of soil compaction, the main reason for decision-making to use the OT. PR and Mac, for most studies, were not considered limiting: PR <2MPa and Mac >0.100 $m^3 m^{-3}$ (Bengough et al., 2011). This indicates that improving the methodologies for diagnosing soil compaction is required. Further details on this topic will be given in the section below.

3.3. Soil physical properties

3.3.1. Soil compaction

OT reduced BD by 6.9% (Fig. 4) and PR by 54.8% (Fig. 5), and increased Mac by 45.4% (Fig. 6) and TP by 10.6% (Fig. 7) at a depth of 0-0.20 m. There was no influence of the factors evaluated (categories) in the response of the soil physical properties to the OT, except for the duration of OT up until the sampling (persistence of tillage) in BD (Fig. 4). The persistence of OT to BD was ≤12 months after OT, indicating rapid soil reconsolidation by the natural rearrangement of soil particles and aggregates and also by the load exerted by the traffic of agricultural machinery and equipment (Botta et al., 2012). However, this was not observed in the other physical properties (PR, Mac, and TP), which showed persistence >24 months (Fig. 5, 6 and 7). Therefore, BD was less sensitive to the structural changes promoted by OT (6.9%), which reflected a lower persistence of OT. Regarding the effectiveness of OT methods, subsoiling (BD = -14.6%; PR = -76.7%) was more effective in reducing BD and PR than chiseling (BD = -5.1%; PR = -56.5%) and plowing/harrowing (BD = -4.0%; PR = -31.6%).

Chiseling (Mac = 44.9%; TP = 10.9%) and plowing/harrowing (Mac = 46.7%; TP = 9.7%) had similar effects on Mac and TP.

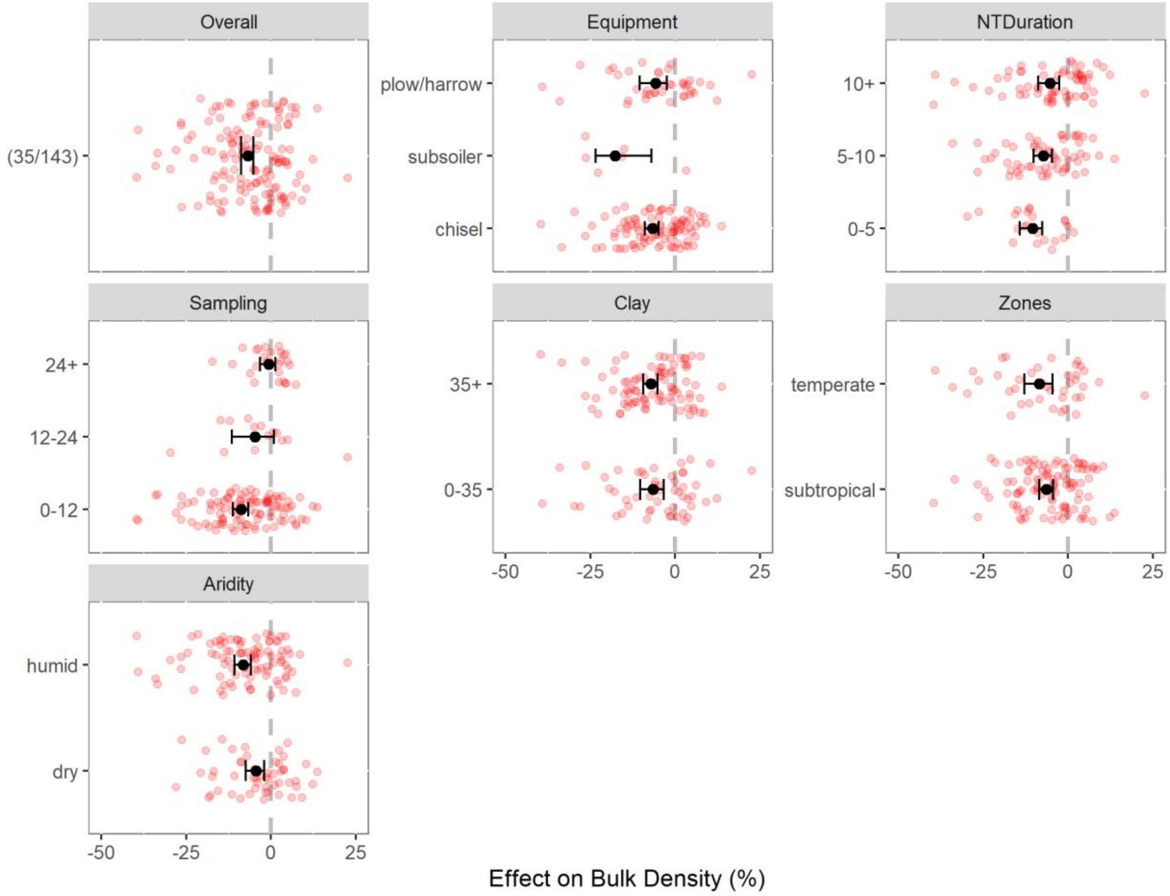


Fig. 4. Effect of occasional tillage relative to no-tillage on bulk density, depth of 0-0.20 m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), climate zone and aridity index. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

The process of soil rearrangement over time is known as the age-hardening phenomenon (Dexter et al., 1988; Moraes et al., 2017; Utomo and Dexter, 1981). This phenomenon results from two main processes; the first involves the rearrangement of soil particles, mainly clay, in new positions of minimum free energy, and the second involves the strengthening of cementation bonds at new points of contact between pairs of mineral particles (Dexter et al., 1988). These processes and the load exerted by the traffic of agricultural machines and implements seem to influence the BD more quickly than soil porosity (TP and Mac) and mechanical impedance (PR). Studies have shown that soil porosity, especially Mac, and PR are soil properties much more sensitive to soil management practices than BD (Lipiec and Hatano, 2003; Peixoto et al., 2019b, 2019a).

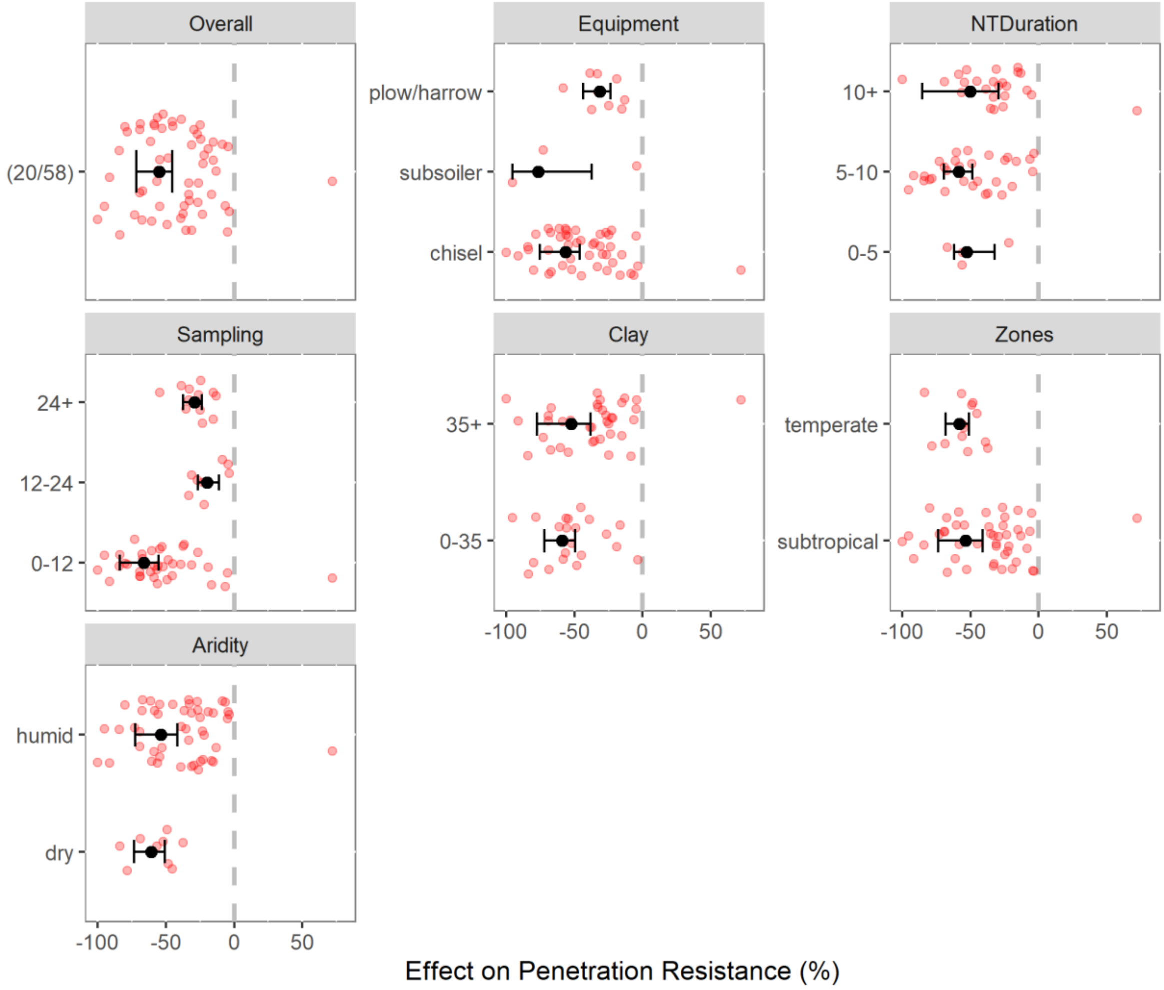


Fig. 5. Effect of occasional tillage relative to no-tillage on penetration resistance, depth of 0-0.20 m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), climate zone and aridity index. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

Problems of soil compaction in areas managed in NT have been reported in the literature, especially in clayey soils (Blanco-Canqui and Ruis, 2018; Moraes et al., 2019, 2017; Nunes et al., 2015a, 2015b; Peixoto et al., 2019a, 2019b; Reichert et al., 2009). One of the main objectives of the OT is to mitigate soil compaction in NT (Blanco-Canqui and Wortmann, 2020), promoting a reduction in the degree of compactness (Fig. A1 Supplementary material) by reducing BD and PR and simultaneously increasing TP and Mac. Soil compaction increases BD and reduces porosity, especially macropores (Bottinelli et al., 2014; Chen et al., 2014; Colombi et al., 2017; Kim et al., 2010), and increases mechanical impedance to root growth (Peixoto et al., 2019a, 2019b). Therefore, soil properties that reflect porosity and mechanical impedance are often used for diagnosis of soil compaction and the effects of methods for its mitigation, whether mechanical (Calonego et al., 2017; Calonego and Rosolem, 2010; Peixoto et al., 2019b, 2019a), chemical (Klein et al., 2007; Peixoto et al., 2019b) or biological (Calonego et al., 2017; Calonego and Rosolem, 2010).

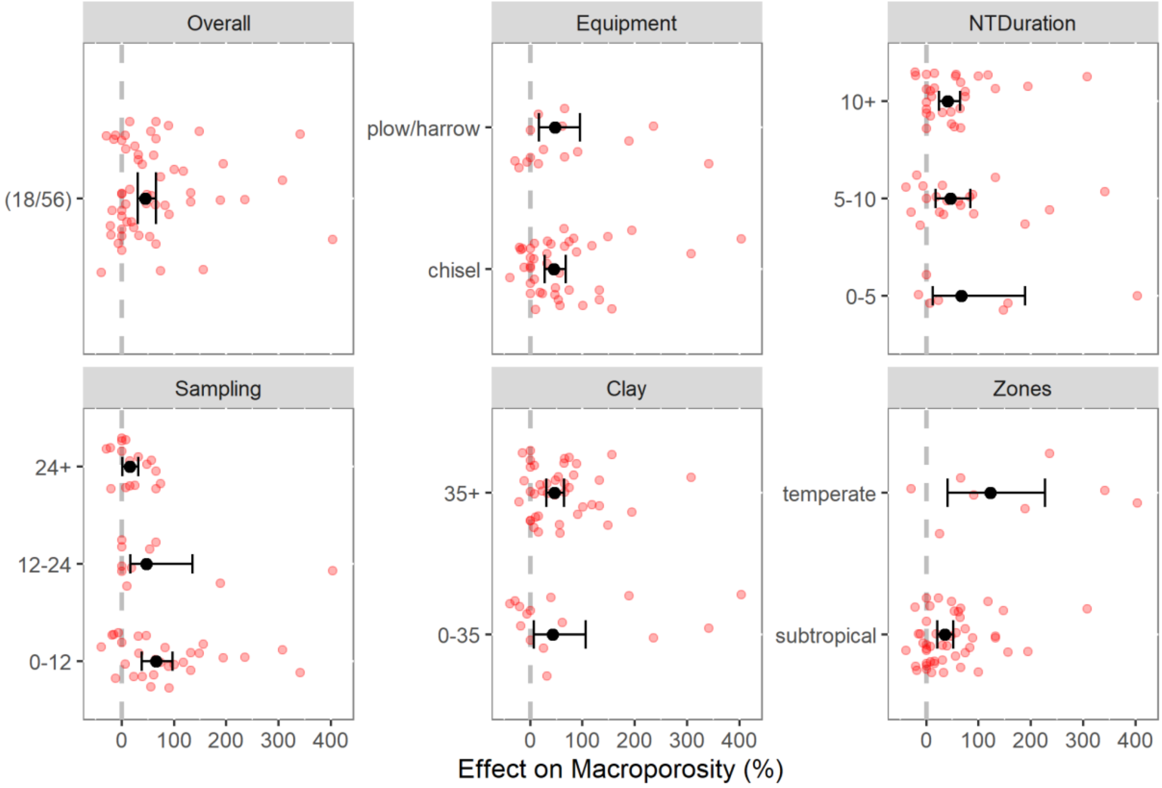


Fig. 6. Effect of occasional tillage relative to no-tillage on macroporosity, depth of 0-0.20 m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), and climate zone. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

Tillage makes soil more vulnerable to deformation by the traffic of agricultural machinery and implements (Hamza and Anderson, 2005), in such a way that recompression has been observed after one (Chan et al., 2006) or two (Veiga et al., 2007) agricultural operations. The ideal soil management to mitigate soil compaction and improve the soil physical and chemical conditions is the complementation of OT with cover crops, in addition to the adequate planning of crop rotation to continuously add organic matter as straw and roots to produce more permanent effects (Bergamin, 2018; Calonego and Rosolem, 2010, 2008; Moreira, 2019; Ralisch et al., 2010).

OT also improved soil physical properties at a depth of 0.20+ m (Fig. A2, A3, A4, and A5 Supplementary material). BD was reduced by 3.2% (Fig. A2 Supplementary material) and PR by 29.0% (Fig. A3 Supplementary material), while Mac by 33.5% (Fig. A4 Supplementary material) and TP increased by 5.2% (Fig. A5 Supplementary material). As in the 0-0.20 m depth, the most sensitive soil physical properties were PR and Mac.

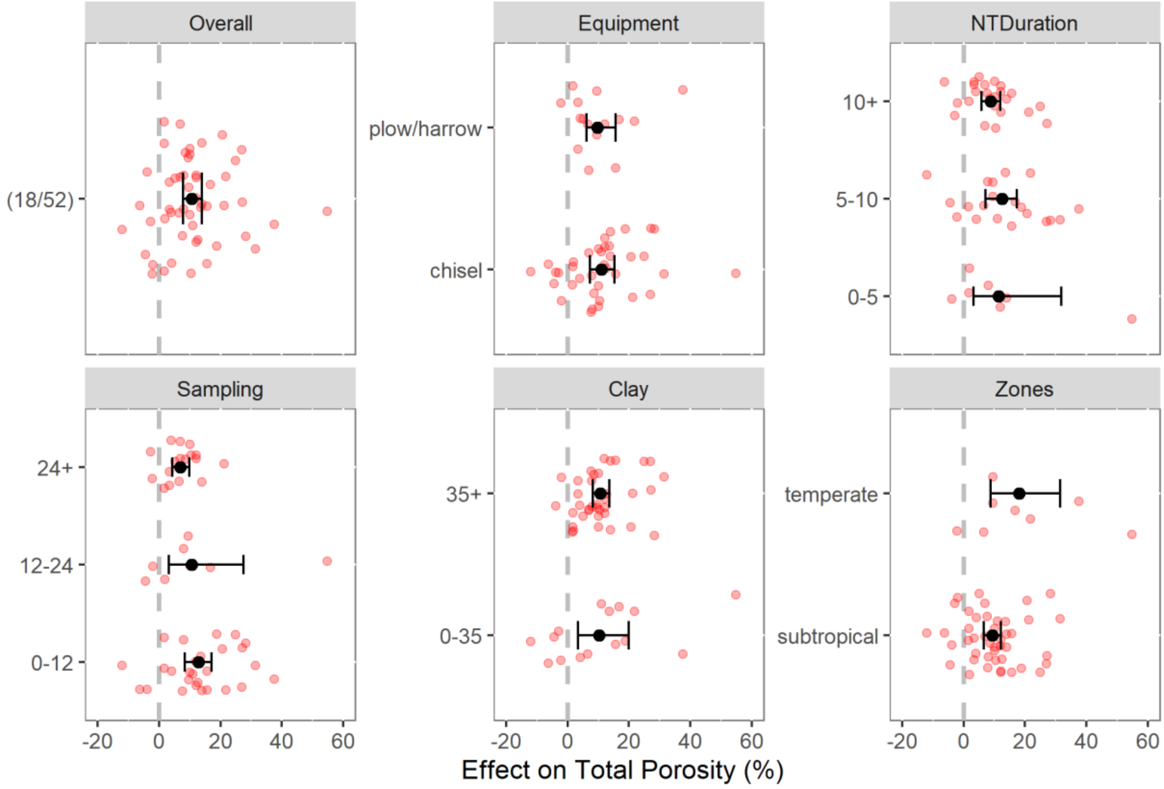


Fig. 7. Effect of occasional tillage relative to no-tillage on total porosity, depth of 0-0.20 m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), and climate zone. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

For the 0.20+ m depth, subsoiling (-11.3%) was more effective in reducing BD than chiseling (-2.8%), and plowing/harrowing had no effects (Fig. A2 Supplementary material). Chiseling corresponds to soil tillage up to 0.40 m and subsoiling, greater than 0.40 m (Soil Science Glossary Terms Committee, 2008), so both methods have the potential to reach a depth of 0.20+ m. Plowing/harrowing generally reaches a depth of 0-0.20 m. However, most articles do not report how effectively the soil tillage operation reached a certain depth, which is a relevant information to evaluate the effectiveness of the operation. OT persistence in BD was >24 months and the effect were similar regardless of the duration of NT. This may be a result of the attenuation of the stresses transmitted by machine traffic from soil surface to subsurface (Lamandé and Schjønning, 2011), which may reduce the process of deep soil recompression. OT reduced BD in soils with clay content >35%, in the subtropical climatic zone and humid climate condition.

PR was reduced by OT regardless of the factors evaluated, except for duration of OT until sampling, where there was no effect between 12 and 24 months (Fig. A3 Supplementary material). However, there were few observations (n = 8) that limited the accuracy of the conclusions.

Only one study evaluated Mac and TP at 0.20+ m depth in soils with clay content ≤35%, in the temperate climate zone and dry weather condition; therefore, clay content, climate zone, and aridity were not considered for these soil physical properties (Fig. A4 and A5 Supplementary material). Plowing/harrowing had similar effect to chiseling in increasing soil porosity, indicating that this soil tillage reached depths below 0.20 m. Only in duration >24 months between OT and sampling, was an effect on soil porosity observed.

3.3.2. Soil aggregate stability

OT reduced soil aggregate stability (Fig. A6 Supplementary material). The AG >2 decreased by 12.5% and the MWD by 10.7%. Few studies have evaluated the impact of OT on soil aggregation (two studies with a total of 12 observations). Thus, more work should be done for a more accurate conclusion. Many studies have shown that soil disturbance reduces the size of soil aggregates (Franzluebbers et al., 1999; Nath and Lal, 2017; Vezzani and Mielniczuk, 2011). Although soil aggregation decreases immediately after tillage, there may be a quick recovery if NT is reestablished soon after tillage (Blanco-Canqui and Wortmann, 2020; Nunes et al., 2015a).

3.4. Soil chemical properties

3.4.1. Soil organic carbon

OT reduced SOC by 4.7% at the 0-0.20 m depth (Fig. 8). The conditions that favored SOC loss include: use of plow/harrow; OT in consolidated NT (>10 years); sampling between 12 and 24 months after OT; soils with clay content ≤35%, and OT in temperate climate. Conventional tillage (plowing and harrowing) inverts the arable layer and mixes the soil, destroying soil aggregates and exposing organic matter to microbial decomposition, increasing losses of labile C (Chen et al., 2009, 2007; Reicosky et al., 1997; Six et al., 2000, 1999). In contrast, chiseling and subsoiling do not invert or mix the soil arable layer, reducing the breakdown of aggregates and the exposure of organic matter to microbial degradation compared to plowing/harrowing.

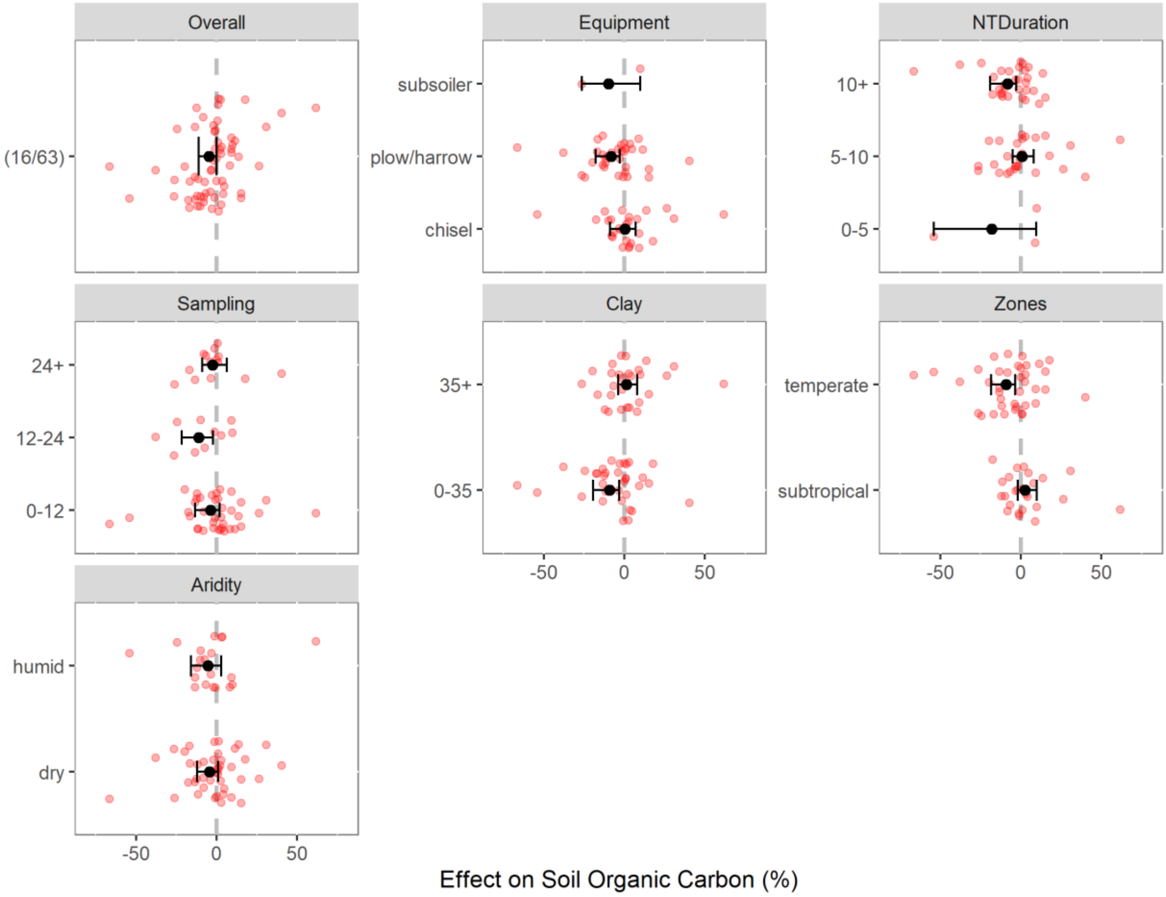


Fig. 8. Effect of occasional tillage relative to no-tillage on soil organic carbon, depth of 0-0.20 m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), climate zone and aridity index. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

The SOC loss in NT with duration >10 years may be related to the increased SOC in consolidated NT, favoring a greater loss of SOC by tillage (Koch and Stockfisch, 2006; Stockfisch et al., 1999). Studies have shown that in NT systems with reduced production of crop residues (straw), generally, there is no difference in the soil organic carbon stock compared to conventional tillage (Ghimire et al., 2012; Palm et al., 2014; Paul et al., 2013). Thus, the OT carried out until the transitional NT may not reduce SOC, and may be an appropriate strategy to solve potential problems following the implementation of NT, without causing a significant reduction to the SOC. In this sense, it should be noticed that it is also in the transitional phase (5-10 years) that a significant effect on crop yields was observed (Fig. 3).

The potential for changes in SOC depends on several factors, including: climate (precipitation and temperature), soil type (texture and mineralogy), and availability of water and nutrients (Palm et al., 2014). Major changes in SOC due to management occur in humid tropical climates, followed by dry tropical, wet temperate and dry temperate (Ogle et al., 2005). In this meta-analysis, no studies were found under tropical climate and there was a reduction in SOC by OT under temperate climate, with no effects under subtropical climate. The stabilization of C in tropical/subtropical and temperate soils is mediated by the soil biota, structure, and their interactions, and also by agricultural management (Six et al., 2002). Normally, soils under temperate climates have a predominance of 2:1 clay minerals, with a greater specific surface area and cation exchange capacity, and relatively lower temperatures compared to soils under tropical climates. These conditions allow a greater ability to stabilize C in soil (Kirschbaum, 1995; Six et al., 2002). Soil tillage can increase aeration and break down aggregates, exposing organic matter to the action of microorganisms, in addition to increasing soil temperature in temperate zones and, therefore, reducing SOC. The increase of 1 ° C in soil temperature can generate a 10% loss in SOC in regions with an annual average temperature of 5 ° C, while this same increase in soil temperature can cause a loss of 3% of SOC for soils with an average annual temperature of 30º C (Kirschbaum, 1995).

Soil texture has a great influence on the shape, stability and resilience of soil structure, as well as on the response of soil structure to climate, biological factors and management (Kay, 1998). The increase in clay content is associated with increased SOC stabilization (Sollins et al., 1996), acting as a cementing agent, uniting particles and decreasing the rate of decomposition and rotation of SOC (Bronick and Lal, 2005). OT promoted a reduction in SOC in soils with ≤35% clay, with no effect observed in clay soils with >35% clay. There is a good correlation between clay content and SOC, at least in regions of similar mineralogy (Burke et al., 1989). In turn, in relation to the vulnerability of SOC losses by soil tillage, as observed in this meta-analysis, there is an inverse correlation with clay content, that is, the less clayey the soil, the greater the SOC losses (Oades, 1988).

OT did not affect SOC at 0.20+ m depth (Fig. A7 Supplementary material). SOC and microbial activity are lower in subsurface, moreover, OT equipment, especially those that cause greater soil mobilization (plow/harrow), have reduced action on the subsurface, corroborating the results found.

3.4.2. Soil acidity and available phosphorus

There was no effect of OT on pH and available P at the 0-0.20 m soil depth (Fig. A8 Supplementary material) and depth of 0.20+ m (Fig. A9 Supplementary material). Soil tillage incorporates crop residues, limestone and fertilizers, reducing the stratification of nutrients in comparison with NT (Blanco-Canqui and Wortmann, 2020). In NT systems there is a problem of accumulation of nutrients, especially the ones that are immobile in soil (e.g. P), and pH increase following the application of limestone without incorporation, close to the soil surface (Barth et al., 2018; Cade-Menun et al., 2010).

OT can reduce nutrient stratification, N immobilization and soil acidity close to the surface (Blanco-Canqui and Wortmann, 2020). However, the evaluation of the average values for the 0-0.20 m depth did not show an OT effect, possibly due to the dilution of this effect by the layer thickness. In addition, OT equipment without inversion (chiseling), which corresponded to 50% of the studies, may not have a significant effect in reducing nutrient stratification and acidity close to the soil surface (Blanco-Canqui and Wortmann, 2020). Unlike what was suggested in a recent review (Blanco-Canqui and Wortmann, 2020), OT does not appear to alter the soil's chemical properties. Further studies should be done to investigate the effects of OT on soil chemical properties.

3.5. Soil biological properties

One of the key benefits of using soil biological properties is their sensitivity to changes in management, in addition to being considered soil quality indicators (Bastida et al., 2008). Few studies have evaluated the effect of OT on soil biological properties (Blanco-Canqui and Wortmann, 2020). The properties with more studies were MBC and TMA.

The response of soil biological properties to soil tillage practices has been measured by estimating the microbial and enzymes activity (Carter, 1991; Kabiri et al., 2016). Microbial biomass is an agent for transformation and cycling of organic matter and nutrients in soil, and a sink or source of labile nutrients (Carter, 1991). MBC has a positive correlation with SOC (Kabiri et al., 2016) and a negative correlation with the intensity of disturbance promoted by management practices (Balota et al., 2004; Zuber and Villamil, 2016). Studies have shown greater microbial abundance in soils under NT, with a more favorable microclimate compared to soils under conventional tillage (Balota et al., 2004; Kaschuk et al., 2011; Zuber and Villamil, 2016). The degree of increase in microbial biomass under NT compared to conventional tillage is variable, with 17% reported by Das et al. (2014) and 98% increase reported by Balota et al. (2004). Also, absence of differences has been reported (Babujia et al., 2010).

OT increased the MBC by 21.2% and did not change the TMA (Fig. A10 Supplementary material). Zuber and Villamil (2016), in a meta-analysis, found that chisel was the only method that did not affect microbial biomass compared to NT. These authors suggested that this type of soil tillage, due to its reduced disturbance, does not change the size of the soil microbial community, which is mainly responsible for the reduction of microbial biomass. A possible explanation for the increased MBC in OT is the low intensity of soil tillage (only one tillage), which promotes an increase in microbial activity by altering soil porosity and temperature, and exposure of organic matter (Balota et al., 2004; Zuber and Villamil, 2016), causing a reduction in the labile C, however, increasing the carbon assimilated by the soil microbiota.

3.6. Soil erosion

Accelerated erosion is a serious problem of soil degradation, especially in developing countries with a tropical and subtropical climate (Lal, 2001). There are several factors that control soil erosion, including water and wind erosivity, soil erodibility, slope and the nature of the vegetation cover (Morgan, 2005). In this context, soil tillage has an influence on some of these factors that control erosion, for example, soil erodibility and vegetation cover, especially mulch, which can alter soil erosion (Lal, 2001). Few studies have evaluated the effects of OT on soil erosion. It was possible to select a soil physical property that reflects the soil erodibility (soil-water infiltration), soil mulch cover after OT and runoff.

OT increased SI by 120% (Fig. 9) and reduced the percentage of soil mulch cover by 40.4% and runoff by 26.1% (Fig. A11 Supplementary material). Despite the few studies evaluating soil mulch cover and runoff, the results are quite consistent in indicating that OT reduces these parameters, especially soil mulch cover. It is observed that the improvements in soil physical conditions, promoted by OT, influenced much more in the reduction of runoff, and consequently, in the losses of soil and water than the soil mulch cover. Studies have observed that the removal of crop residues from the soil surface increases soil losses (Bradford and Huang, 1994; He et al., 2018). However, the reduction of soil mulch cover in OT compared to NT did not cause greater runoff. This occurred due to some factors: 1) improvement of the soil physical conditions (>TP and Mac; <BD and PR), which more than doubled the SI; 2) most studies used the chisel as an OT equipment, which promotes less disturbance in the soil surface compared to plow/harrow; 3) after OT the management of the area was maintained under NT system.

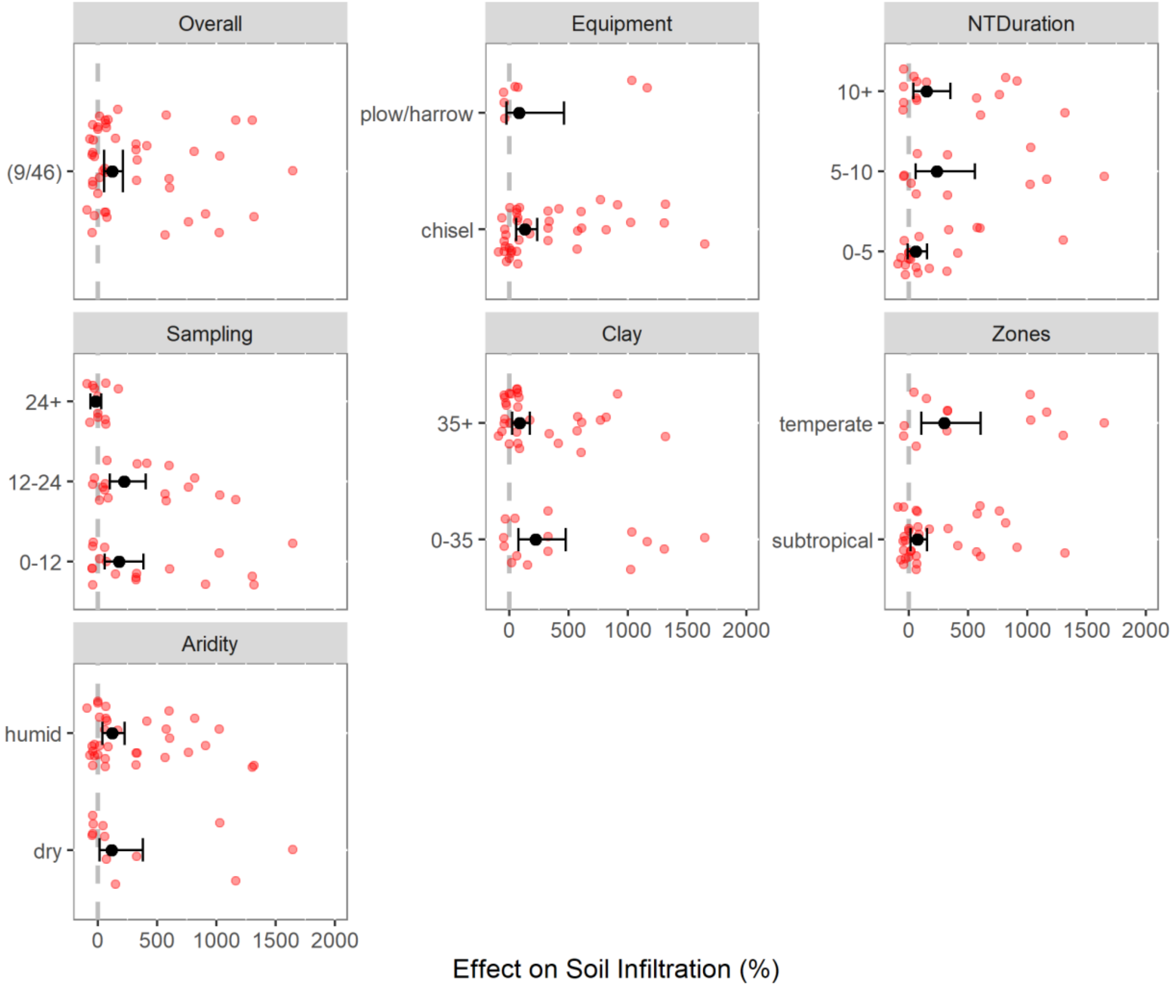


Fig. 9. Effect of occasional tillage relative to no-tillage on soil-water infiltration, depending on the OT equipment, duration of no-tillage (years), duration of OT until sampling (months), clay content (%), climate zone and aridity index. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

The increase in SI was independent of soil texture, climate zone and aridity condition (Fig. 9). OT persistence in the SI was up to 24 months. This shows that soil properties that are very sensitive to soil use and management, such as SI and hydraulic soil conductivity, often called dynamic indicators, can also reconsolidate more quickly than static indicators (Lozano et al., 2016), like BD, TP and Mac, especially in the case of occasional tillage.

There was no effect of OT on SI in initial/intermediate NT (0-5 years). The initial/intermediate NT, due to the soil tillage for implementation, presents greater soil porosity (Reichert et al., 2016; Veiga et al., 2007), reducing the effect of OT in the SI. Among OT equipment, chisel increased SI by 128%, whereas plow/harrow had no effect. Few studies have evaluated the effect of plow/harrow on SI, and a safe conclusion on the effect of this OT method is not possible. Soil tillage usually increases SI, mainly due to the increase in macropores (Lipiec et al., 2006).

3.7. Weed control

One of the objectives of using OT is to assist on weeds control (Blanco-Canqui and Wortmann, 2020; Dang et al., 2015b, 2015a). Soil tillage has always been used in order to promote a suitable soil physical environment for the emergence and development of plants, in addition to incorporating liming and fertilizers and weeds control (Bronick and Lal, 2005; Lal et al., 2007). However, with the development of the herbicide 2,4-D, after the second World War, a transition began from conventional tillage (plowing and harrowing) to various forms of conservation tillage (Lal et al., 2007).

NT is gaining more and more prominence for its sustainable character, with minimal soil disturbance, permanent soil cover, planned crop rotation and succession, and integrated weed management (Bajwa, 2014). However, weed control is one of the biggest challenges for maintaining NT, mainly because the ecology and management of weeds is different from that observed for conventional tillage. Moreover, there are issues related to resistance to herbicides, inefficiency in the crop rotation, and crop residues production (Bajwa, 2014; Chauhan et al., 2012; Nichols et al., 2015). Several literature reviews have addressed the problem of weed control in conservation agriculture (Bajwa, 2014; Chauhan et al., 2012; Lee and Thierfelder, 2017; Nichols et al., 2015). In this sense, farmers and researchers have used OT as a complementary technique in the integrated management of weeds in NT (Dang et al., 2018, 2015a, 2015b).

In recent years, cases of weed resistant to glyphosate have increased worldwide. In Brazil, this increase occurred after frequent use of the product not only for desiccation, but also as a post-emergent herbicide in soybean, cotton, and corn crops, currently resistant to glyphosate. Thus, the active ingredient that was previously used only once or twice per crop, in desiccations, started to be used several times in the same agricultural year, increasing the pressure of selection in the environment and, consequently, the reports of weeds resistance cases (Moreira, 2019).

OT has reduced at least 70% of the number of weeds in NT managed areas (Fig. A12 Supplementary material). In a recent review, Nichols et al. (2015) discussed the effect of soil tillage on weed dynamics. These authors reported that the studies found an effect of the tillage practices in the seed bank of weeds in the soil, some reducing and others increasing the size of the seed bank, depending mainly on the species of plant, climate, duration of the experiment and history of the area. NT results in accumulation of weed seeds (60-90%) in the first 5 cm of the soil, where they are more likely to germinate, but are also more exposed to mortality through the action of predators and climatic variation (Nichols et al., 2015).

OT with the exclusive purpose of controlling weeds would not be indicated, as several cultural practices can be adopted to control weeds in NT, which together can generate more satisfactory results than the sole OT. They are: maintenance of crop residues on the soil surface, which may decrease the average soil temperature, restrict the availability of light, function as a physical barrier and can have potential allelopathic effects; crop rotation that can have an allelopathic effect and promote rotation of the mechanisms of action of herbicides; selection of highly competitive varieties; adjustment in planting arrangement and plant density; change of planting dates, etc. (Nichols et al., 2015).

One of the paths to effective and sustainable weed management is the diversification of crops in production systems, including not only soybean/maize or soybean/cotton systems, but new crops. As an example, corn intercropped with brachiaria grass or plant “mix”, using more than one intercropped crop; the overgrowth of grasses in soybean; and rotation of herbicide, applying other molecules than glyphosate, even in crops resistant to glyphosate such as RR transgenic soybean and maize (rotate herbicides with different mechanisms of action) has been used successfully in Brazil (Moreira, 2019).

4. Considerations on occasional tillage

NT is a very effective management system for minimizing soil disturbances and crop residues, controlling evaporation, minimizing erosion processes, sequestering C in soil, reducing costs and the need for energy (Derpsch et al., 2010; Kassam et al., 2019; Lal et al., 2007). Therefore, unless there is a technical demand, soil tillage should be avoided.

The potential benefits of OT to soil, crops and environment include alleviation of soil compaction; reduction of SOC and nutrient stratification; incorporation of liming; control of herbicide-resistant weeds, etc. Based on these potential benefits, some aspects related to NT management can avoid or reduce the need for OT. In a recent review, Blanco-Canqui and Wortmann (2020) suggested alternatives to OT, such as: controlled traffic, cover plants, diversity in crop rotation and reduced and short-term (rotated) soil tillage. In addition to the points highlighted by the authors, some others are added in this section.

4.1.Implementation of no-tillage system

The implementation of NT requires prior construction of soil fertility and mitigation of possible soil compaction problems or natural density. The construction of soil fertility consists of the successive application of limestone and fertilizers, leading to an increase in soil macro- and micronutrients content to levels interpreted as high or even very high, associated with practices that increase soil organic matter levels (Lopes and Guilherme, 2016; Moreira, 2019; Resende et al., 2016). In this respect, a fundamental factor is the application of the proper dose of limestone and its incorporation in depth, at least up to 40 cm (Moreira, 2019). The application of limestone without incorporation limits its efficiency in reducing soil acidity and increasing base saturation; moreover, it can restrict the development of plants roots within the topsoil, leaving crops more sensitive to water stress. However, in consolidated NT systems and regions of Brazil with high annual rainfall, there are reports that the application of lime on soil surface has been sufficient to alleviate soil acidity problems and increase crop yields (Auler et al., 2019; Caires, 2013; Caires et al., 2015, 2006).

The construction of soil fertility during the implementation of NT must be associated with diversification of crops, for example, use of cover plants, crop rotation, succession and intercropping. Nunes et al. (2018) observed that soils under consolidated NT presented a physical, chemical and biological environment more favorable to the development of plants than under soil tillage. In addition, the introduction of cover crops (mixture of grasses and legumes) enhanced the beneficial effects already observed in NT.

Implementation of NT with the construction of soil fertility and diversification of crops can reduce the stratification of nutrients and organic matter, promote root growth in depth, alleviate possible problems of soil compaction by the in-depth incorporation of limestone and biopores formed by plant roots, and reduce possible damage resulting from water stress. Therefore, adequate implementation of NT can reduce possible problems that culminate in the decision-making towards the use of OT.

4.2.Suitable diagnosis and monitoring of soil compaction

Mitigating soil compaction is the main objective of using OT, as mentioned above, in more than 70% of the studies (Fig. 2). Soil compaction is a serious problem for the sustainability of agricultural systems because it restricts root growth, gas exchange and water and nutrients uptake by plant roots (Bengough et al., 2006; Correa et al., 2019; Lipiec et al., 2012; Szatanik-Kloc et al., 2018). However, the response of crops to the degree of compactness has parabolic behavior (Arvidsson and Hakansson, 1991; Håkansson, 1990; Håkansson and Lipiec, 2000; Lipiec et al., 1991), that is, there is an optimum degree of compactness for maximum crop yield. As reported in this meta-analysis, in general, OT did not promote an increase in soybean, maize, sorghum and wheat yields (Fig. 3); however, it improved the diagnostic properties of soil compaction: BD, PR, Mac and TP (Fig. 4, 5, 6, e 7). Therefore, it is unlikely that soil compaction is being properly diagnosed for decision making regarding the use of OT. It is worth noting that studies that applied artificial soil compaction (traffic of machines or implements in order to increase the degree of compactness in NT) were not included in this meta-analysis.

The problem in the diagnosis of soil compaction becomes even clearer when evaluating the values of PR and Mac in NT in the studies selected in this meta-analysis. Approximately 70% of the observations had PR <2 MPa and 75% Mac >0.100 $m^3 m^{-3}$ at depth 0-0.20 m (Fig. 10). Typically, PR >2 MPa, air-filled porosity <0.10 $m^3 m^{-3}$, and matric potential drier than -1.5 MPa are regarded to limit root elongation, and may reduce its elongation rate by at least 50% (Bengough and Mullins, 1990; Bengough et al., 2011; Taylor et al., 1966; Taylor and Ratliff, 1969). Besides, in conservation agriculture, which includes NT, the limiting PR values are greater than 2 MPa due to biopores formed by roots and macrofauna, forming preferential paths presumably not detected by the penetrometer (Blanco-Canqui and Ruis, 2018; Landl et al., 2019; Moraes et al., 2014; Tormena et al., 2007). Therefore, in most studies, mechanical impedance and soil aeration did not limit the growth and development of crops.

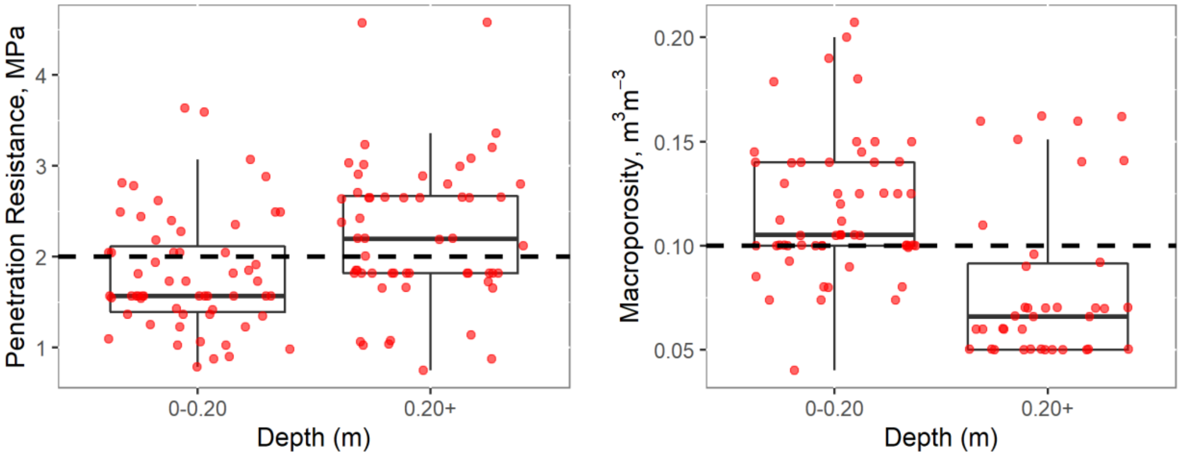


Fig. 10. Penetration resistance (n = 115) and macroporosity (n = 95), as a function of the soil depth, managed in NT. The dashed line indicates the critical limit for each soil physical property; continuous line inside the box is median; the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles); the upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the inter-quartile range, or distance between the first and third quartiles); the lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge; data beyond the end of the whiskers are called "outlying" points and are plotted individually.

The most widespread method of diagnosing soil compaction is measuring PR with a penetrometer. It is a simple, quick, and easy method to determine in laboratory and field. However, PR is extremely affected by soil moisture (Busscher, 1990; Busscher et al., 1997; Vaz et al., 2011), which can lead to inadequate interpretations on the actual state of soil compaction (Peixoto et al., 2019a). In addition, studies have shown that the determination of PR with soil in field capacity, which is the recommended condition and used in almost all studies, has low sensitivity in assessing the state of soil compaction, especially the effect of machinery traffic and mitigation of soil compaction (Bölenius et al., 2018; Catania et al., 2018; Peixoto et al., 2019a).

In order to assist farmers and the scientific community in decision-making processes about the use of OT, two studies were performed with Oxisols in Brazil. The first tested the potential of 15 soil physical properties in predicting soybean yield, with PR being the most important soil physical indicator (Peixoto et al., 2019b). The second proposed a methodology for the diagnosis of soil compaction in NT using PR as an indicator, suggesting its assessment in soil moisture close to the matric potential of -0.10 MPa (drier than the field capacity) and the use of a reference area with high crop yield for a more accurate diagnosis of the state of soil compaction and its effects on crop yield (Peixoto et al., 2019a).

5. Conclusions

NT promotes numerous agronomic and environmental benefits. However, many challenges have emerged with the increased adoption of this soil management system in the main regions producing annual crops around the world. The main challenges are: soil compaction; crop diversification and biomass production that promotes adequate soil protection and input of organic matter; vertical stratification of organic matter and nutrients; and weed management. These challenges are mainly due to the inadequate implementation and management of NT, such as poor construction of soil fertility, inadequate crop rotation, succession and intercropping, traffic in inadequate soil moisture conditions, lack of use of controlled traffic, and problems in the cultural management of weeds.

These challenges culminated with the occasional use of soil tillage in areas under NT, characterizing the OT. However, the following question arose with the increasing adoption of OT: is it necessary to use, even if occasionally, soil tillage methods in NT? From the results of this meta-analysis it was possible to conclude that:

1) Overall, OT did not affect the yield of annual crops, but increased yields were observed in regions with water restrictions, and soils with low retention capacity and water availability;

2) OT improved soil physical properties related to soil compaction (PR, BD, Mac and TP), with persistence, usually >24 months, and reduced the soil aggregates stability;

3) OT reduced soil organic carbon, especially when plow/harrow was used as OT equipment and when the NT was already consolidated;

4) OT did not affect pH and available P, but it can be effective in improving soil fertility in the subsurface soil when OT is used to apply limestone at depth;

5) OT increased microbial biomass carbon, but had no effect on total microbial activity;

6) OT reduced soil erosion by increasing soil-water infiltration and reducing runoff, although it reduced the percentage of soil mulch cover; and

7) Finally, OT improved weed management by reducing the number of weeds.

Based on the conclusions, it is suggested that the challenges of adopting the NT should be faced, not with the return of soil tillage, which was used in the past and which brought numerous agronomic and environmental problems, but with the correct and interconnected application of NT principles, which include the proper implementation of NT (improvement of soil fertility and physical conditions), diversification of crops and permanent soil cover, controlled traffic and in adequate conditions of soil moisture, improvement of weed management, and use of methods of diagnosis and monitoring of soil compaction that reflect the soil physical conditions and their relationship with crop yields.

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7. References

Adams, D.C., Gurevitch, J., Rosenberg, M.S., 1997. Resampling tests for meta-analysis of ecological data. Ecology 78, 1277–1283. https://doi.org/10.1890/0012-9658(1997)078[1277:RTFMAO]2.0.CO;2

Arvidsson, J., Håkansson, I., 1991. A model for estimating crop yield losses caused by soil compaction. Soil Tillage Res. 20, 319–332. https://doi.org/10.1016/0167-1987(91)90046-Z

Auler, A.C., Caires, E.F., Pires, L.F., Galetto, S.L., Romaniw, J., Charnobay, A.C., 2019. Lime effects in a no-tillage system on Inceptisols in Southern Brazil. Geoderma Reg. 16, e00206. https://doi.org/10.1016/j.geodrs.2019.e00206

Babujia, L.C., Hungria, M., Franchini, J.C., Brookes, P.C., 2010. Microbial biomass and activity at various soil depths in a Brazilian oxisol after two decades of no-tillage and conventional tillage. Soil Biol. Biochem. 42, 2174–2181. https://doi.org/10.1016/j.soilbio.2010.08.013

Bajwa, A.A., 2014. Sustainable weed management in conservation agriculture. Crop Prot. 65, 105–113. https://doi.org/10.1016/j.cropro.2014.07.014

Balota, E.L., Colozzi Filho, A., Andrade, D.S., Dick, R.P., 2004. Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil Tillage Res. 77, 137–145. https://doi.org/10.1016/j.still.2003.12.003

Barth, V.P., Reardon, C.L., Coffey, T., Klein, A.M., McFarland, C., Huggins, D.R., Sullivan, T.S., 2018. Stratification of soil chemical and microbial properties under no-till after liming. Appl. Soil Ecol. 130, 169–177. https://doi.org/10.1016/j.apsoil.2018.06.001

Bastida, F., Zsolnay, A., Hernández, T., García, C., 2008. Past, present and future of soil quality indices: A biological perspective. Geoderma 147, 159–171. https://doi.org/10.1016/j.geoderma.2008.08.007

Bengough, A., Mullins, C., 1990. Mechanical impedance to root growth: a review of experimental techniques and root growth responses. J. soil Sci. 41, 341–358. https://doi.org/10.1111/j.1365-2389.1990.tb00070.x

Bengough, A.G., Bransby, M.F., Hans, J., McKenna, S.J., Roberts, T.J., Valentine, T.A., 2006. Root responses to soil physical conditions; growth dynamics from field to cell. J. Exp. Bot. 57, 437–447. https://doi.org/10.1093/jxb/erj003

Bengough, A.G., McKenzie, B.M., Hallett, P.D., Valentine, T.A., 2011. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. J. Exp. Bot. 62, 59–68. https://doi.org/10.1093/jxb/erq350

Bergamin, A.C., 2018. Compactação do solo em sistemas intensivos de produção. Informações Agronômicas 164, 1–9.

Blanco-Canqui, H., Ruis, S.J., 2018. No-tillage and soil physical environment. Geoderma 326, 164–200. https://doi.org/10.1016/j.geoderma.2018.03.011

Blanco-Canqui, H., Wortmann, C.S., 2020. Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil Tillage Res. 198, 104534. https://doi.org/10.1016/j.still.2019.104534

Bölenius, E., Wetterlind, J., Keller, T., 2018. Can within field yield variation be explained using horizontal penetrometer resistance and electrical conductivity measurements? Results from three Swedish fields. Acta Agric. Scand. Sect. B — Soil Plant Sci. 68, 690–700. https://doi.org/10.1080/09064710.2018.1464201

Botta, G.F., Tolon-Becerra, A., Tourn, M., Lastra-Bravo, X., Rivero, D., 2012. Agricultural traffic: Motion resistance and soil compaction in relation to tractor design and different soil conditions. Soil Tillage Res. 120, 92–98. https://doi.org/10.1016/j.still.2011.11.008

Bottinelli, N., Hallaire, V., Goutal, N., Bonnaud, P., Ranger, J., 2014. Impact of heavy traffic on soil macroporosity of two silty forest soils: Initial effect and short-term recovery. Geoderma 217–218, 10–17. https://doi.org/10.1016/j.geoderma.2013.10.025

Bradford, J.M., Huang, C. hua, 1994. Interrill soil erosion as affected by tillage and residue cover. Soil Tillage Res. 31, 353–361. https://doi.org/10.1016/0167-1987(94)90041-8

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22. https://doi.org/10.1016/J.GEODERMA.2004.03.005

Burke, I.C., Yonker, C.M., Parton, W.J., Cole, C. V., Flach, K., Schimel, D.S., 1989. Texture, climate, and cultivation effects on soil organic matter content in US grassland soils. Soil Sci. Soc. Am. J. 53, 800–805. https://doi.org/10.2136/sssaj1989.03615995005300030029x

Busscher, W.J., 1990. Adjustment of flat-tipped penetrometer resistance data to a common water content. Trans. Am. Soc. Agric. Eng. 33, 519–524. https://doi.org/10.13031/2013.31360

Busscher, W.J., Bauer, P.J., Camp, C.R., Sojka, R.E., 1997. Correction of cone index for soil water content differences in a coastal plain soil. Soil Tillage Res. 43, 205–217. https://doi.org/10.1016/S0167-1987(97)00015-9

Cade-Menun, B.J., Carter, M.R., James, D.C., Liu, C.W., 2010. Phosphorus Forms and Chemistry in the Soil Profile under Long-Term Conservation Tillage: A Phosphorus-31 Nuclear Magnetic Resonance Study. J. Environ. Qual. 39, 1647–1656. https://doi.org/10.2134/jeq2009.0491

Caires, E.F., 2013. Correção da acidez do solo em sistema plantio direto. Informações Agronômicas 141, 1–13.

Caires, E.F., Barth, G., Garbuio, F.J., 2006. Lime application in the establishment of a no-till system for grain crop production in Southern Brazil. Soil Tillage Res. 89, 3–12. https://doi.org/10.1016/j.still.2005.06.006

Caires, E.F., Haliski, A., Bini, A.R., Scharr, D.A., 2015. Surface liming and nitrogen fertilization for crop grain production under no-till management in Brazil. Eur. J. Agron. 66, 41–53. https://doi.org/10.1016/j.eja.2015.02.008

Calonego, J.C., Raphael, J.P.A., Rigon, J.P.G., Oliveira Neto, L. de., Rosolem, C.A., 2017. Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. Eur. J. Agron. 85, 31–37. https://doi.org/10.1016/j.eja.2017.02.001

Calonego, J.C., Rosolem, C.A., 2010. Soybean root growth and yield in rotation with cover crops under chiseling and no-till. Eur. J. Agron. 33, 242–249. https://doi.org/10.1016/j.eja.2010.06.002

Calonego, J.C., Rosolem, C.A., 2008. Estabilidade de agregados do solo após manejo com rotações de culturas e escarificação. Rev. Bras. Ciênc. Solo 32, 1399–1407. https://doi.org/10.1590/S0100-06832008000400004

Camara, R.K., Klein, V.A., 2005. Escarificação em plantio direto como técnica de conservação do solo e da água. Rev. Bras. Ciênc. Solo 29, 789–796. https://doi.org/10.1590/S0100-06832005000500014

Carter, M.R., 1991. The influence of tillage on the proportion of organic carbon and nitrogen in the microbial biomass of medium-textured soils in a humid climate. Biol. Fertil. Soils 11, 135–139. https://doi.org/10.1007/BF00336378

Catania, P., Badalucco, L., Laudicina, V.A., Vallone, M., 2018. Effects of tilling methods on soil penetration resistance, organic carbon and water stable aggregates in a vineyard of semiarid Mediterranean environment. Environ. Earth Sci. 77, 348. https://doi.org/10.1007/s12665-018-7520-5

Cecagno, D., Costa, S.E.V.A., Anghinoni, I., Kunrath, T.R., Martins, A.P., Reichert, J.M., Gubiani, P.I., Balerini, F., Fink, J.R., Carvalho, P.C.F., 2016. Least limiting water range and soybean yield in system under different grazing different grazing intensities. Soil Tillage Res. 156, 54–62. https://doi.org/10.1016/j.still.2015.10.005

Chan, K.Y., Oates, A., Swan, A.D., Hayes, R.C., Dear, B.S., Peoples, M.B., 2006. Agronomic consequences of tractor wheel compaction on a clay soil. Soil Tillage Res. 89, 13–21. https://doi.org/10.1016/j.still.2005.06.007

Chauhan, B.S., Singh, R.G., Mahajan, G., 2012. Ecology and management of weeds under conservation agriculture: A review. Crop Prot. 38, 57–65. https://doi.org/10.1016/j.cropro.2012.03.010

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 Tillage Res. 136, 61–69. https://doi.org/10.1016/j.still.2013.09.004

Chen, H., Billen, N., Stahr, K., Kuzyakov, Y., 2007. Effects of nitrogen and intensive mixing on decomposition of 14C-labelled maize (Zea mays L.) residue in soils of different land use types. Soil Tillage Res. 96, 114–123. https://doi.org/10.1016/j.still.2007.04.004

Chen, H., Hou, R., Gong, Y., Li, H., Fan, M., Kuzyakov, Y., 2009. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. Soil Tillage Res. 106, 85–94. https://doi.org/10.1016/j.still.2009.09.009

Colombi, T., Braun, S., Keller, T., Walter, A., 2017. Artificial macropores attract crop roots and enhance plant productivity on compacted soils. Sci. Total Environ. 574, 1283–1293. https://doi.org/10.1016/j.scitotenv.2016.07.194

Correa, J., Postma, J.A., Watt, M., Wojciechowski, T., 2019. Soil compaction and the architectural plasticity of root systems. J. Exp. Bot. 70, 6019–6034. https://doi.org/10.1093/jxb/erz383

Dang, Y.P., Balzer, A., Crawford, M., Rincon-Florez, V., Liu, H., Melland, A.R., Antille, D., Kodur, S., Bell, M.J., Whish, J.P.M., Lai, Y., Seymour, N., Carvalhais, L.C., Schenk, P., 2018. Strategic tillage in conservation agricultural systems of north-eastern australia: Why, where, when and how? Environ. Sci. Pollut. Res. 25, 1000–1015. https://doi.org/10.1007/s11356-017-8937-1

Dang, Y.P., Moody, P.W., Bell, M.J., Seymour, N.P., Dalal, R.C., Freebairn, D.M., Walker, S.R., 2015a. Strategic tillage in no-till farming systems in Australia’s northern grains-growing regions: II. Implications for agronomy, soil and environment. Soil Tillage Res. 152, 115–123. https://doi.org/10.1016/j.still.2014.12.013

Dang, Y.P., Seymour, N.P., Walker, S.R., Bell, M.J., Freebairn, D.M., 2015b. Strategic tillage in no-till farming systems in Australia’s northern grains-growing regions: I. Drivers and implementation. Soil Tillage Res. 152, 104–114. https://doi.org/10.1016/j.still.2015.03.009

Das, A., Lal, R., Patel, D.P., Idapuganti, R.G., Layek, J., Ngachan, S. V., Ghosh, P.K., Bordoloi, J., Kumar, M., 2014. Effects of tillage and biomass on soil quality and productivity of lowland rice cultivation by small scale farmers in North Eastern India. Soil Tillage Res. 143, 50–58. https://doi.org/10.1016/j.still.2014.05.012

Denardin, J.E., Faganello, A., Santi, A., 2008. Falhas na implementação do sistema plantio direto levam à degradação do solo. Rev. Plantio Direto 18, 3–4.

Derpsch, R., 2008. No-tillage and conservation agriculture: a progress report, in: Goddard, T., Zoebisch, M.A., Gan, Y.T., Ellis, W., Watson, A., Sombatpanit, S. (Eds.), No-till Farming Systems. World Association of Soil and Water Conservation, Bangkok, Thailand, pp. 7–39.

Derpsch, R., Friedrich, T., Kassam, A., Hongwen, L., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. Int. J. Agric. Biol. Eng. 3, 1–25. https://doi.org/10.3965/j.issn.1934-6344.2010.01.001-025

Dexter, A.R., Horn, R., Kemper, W.D., 1988. Two mechanisms for age-hardening of soil. J. Soil Sci. 39, 163–175. https://doi.org/10.1111/j.1365-2389.1988.tb01203.x

Drescher, M.S., Eltz, F.L.F., Denardin, J.E., Faganello, A., 2011. Persistência do efeito de intervenções mecânicas para a descompactação de solos sob plantio direto. Rev. Bras. Ciênc. Solo 35, 1713–1722. https://doi.org/10.1590/S0100-06832011000500026

Franzluebbers, A.J., Langdale, G.W., Schomberg, H.H., 1999. Soil Carbon, Nitrogen, and Aggregation in Response to Type and Frequency of Tillage. Soil Sci. Soc. Am. J. 63, 349–355. https://doi.org/10.2136/sssaj1999.03615995006300020012x

Gesch, R.W., Cermak, S.C., 2011. Sowing Date and Tillage Effects on Fall-Seeded Camelina in the Northern Corn Belt. Agron. J. 103, 980–987. https://doi.org/10.2134/agronj2010.0485

Ghimire, R., Adhikari, K.R., Chen, Z.-S., Shah, S.C., Dahal, K.R., 2012. Soil organic carbon sequestration as affected by tillage, crop residue, and nitrogen application in rice–wheat rotation system. Paddy Water Environ. 10, 95–102. https://doi.org/10.1007/s10333-011-0268-0

Håkansson, I., 1990. A method for characterizing the state of compactness of the plough layer. Soil Tillage Res. 16, 105–120. https://doi.org/10.1016/0167-1987(90)90024-8

Håkansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res. 53, 71–85. https://doi.org/10.1016/S0167-1987(99)00095-1

Hakojärvi, M., Hautala, M., Ristolainen, A., Alakukku, L., 2013. Yield variation of spring cereals in relation to selected soil physical properties on three clay soil fields. Eur. J. Agron. 49, 1–11. https://doi.org/10.1016/j.eja.2013.03.003

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems. Soil Tillage Res. 82, 121–145. https://doi.org/10.1016/j.still.2004.08.009

He, Y., Presley, D.R., Tatarko, J., Blanco-Canqui, H., 2018. Crop residue harvest impacts wind erodibility and simulated soil loss in the Central Great Plains. GCB Bioenergy 10, 213–226. https://doi.org/10.1111/gcbb.12483

Hedges, L. V, Gurevitch, J., Curtis, P.S., 1999. The Meta-Analysis of Response Ratios in Experimental Ecology. Ecology 80, 1150. https://doi.org/10.2307/177062

Kabiri, V., Raiesi, F., Ghazavi, M.A., 2016. Tillage effects on soil microbial biomass, SOM mineralization and enzyme activity in a semi-arid Calcixerepts. Agric. Ecosyst. Environ. 232, 73–84. https://doi.org/10.1016/j.agee.2016.07.022

Kaschuk, G., Alberton, O., Hungria, M., 2011. Quantifying effects of different agricultural land uses on soil microbial biomass and activity in Brazilian biomes: Inferences to improve soil quality. Plant Soil 338, 467–481. https://doi.org/10.1007/s11104-010-0559-z

Kassam, A., Friedrich, T., Derpsch, R., 2019. Global spread of Conservation Agriculture. Int. J. Environ. Stud. 76, 29–51. https://doi.org/10.1080/00207233.2018.1494927

Kay, B.D., 1998. Soil Structure and Organic Carbon: A Review, in: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. Boca Raton: CRC Press, pp. 162–190.

Kim, H., Anderson, S.H., Motavalli, P.P., Gantzer, C.J., 2010. Compaction effects on soil macropore geometry and related parameters for an arable field. Geoderma 160, 244–251. https://doi.org/10.1016/j.geoderma.2010.09.030

Kirschbaum, M.U.F., 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biol. Biochem. 27, 753–760. https://doi.org/10.1016/0038-0717(94)00242-S

Klein, V.A., Dallmeyer, A.U., Alexandre, P., Escosteguy, V., Fioreze, I., Vieira, M.L., Durigon, F.F., Fávero, F., 2007. Adaptação de um equipamento para incorporação de calcário em solos sob plantio direto. Rev. Ciências Agroveterinárias 6, 95–103.

Koch, H.J., Stockfisch, N., 2006. Loss of soil organic matter upon ploughing under a loess soil after several years of conservation tillage. Soil Tillage Res. 86, 73–83. https://doi.org/10.1016/j.still.2005.02.029

Lal, R., 2009. Challenges and opportunities in soil organic matter research. Eur. J. Soil Sci. 60, 158–169. https://doi.org/10.1111/j.1365-2389.2008.01114.x

Lal, R., 2001. Soil degradation by erosion. Land Degrad. Dev. 12, 519–539. https://doi.org/10.1002/ldr.472

Lal, R., Reicosky, D.C., Hanson, J.D., 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res. 93, 1–12. https://doi.org/10.1016/j.still.2006.11.004

Lamandé, M., Schjønning, P., 2011. Transmission of vertical stress in a real soil profile. Part II: Effect of tyre size, inflation pressure and wheel load. Soil Tillage Res. 114, 71–77. https://doi.org/10.1016/j.still.2010.08.011

Landl, M., Schnepf, A., Uteau, D., Peth, S., Athmann, M., Kautz, T., Perkons, U., Vereecken, H., Vanderborght, J., 2019. Modeling the Impact of Biopores on Root Growth and Root Water Uptake. Vadose Zone J. 18, 1–20. https://doi.org/10.2136/vzj2018.11.0196

Lee, N., Thierfelder, C., 2017. Weed control under conservation agriculture in dryland smallholder farming systems of southern Africa. A review. Agron. Sustain. Dev. 37, 48. https://doi.org/10.1007/s13593-017-0453-7

Lipiec, J., Hatano, R., 2003. Quantification of compaction effects on soil physical properties and crop growth. Geoderma 116, 107–136. https://doi.org/10.1016/S0016-7061(03)00097-1

Lipiec, J., Hing;kansson, I., Tarkiewicz, S., Kossowski, J., 1991. Soil physical properties and growth of spring barley as related to the degree of compactness of two soils. Soil Tillage Res. 19, 307–317. https://doi.org/10.1016/0167-1987(91)90098-I

Lipiec, J., Horn, R., Pietrusiewicz, J., Siczek, A., 2012. Effects of soil compaction on root elongation and anatomy of different cereal plant species. Soil Tillage Res. 121, 74–81. https://doi.org/10.1016/j.still.2012.01.013

Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil Tillage Res. 89, 210–220. https://doi.org/10.1016/j.still.2005.07.012

Lopes, A.S., Guimarães Guilherme, L.R., 2016. A Career Perspective on Soil Management in the Cerrado Region of Brazil. Adv. Agron. 137, 1–72. https://doi.org/10.1016/bs.agron.2015.12.004

López-Garrido, R., Madejón, E., León-Camacho, M., Girón, I., Moreno, F., Murillo, J.M., 2014. Reduced tillage as an alternative to no-tillage under Mediterranean conditions: A case study. Soil Tillage Res. 140, 40–47. https://doi.org/10.1016/j.still.2014.02.008

Lozano, L.A., Soracco, C.G., Villarreal, R., Ressia, J.M., Sarli, G.O., Filgueira, R.R., 2016. Soil Physical Quality and Soybean Yield as Affected by Chiseling and Subsoiling of a No-Till Soil. Rev. Bras. Ciênc. Solo 40, 1–12. https://doi.org/10.1590/18069657rbcs20150160

Mahl, D., Gamero, C.A., Benez, S.H., Furlani, C.E.A., Silva, A.R.B., 2004. Demanda energética e eficiência da distribuição de sementes de milho sob variação de velocidade e condição de solo. Eng. Agrícola 24, 150–157. https://doi.org/10.1590/S0100-69162004000100017

Moraes, M.T. de, Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.R. da, 2014. Critical limits of soil penetration resistance in a rhodic Eutrudox. Rev. Bras. Ciênc. Solo 38, 288–298. https://doi.org/10.1590/S0100-06832014000100029

Moraes, M.T. de, Luz, F.B. da, Debiasi, H., Franchini, J.C., Silva, V.R. da, 2019. Soil load support capacity increases with time without soil mobilization as a result of age-hardening phenomenon. Soil Tillage Res. 186, 128–134. https://doi.org/10.1016/j.still.2018.09.009

Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.R., Luz, F.B., 2017. Age-hardening phenomena in an oxisol from the subtropical region of Brazil. Soil Tillage Res. 170, 27–37. https://doi.org/10.1016/j.still.2017.03.002

Moreira, S.G., 2019. Desafios para a sustentabilidade dos sistemas de produção com culturas anuais. Informações Agronômicas 1–12.

Morgan, R.P.C., 2005. Soil Erosion and Conservation. Longman, London.

Nath, A.J., Lal, R., 2017. Effects of Tillage Practices and Land Use Management on Soil Aggregates and Soil Organic Carbon in the North Appalachian Region, USA. Pedosphere 27, 172–176. https://doi.org/10.1016/S1002-0160(17)60301-1

Nichols, V., Verhulst, N., Cox, R., Govaerts, B., 2015. Weed dynamics and conservation agriculture principles: A review. F. Crop. Res. 183, 56–68. https://doi.org/10.1016/j.fcr.2015.07.012

Nunes, M.R., Denardin, J.E., Pauletto, E.A., Faganello, A., Pinto, L.F.S., 2015a. Effect of soil chiseling on soil structure and root growth for a clayey soil under no-tillage. Geoderma 259–260, 149–155. https://doi.org/10.1016/j.geoderma.2015.06.003

Nunes, M.R., Denardin, J.E., Pauletto, E.A., Faganello, A., Pinto, L.F.S., 2015b. Mitigation of clayey soil compaction managed under no-tillage. Soil Tillage Res. 148, 119–126. https://doi.org/10.1016/j.still.2014.12.007

Nunes, M.R., van Es, H.M., Schindelbeck, R., Ristow, A.J., Ryan, M., 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma 328, 30–43. https://doi.org/10.1016/j.geoderma.2018.04.031

Oades, J.M., 1988. The retention of organic matter in soils. Biogeochemistry 5, 35–70. https://doi.org/10.1007/BF02180317

Ogle, S.M., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72, 87–121. https://doi.org/10.1007/s10533-004-0360-2

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., Grace, P., 2014. Conservation agriculture and ecosystem services: An overview. Agric. Ecosyst. Environ. 187, 87–105. https://doi.org/10.1016/j.agee.2013.10.010

Paul, B.K., Vanlauwe, B., Ayuke, F., Gassner, A., Hoogmoed, M., Hurisso, T.T., Koala, S., Lelei, D., Ndabamenye, T., Six, J., Pulleman, M.M., 2013. Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity. Agric. Ecosyst. Environ. 164, 14–22. https://doi.org/10.1016/j.agee.2012.10.003

Peixoto, D.S., Silva, B.M., de Oliveira, G.C., Moreira, S.G., da Silva, F., Curi, N., 2019a. A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. Soil Tillage Res. 194, 104307. https://doi.org/10.1016/j.still.2019.104307

Peixoto, D.S., Silva, B.M., Silva, S.H.G., Karlen, D.L., Moreira, S.G., Silva, A.A.P., Resende, Á.V., Norton, L.D., Curi, N., 2019b. Diagnosing, Ameliorating, and Monitoring Soil Compaction in No-Till Brazilian Soils. Agrosystems, Geosci. Environ. 2, 180035. https://doi.org/10.2134/age2018.09.0035

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015a. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365–368. https://doi.org/10.1038/nature13809

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015b. When does no-till yield more? A global meta-analysis. F. Crop. Res. 183, 156–168. https://doi.org/10.1016/j.fcr.2015.07.020

R Development Core Team, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Viena, Austria.

Ralisch, R., Almeida, E. de, Silva, A.P. da, Pereira Neto, O.C., Guimarães, M. de F., 2010. Morphostructural characterization of soil conventionally tilled with mechanized and animal traction with and without cover crop. Rev. Bras. Ciênc. Solo 34, 1795–1802. https://doi.org/10.1590/S0100-06832010000600003

Reichert, J.M., da Rosa, V.T., Vogelmann, E.S., da Rosa, D.P., Horn, R., Reinert, D.J., Sattler, A., Denardin, J.E., 2016. Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. Soil Tillage Res. 158, 123–136. https://doi.org/10.1016/j.still.2015.11.010

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

Reicosky, D.C., 2015. Conservation tillage is not conservation agriculture. J. Soil Water Conserv. 70, 103A-108A. https://doi.org/10.2489/jswc.70.5.103A

Reicosky, D.C., Dugas, W.A., Torbert, H.A., 1997. Tillage-induced soil carbon dioxide loss from different cropping systems. Soil Tillage Res. 41, 105–118. https://doi.org/10.1016/S0167-1987(96)01080-X

Resende, Á.V., Fontoura, S.M.V., Borghi, E., Santos, F.C., Kappes, C., Moreira, S.G., Oliveira Júnior, A., Borin, A.L.D.C., 2016. Solos de fertilidade construída: características, funcionamento e manejo. Informações agronômicas 156, 1–19.

Salton, J.C., Hernani, L.C., Fontes, C.Z., 1998. Sistema Plantio Direto. O produtor pergunta, a Embrapa responde, Embrapa - CPAO. Embrapa - CPAO, Brasília, DF.

Schneider, F., Don, A., Hennings, I., Schmittmann, O., Seidel, S.J., 2017. The effect of deep tillage on crop yield – What do we really know? Soil Tillage Res. 174, 193–204. https://doi.org/10.1016/j.still.2017.07.005

Seki, A.S., Seki, F.G., Jasper, S.P., Silva, P.R.A., Benez, S.H., 2015. Effects of soil decompaction techniques in an area under a system of direct seeding. Rev. Ciênc. Agron. 46, 460–468. https://doi.org/10.5935/1806-6690.20150027

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6

Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and Soil Organic Matter Dynamics under Conventional and No-Tillage Systems. Soil Sci. Soc. Am. J. 63, 1350–1358. https://doi.org/10.2136/sssaj1999.6351350x

Six, J., Feller, C., Denef, K., Ogle, S.M., de Moraes, J.C., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage. Agronomie 22, 755–775. https://doi.org/10.1051/agro:2002043

Soil Science Glossary Terms Committee, 2008. Glossary of soil science terms. Soil Science Society of America Journal, Madison, WI.

Sollins, P., Homann, P., Caldwell, B.A., 1996. Stabilization and destabilization of soil organic matter: mechanisms and controls. Geoderma 74, 65–105. https://doi.org/10.1016/S0016-7061(96)00036-5

Stockfisch, N., Forstreuter, T., Ehlers, W., 1999. Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. Soil Tillage Res. 52, 91–101. https://doi.org/10.1016/S0167-1987(99)00063-X

Szatanik-Kloc, A., Horn, R., Lipiec, J., Siczek, A., Szerement, J., 2018. Soil compaction-induced changes of physicochemical properties of cereal roots. Soil Tillage Res. 175, 226–233. https://doi.org/10.1016/j.still.2017.08.016

Taylor, H.M., Ratliff, L.F., 1969. Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Sci. 108, 113–119.

Taylor, H.M., Roberson, G.M., Parker Jr., J.J., 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102, 18–22.

Tisdale, S.L., Nelson, W.L., Beaton, J.D., 1985. Soil fertility and fertilizers. Collier Macmillan Publishers, London.

Tormena, C.A., Araújo, M.A., Fidalski, J., Da Costa, J.M., 2007. Variação temporal do intervalo hídrico ótimo de um latossolo vermelho distroférrico sob sistemas de plantio direto. Rev. Bras. Cienc. Solo 31, 211–219. https://doi.org/10.1590/s0100-06832007000200003

Trabucco, A., Zomer, R.J., 2019. Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database v2. figshare., Dataset. https://doi.org/10.6084/m9.figshare.7504448.v3

Utomo, W.H., Dexter, A.R., 1981. Age hardening of agricultural top soils. J. Soil Sci. 32, 335–350. https://doi.org/10.1111/j.1365-2389.1981.tb01710.x

Vaz, C.M.P., Manieri, J.M., de Maria, I.C., Tuller, M., 2011. Modeling and correction of soil penetration resistance for varying soil water content. Geoderma 166, 92–101. https://doi.org/10.1016/j.geoderma.2011.07.016

Veiga, M., Horn, R., Reinert, D.J., Reichert, J.M., 2007. Soil compressibility and penetrability of an Oxisol from southern Brazil, as affected by long-term tillage systems. Soil Tillage Res. 92, 104–113. https://doi.org/10.1016/j.still.2006.01.008

Vezzani, F.M., Mielniczuk, J., 2011. Agregação e estoque de carbono em argissolo submetido a diferentes práticas de manejo agrícola. Rev. Bras. Cienc. Solo 35, 213–223. https://doi.org/10.1590/S0100-06832011000100020

Zuber, S.M., Villamil, M.B., 2016. Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. Soil Biol. Biochem. 97, 176–187. https://doi.org/10.1016/J.SOILBIO.2016.03.011

8. Appendix A – Supplementary material

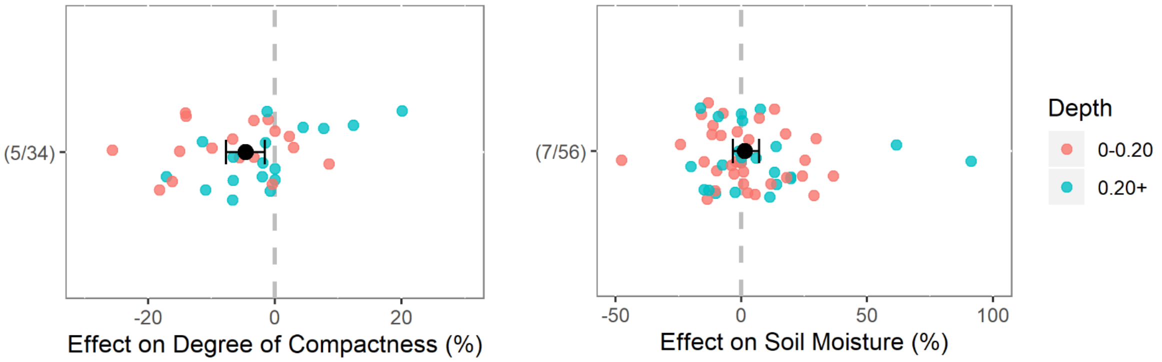

Fig. A1. Effect of occasional tillage relative to no-tillage on degree of compactness and soil moisture at depths of 0-0.20 m and 0.20+ m. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the dots represent the observations. The total number of studies and observations is shown in parentheses.

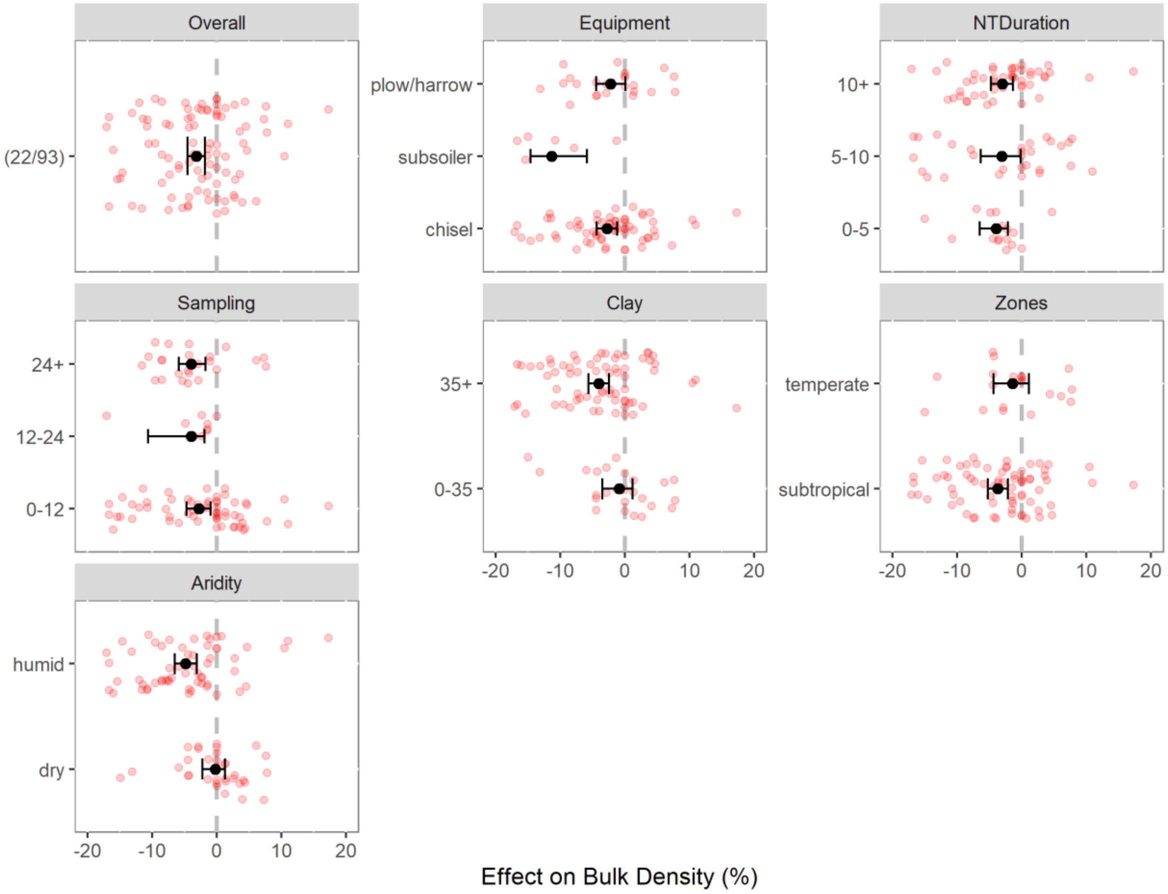

Fig. A2. Effect of occasional tillage relative to no-tillage on bulk density, depth of 0.20+ m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), climate zone and aridity index. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

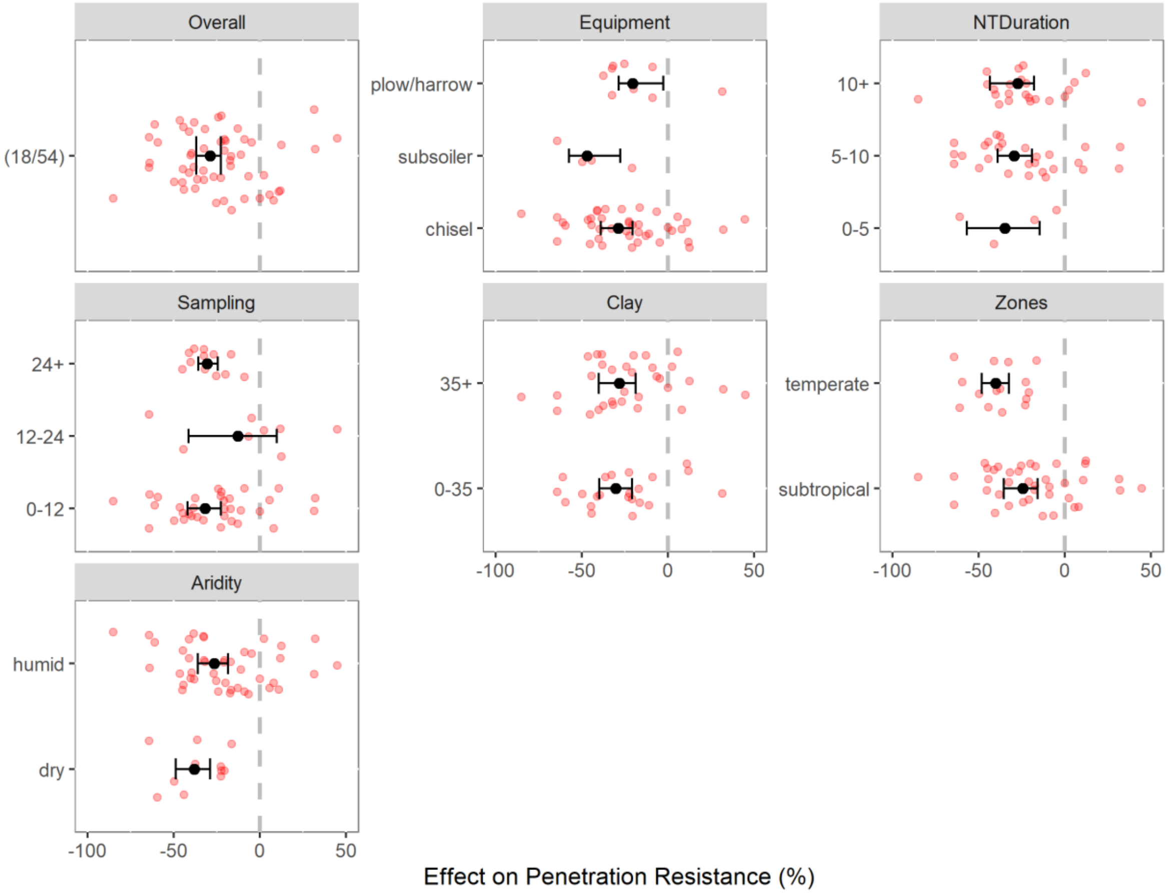

Fig. A3. Effect of occasional tillage relative to no-tillage on penetration resistance, depth of 0.20+ m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), climate zone and aridity index. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

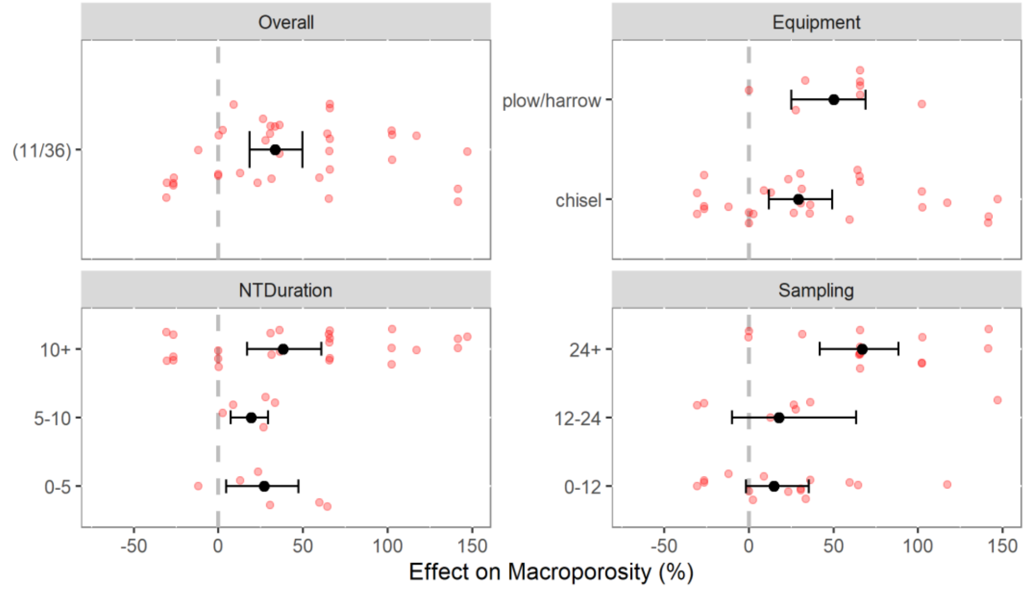

Fig. A4. Effect of occasional tillage relative to no-tillage on macroporosity, depth of 0.20+ m, as a function of OT equipment, duration of NT (years), and duration of OT until sampling (months). The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

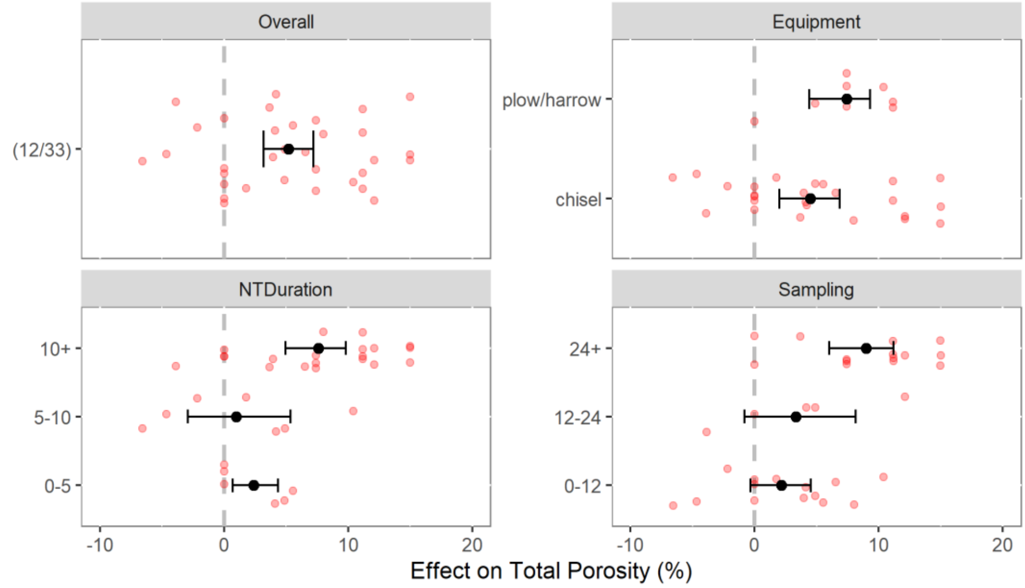

Fig. A5. Effect of occasional tillage relative to no-tillage on total porosity, depth of 0.20+ m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months). The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

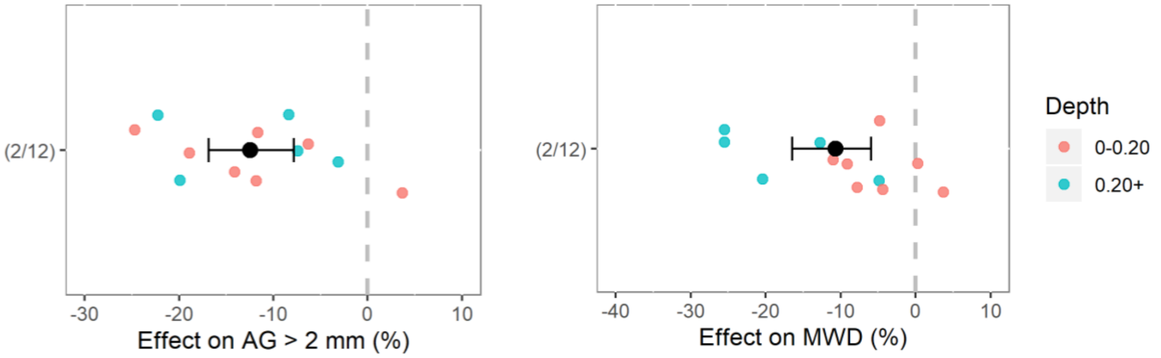

Fig. A4. Effect of occasional tillage relative to no-tillage on macroporosity, depth of 0.20+ m, as a function of OT equipment, duration of NT (years), and duration of OT until sampling (months). The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

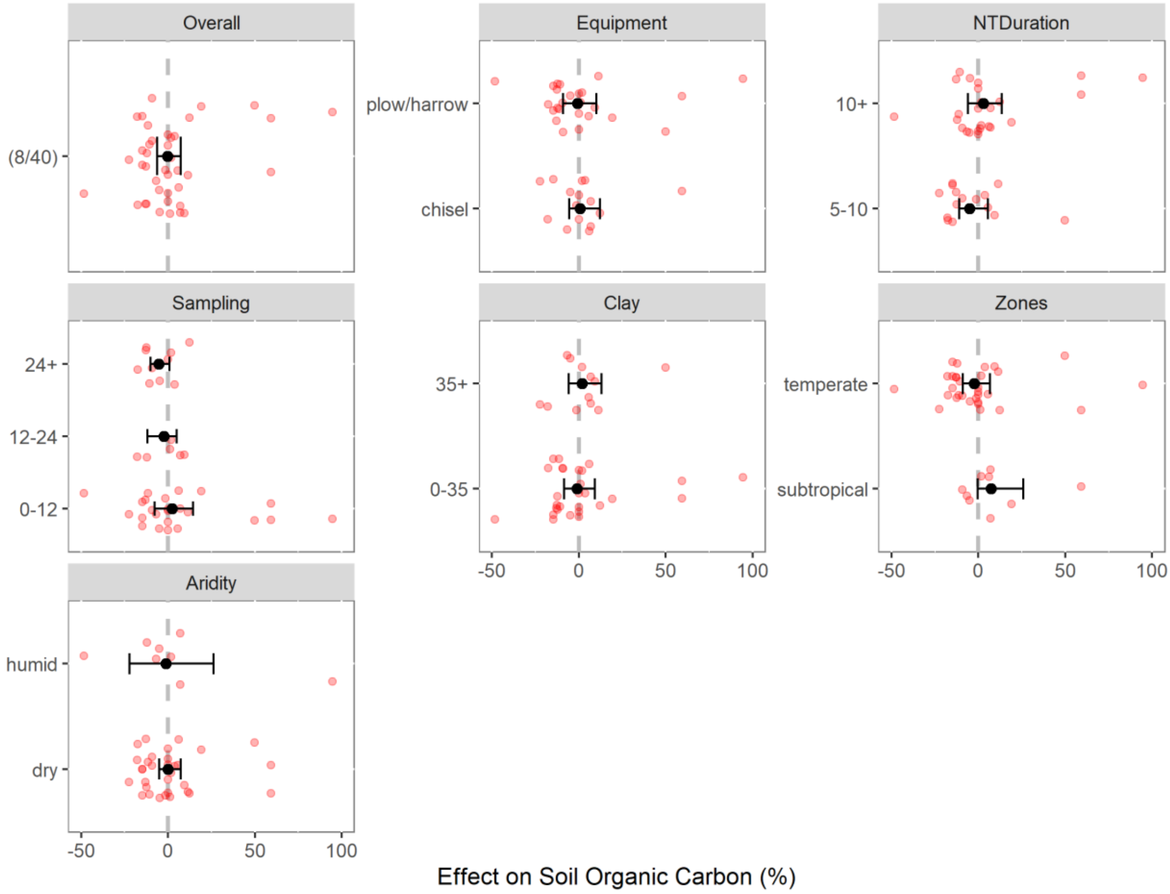

Fig. A7. Effect of occasional tillage relative to no-tillage on soil organic carbon, depth of 0.20+ m, as a function of OT equipment, duration of NT (years), duration of OT until sampling (months), clay content (%), climate zone and aridity index. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the red dots represent the observations. The total number of studies and observations is shown in parentheses.

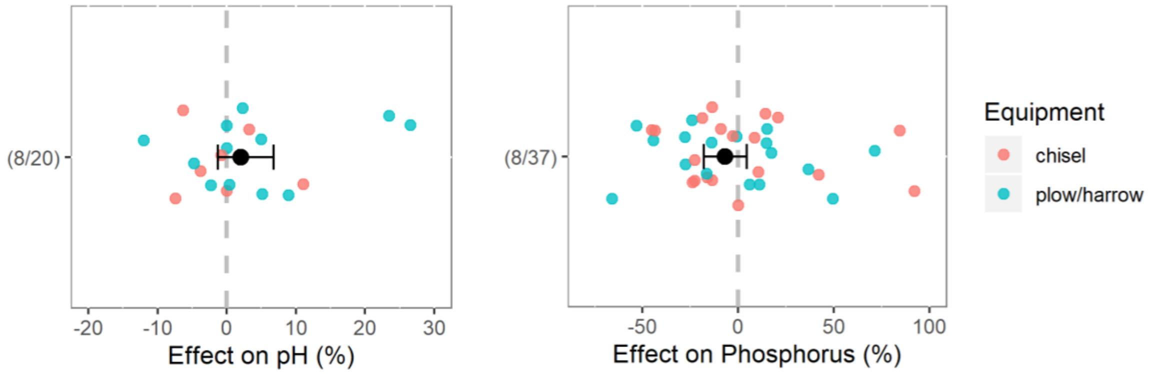

Fig. A8. Effect of occasional tillage relative to no-tillage on soil pH and available P, depth of 0-0.20 m, depending on the OT equipment. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the dots represent the observations. The total number of studies and observations is shown in parentheses.

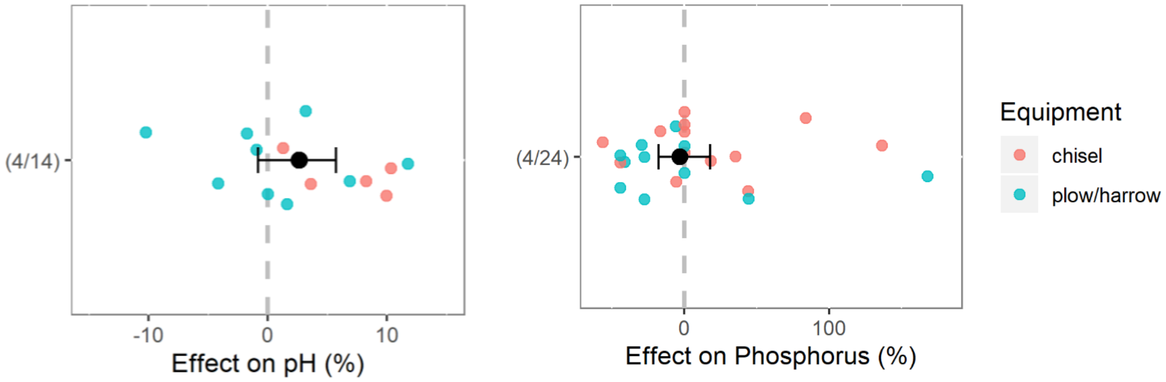

Fig. A9. Effect of occasional tillage relative to no-tillage on soil pH and available P, depth 0.20+ m, depending on the OT equipment. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the dots represent the observations. The total number of studies and observations is shown in parentheses.

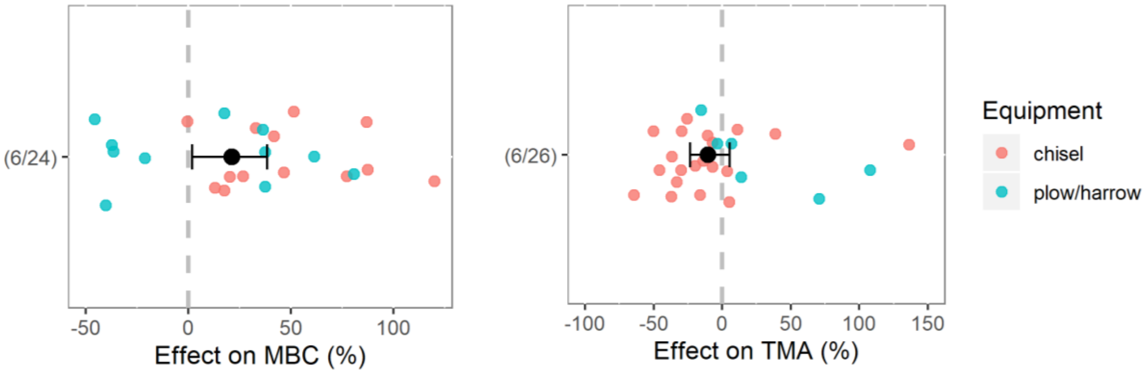

Fig. A10. Effect of occasional tillage relative to no-tillage in microbial biomass carbon (MBC) and total microbial activity (TMA), at depth of 0-0.20 m, depending on the OT equipment. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the dots represent the observations. The total number of studies and observations is shown in parentheses.

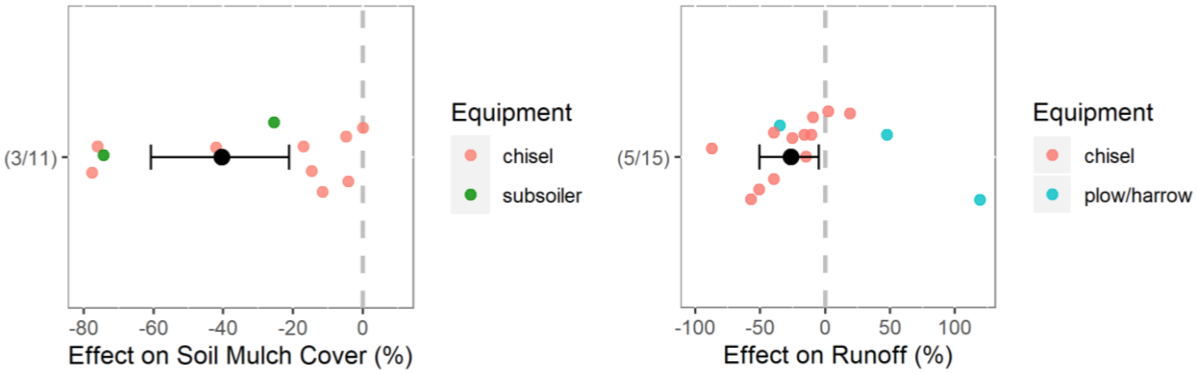

Fig. A11. Effect of occasional tillage relative to no-tillage on soil mulch cover and runoff depending on the OT equipment. The error bar represents the 95% bootstrap confidence interval of the response ratio (%) and the dots represent the observations. The total number of studies and observations is shown in parentheses.

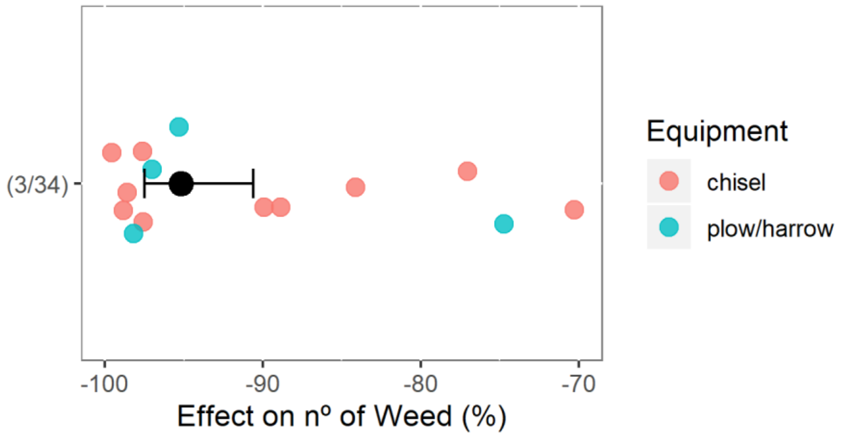

Fig. A12. Effect of occasional tillage relative to no-tillage on the number of weeds depending on the OT equipment. The error bar represents the 95% bootstrap confidence interval of the response rate (%) and the dots represent the observations. The total number of studies and observations is shown in parentheses.

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PAPER 2 - DIAGNOSING, AMELIORATING, AND MONITORING SOIL COMPACTION IN NO-TILL BRAZILIAN SOILS

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Core Ideas

- One-time tillage increased soybean yield as a result of improving soil physical properties.
- Penetration resistance, air capacity, macroporosity, relative field capacity, and S index were the soil physical properties that best predicted soybean yield.
- The most sensitive soil physical properties for detecting structural related alterations were equally important for predicting soybean yield.
- Penetration resistance is the indicator that addresses no-tillage soil compaction and its effect on soybean yield.

Abstract

Soil compaction can significantly reduce crop yield. Our objective was to identify the most sensitive soil physical property and process indicators related to crop yield using a Random Forest algorithm (RFA). This machine-learning, decision-making tool was used with field-scale data from five soil management treatments designed to ameliorate compaction in no-tillage (NT) fields. The treatments were: T1, NT for 10 yr (control); T2, NT with surface application of 3.6 Mg ha^{-1} of agricultural gypsum; T3, NT with subsoiling plus 1.44 Mg ha^{-1} of highly reactive limestone applied to a depth of 0.60 m; T4, NT planting following chisel plowing at a depth of 0.26 m; and T5, NT with subsoiling to a depth of 0.60 m plus 1.44 Mg ha^{-1} of surface-applied, highly reactive limestone. Fifteen soil physical properties and processes related to growth and yield of soybean [*Glycine max* (L.) Merr.] were measured. Mechanical intervention, specifically subsoiling, improved soil physical properties and increased soybean yield cultivated following occasional tillage. The RFA ranked penetration resistance (PR), air capacity, macroporosity, relative field capacity, and the Dexter-S index as the most sensitive soil physical indicators affecting soybean yield. Those indicators were also sensitive to changes in soil structure due to subsoiling. We conclude that the RFA was an effective tool for screening indicators and that those chosen can be effective for monitoring soil compaction and its effect on soybean yield. Penetration resistance may be used to guide on-farm decision-making regarding when and how NT soil compaction should be addressed.

1. Introduction

No-tillage (NT) has been adopted globally on more than 155 million ha (FAO, 2016) and is expanding at approximately 6 million ha yr^{-1} because of both economic and environmental benefits (Derpsch et al., 2010; Pittelkow et al., 2015). In Brazil, NT covers more than 32 million ha mostly used for soybean [*Glycine max* (L.) Merr.], but compaction is becoming a more frequently observed problem on clay-textured soils (Reichert et al., 2009; Nunes et al., 2014; Nunes et al., 2015). Mechanized operations are the primary cause for soil compaction, since wheel-traffic during as many as three cropping cycles per year may occur on 100, 60, and 30% of the soil surface with conventional-, minimum-, and no-tillage, respectively (Tullberg, 1990). Furthermore, although NT has many advantages, including trafficability, its implementation on wet soils can cause a progressive increase in compaction with every cropping cycle (Hamza and Anderson, 2005).

Soil compaction limits plant root development (Bengough et al., 2011; Lipiec et al., 2012) due to increased bulk density (BD), penetration resistance (PR), and reduced permeability (Hamza and Anderson, 2005), which collectively limit gas exchange (air and water vapor) as well as nutrient uptake by roots (Lipiec and Stepniewski, 1995). Mechanical strategies suggested to mitigate NT soil compaction include equipping seeders with fixed shanks or openers that disturb soil to a depth of ~0.17 m (Nunes et al., 2014; Nunes et al., 2015); chiseling to a depth of ~0.20 to 0.30 m every year or occasionally (Secco et al., 2009; Calonego and Rosolem, 2010; Calonego et al., 2017); combining tillage (disc plow and disc harrow to a depth of ~0.20 m) with lime application (Fidalski et al., 2015), or subsoiling diagonally across the field at a depth of ~0.60 m (Wang et al., 2014; Bobade et al., 2016).

Increasing observations of NT compaction coupled with the well-documented adverse effects of compaction are creating a soil and crop management dilemma for many Brazilian farmers. They adopted NT to reduce soil erosion and energy needs, increase soil organic matter, and improve soil structure and soil biological attributes (Grandy et al., 2006; Lal et al., 2007; Derpsch et al., 2010; Soane et al., 2012). Now, the need (real or perceived) to mitigate NT compaction is threatening to destroy many of the long-term NT benefits (Caires et al., 2006; Stavi et al., 2011; Zhang et al., 2017).

To determine the best course of action, on-farm field-scale studies and detailed monitoring of soil physical properties as well as crop responses to various mitigation strategies are being recommended. This requires being able to identify the most sensitive and responsive soil physical properties that can limit or enhance crop yield. Identification of the most sensitive indicators will also require identification of new screening tools to ensure cost-effective, meaningful, and efficient monitoring.

Soil physical factors that directly affect crop yield include water, oxygen, temperature, and mechanical resistance (Letey, 1985). The status of these factors can be quantified by using soil physical quality indicators to identify soil compaction and establish crop yield relationships (Arshad et al., 1996; Nortcliff, 2002; Reynolds et al., 2009). These relationships, however, are often influenced by climatic conditions (Letey, 1985; Bölenius et al., 2017), making it difficult to establish direct relationships. As a result, studies have shown that during rainy periods there is often no correlation between soil physical properties and crop yield (Secco et al., 2004; Klein and Camara, 2007; Calonego and Rosolem, 2010; Hakojärvi et al., 2013; Girardello et al., 2014; Cecagno et al., 2016; Calonego et al., 2017).

Tools used to assess causal relationships among soil properties or between selected indicators and crop yield include Pearson's correlation (Shukla et al., 2004; Montanari et al., 2010; Silva et al., 2017), multivariate analysis (Shukla et al., 2004; Santi et al., 2012; Bölenius et al., 2017), and simple as well as multiple linear regression (Flowers and Lal, 1998; Busscher et al., 2001; Montanari et al., 2010; Bölenius et al., 2017). Each method has a variety of strengths and weakness with one of the most limiting being the amount of data needed to accurately measure or model the relationships. Recent advances in computational methods and development of machine learning techniques have greatly enhanced prediction capacity for and modeling of nonlinear relationships in agriculture. The Random Forest algorithm (RFA) (Breiman, 2001) is one method that has been widely applied because of its high accuracy, capacity to identify important co-variables, ability to model complex interactions, flexibility for statistical analysis, and ability to compensate for missing values (Cutler et al., 2007). However, few studies have used RFA to estimate crop yield (Vincenzi et al., 2011; Fukuda et al., 2013; Everingham et al., 2016; Smidt et al., 2016), and only Smidt et al. (2016) included soil physical properties and available water supply as predictor variables.

We hypothesized that a RFA could efficiently identify soil physical properties sensitive to compaction in NT systems, detect short-term alterations in soil structure in response to management practices, and relate those changes to soybean yield in Brazil. Furthermore, by identifying the most sensitive and responsive soil physical property indicators, it will be possible to improve decision-making processes regarding when and how interventions should be made to reduce effects of NT soil compaction. Our objectives were to (i) assess effects of various management strategies for ameliorating compacted soils by measuring soil physical property, soybean growth, and yield responses; and (ii) identify critical soil physical property indicators describing soybean yield response to soil structure changes using RFA, Pearson's linear correlation, and principal component analysis (PCA) as complementary response tools.

2. Material and methods

2.1. Field experiment location and description

An on-farm field study using commercial equipment was conducted on Santa Helena farm at 21°15′39″ S latitude and 44°31′04″ W longitude within the Campo das Vertentes mesoregion near Nazareno town in the Minas Gerais State of Brazil. The average altitude is 1020 m and the climate, according to Köppen climatic classification, is Cwa with cold/dry winters and hot/rainy summers. Average annual rainfall and temperature are 1300 mm and 19.7°C, respectively (Fig. 1). The soil is classified as Typic Hapludox (Soil Survey Staff, 2014) with clay, silt, and sand contents within the 0- to 0.30-m depth of 530, 250, and 220 g kg^{-1}, respectively.

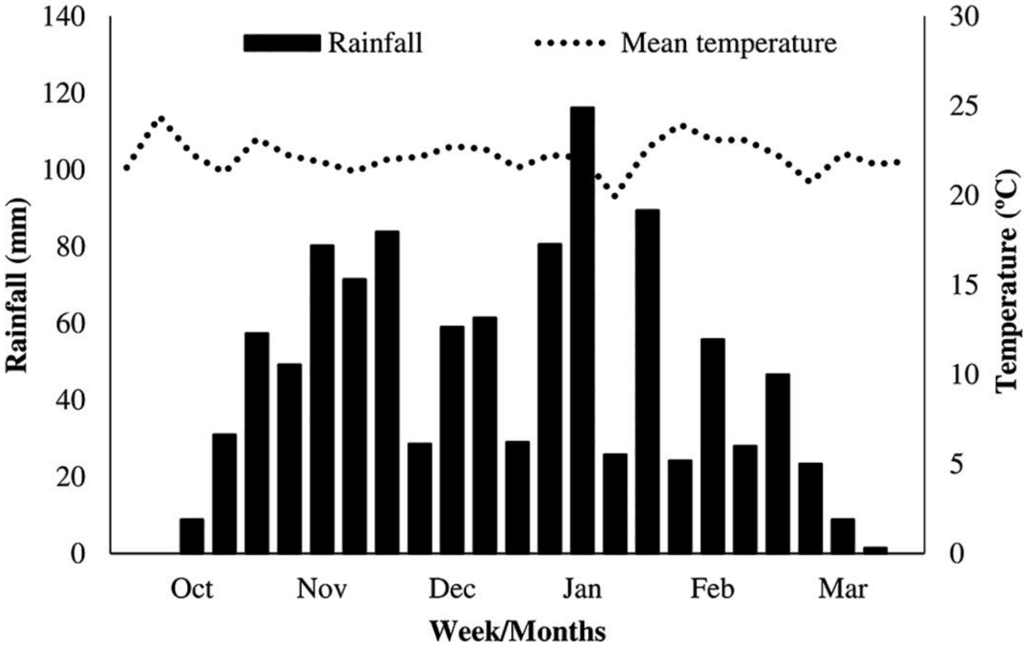

Fig. 1. Weekly average rainfall and temperature for the 2015–2016 summer cultivation.

Five farmer-selected strategies combining physical and chemical manipulations to address NT soil compaction were established in 18 m wide and 80 m long (1440 m^2) strips. Five treatments were studied (Fig. 2):

T1: NT for 10 yr (control)

T2: NT with surface application of 3.6 Mg ha^{-1} of agricultural gypsum

T3: NT with subsoiling plus 1.44 Mg ha^{-1} of highly reactive limestone (relative power of total neutralization = 180%) applied to a depth of 0.60 m between each row

T4: NT planting following chisel plowing at a depth of 0.26 m

T5: NT with subsoiling to a depth of 0.60 m plus 1.44 Mg ha^{-1} of surface-applied, highly reactive limestone (relative power of total neutralization = 180%)

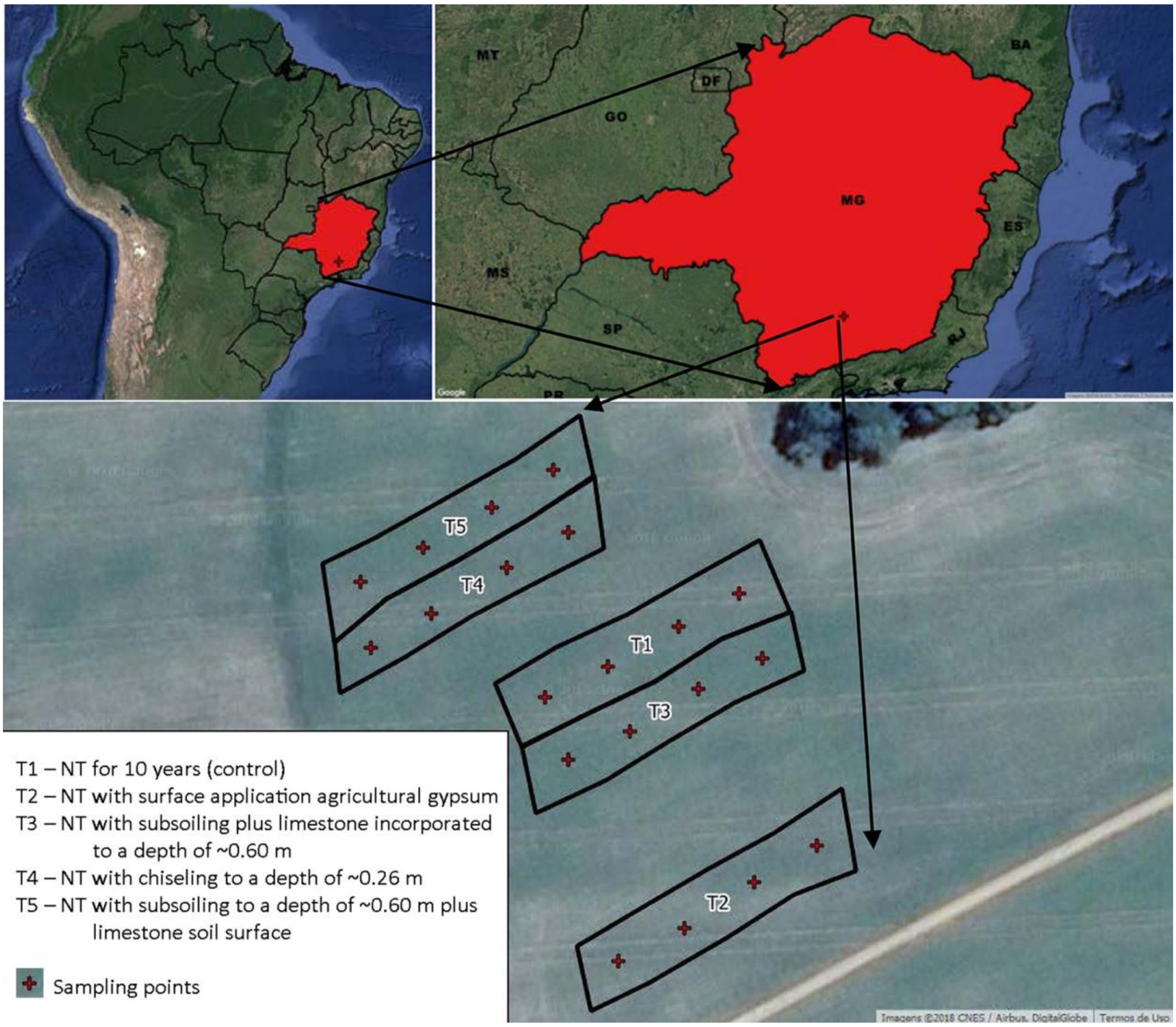

Fig. 2. On-farm experimental layout used to evaluate five mitigation strategies for NT soil compaction in a Brazilian soybean field.

The width of each treatment corresponded to two passes with an NT drill. True statistical replication was not feasible, so data were collected from four, 360 m^2 pseudo-replicates within each treatment strip. The experimental area has soil homogeneity (Typic Hapludox), similar slope gradient, and equal cropping and management history. A similar statistical approach, using pseudo-replicates, was successfully used in prior studies (Shukla and Lal, 2005; Stavi et al., 2011; Cecagno et al., 2016).

The tillage and chemical amendment treatments were established in September 2015. Soybean (a Syngenta VTOP conventional cultivar) was sown in November 2015 and harvested in March 2016. The crop was fertilized based on soil analyses and considering potential nutrient requirements of the soybean crop (Novais, 1999). At planting, 81 and 120 kg ha^{-1} of P_2O_5 and K_2O fertilizer, respectively, were applied using mono-ammonium phosphate (MAP) and muriate of potash (KCl). Mono-ammonium phosphate was applied in the seed furrow and KCl was broadcast just before planting. Weed, pest, and disease management operations were selected and implemented by our farmer-cooperator. The crop sequence used on the farm consists of a soybean (*Glycine max*) and corn (*Zea mays* L.) rotation during the summer (November–March) followed by wheat (*Triticum aestivum* L.) or dry bean (*Phaseolus vulgaris* L.) during the winter (March–June). When soil moisture conditions favor the plants development, oat (*Avena sativa* L.) was cultivated after the winter crop.

Chemical characteristics for five on-farm treatments following a soybean crop grown from November 2015 through March 2016 are presented in Table 1. The soil compaction status within each NT plot was assessed using a morphological description following 10 yr of no-till planting.

Table 1. Chemical characterization of the soil in the experimental area after a summer soybean crop grown from November 2015 through March 2016.†

Treatment	pH	SOM	V	Ca^{2+}	Mg^{2+}	T	Al^{3+}	K	P
		g kg^{-1}	%	—— cmol$_c$ dm^{-3}——				—— mg dm^{-3}——	
				0.00-0.20 m					
T1	5.34	37.2	54.30	2.70	0.55	6.38	0.10	75.50	3.24
T2	5.06	39.2	43.69	2.08	0.55	6.53	0.03	87.00	6.20
T3	5.40	34.5	51.75	2.19	0.61	5.76	0.00	76.00	3.11
T4	5.21	36.1	48.61	2.11	0.53	6.02	0.02	97.25	6.05
T5	4.95	38.8	42.75	1.95	0.56	6.44	0.05	97.00	9.08
				0.20-0.40 m					
T1	5.43	33.8	41.43	1.58	0.38	5.06	0.09	59.00	0.91
T2	5.20	35.6	33.10	1.30	0.35	5.58	0.01	73.00	1.13
T3	5.35	33.1	40.40	1.48	0.38	5.05	0.00	54.00	0.99
T4	5.55	33.8	38.39	1.23	0.30	4.31	0.01	55.00	0.85
T5	5.75	34.9	39.03	1.50	0.45	5.13	0.03	60.00	1.66

† SOM, soil organic matter; V, base saturation; T, potential cation exchange capacity; P – extractor Mehlich1; T1, NT for 10 yr (control); T2, NT with surface application of 3.6 Mg ha^{-1} of agricultural gypsum; T3, NT with subsoiling plus 1.44 Mg ha^{-1} of highly reactive limestone (relative power of total neutralization = 180%) applied to a depth of ~0.60 m; T4, NT planting following chisel plowing at a

depth of ~0.26 m; and T5, NT with subsoiling to a depth of ~0.60 m plus 1.44 Mg ha^{-1} of surface-applied, highly reactive limestone (relative power of total neutralization = 180%).

2.2. Soil and plant sampling and analysis

Soil samples were analyzed for water pH (soil/water ratio of 1:2.5), soil organic matter (Walkley and Black, 1934), exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+}, and plant-available K and P (Sparks et al., 1996). At harvest, plant height (PHeight) and first pod height (Inser1stpod) were measured from the soil surface to the plant's apex or first pod, respectively, using a ruler on five randomly selected plants from each plot. Seed yield was measured by collecting the beans from five adjacent, 5-m rows spaced 0.6 m apart in each plot (i.e., 15 m^2). Seed weight was corrected to a water content of 130 g kg^{-1} (13%) and converted to Mg ha^{-1}.

Following soybean harvest, soil samples were collected from 0.00- to 0.05-, 0.20- to 0.25-, and 0.30- to 0.35-m depth increments within each plot, using volumetric cylinders (0.025 m height × 0.06 m diam.). Those three depth increments were chosen because soil structure to a depth of 0.60 m is very homogeneous. The samples were saturated and placed on an automated tension table (Ecotech) where they drained to matric potentials of –1, –2, –4, –6, and –10 kPa. They were then placed in a Richards porous plate chamber and drained to matric potentials of −33, −100, −500, and −1500 kPa (Klute, 1986). The matric potential data and RETC software were used to compute a water retention curve with the Mualen restriction (van Genuchten, 1980).

Porosity of the soil macropore domain (PORp), air capacity (AC), relative field capacity (RFC), and air capacity of soil matrix (ACm) were calculated using the water retention curve as described by Reynolds et al. (2002, 2009). Plant-available water capacity (PAWC) was estimated as the difference between field capacity (−10 kPa) and permanent wilting point (−1500 kPa). Readily available water (RAW) was calculated using field capacity (−10 kPa) as the superior limit and −100 kPa as the inferior limit. Those soil physical properties were also used to estimate field capacity as the soil water content at the inflection point of the water retention curve (PAWCip) and (RAWip) (Silva et al., 2014), and to calculate the S index (Dexter, 2004) and integral energy (IE) based on PAWC (Asgarzadeh et al., 2011) using the SAWCal software (Asgarzadeh et al., 2014). Bulk density (BD) was determined volumetrically (Grossman and Reinsch, 2002). Total porosity (TP = 1 – BD/PD) was computed using particle density (PD) values obtained by the volumetric flask method (Flint and Flint, 2002). Microporosity (Mic) at −6 kPa, and macroporosity (Mac; Mac = PT – Mic) were also calculated for each sample.

Soil PR was measured before soybean harvest in March 2016 using a dynamic impact penetrometer (model IAA/PLANALSUCARSTOLF) and is reported as a cone index (Stolf, 1991). The PR measurements were replicated three times in each plot, and the mean was determined and represented one replicate per plot. In this way, 12 probings were done in each treatment ($N = 60$). To account for the impact of soil moisture content, PR measurements were made for all treatments within a short period of time at a water content near field capacity.

2.3. Statistical analysis

Descriptive statistics were computed to evaluate variability of soil physical property and plant response date in response to treatments designed to ameliorate NT soil compaction. Using plot data from the non-replicated on-farm study, an analysis of variance (ANOVA) was computed for each sampling depth. The degrees of freedom for each treatment were partitioned to create orthogonal contrasts for NT control vs. NT plus chemical, physical (chiseling or subsoiling), or combined strategies to ameliorate compaction (T1 and T2 vs. T3, T4, and T5); gypsum effects (T1 vs. T2); subsoiling vs. chiseling (T3 and T5 vs. T4); and subsoiling with surface or deep-placement of agricultural limestone (T3 vs. T5). These contrasts were evaluated using the ANOVA residual mean square. Calculations were performed using R software (R Development Core Team, 2017).

2.3.1. Quantification of plant response to soil physical properties

To quantify how plants responded to various chemical and physical treatments implemented in an on-farm study to ameliorate NT soil compaction, multivariate analysis (principal component analysis) and linear correlation were applied to the measured and calculated data. The results were then used as input for an RFA to rank the importance of various soil physical property variables with regard to estimating soybean yield response. Details for each phase of the analysis are described below.

Linear Correlation and Principal Component Analysis. Pearson linear correlation ($p < 0.05$) was used to quantify relationships between soil physical properties and soybean response variables. First, however, to avoid redundancy and reduce the number of soil physical properties within each treatment groups, a PCA was performed, which divides the original variables into smaller groups of statistical variables (factors) with minimum loss of information (Hair et al., 2009). For this study our initial 18-variable dataset could be characterized by two new latent variables and viewed within biplots. These analyses were also performed using the R software package FactoMineR (Lê et al., 2008).

Random Forest Algorithm Analysis. The RFA modeling is a non-parametric technique developed by Breiman (2001) as an extension to CART (Classification and Regression Trees). Its purpose is to improve prediction accuracy by combining several “trees” generated from a random vector that is sampled independently, assuming the same distribution for all trees in the “forest.” Tree branches are determined based on a subset of covariables chosen randomly from all covariables. The result thus provides a mean representing all trees (Breiman, 2001).

The RFA was generated using the Random Forest software package in R (Liaw and Wiener, 2002). To use an RFA, three parameters must be defined: the number of trees in the forest (ntree), the minimum number of data in each terminal node (nodesize), and the number of variables used in each tree (mtry) (Liaw and Wiener, 2002). For this study ntree = 1000, nodesize = the standard for regression analyses (i.e., five for each terminal node), and mtry = one-third (i.e., 3 of 9) of the total number of predicting variables (Liaw and Wiener, 2002). Yield was predicted using soil physical properties for each depth increment, thus generating four models (i.e., one for each depth increment plus the entire 0.35-m profile). The result is that the increment error percentage in RFA models (%incMSE) demonstrates the importance of each variable with regard to predicting soybean yield.

Finally, the prediction model was validated using an independent dataset. Thus, for each depth increment, data from three plots per treatment were used for calibration and one for validation. Performance of each RFA model was further evaluated by comparing estimated and observed values, proportion of variance explained (Var_{ex}), coefficient of determination (R^2) means, root mean square error (RMSE) and root mean square error relative to the average experimental yield (RRMSE).

3. Results and discussion

3.1. Soil physical property and plant response

Subsoiling (T3 and T5) and chiseling (T4) increased soybean yield and resulted in lower Inser1stpod values than treatments without mechanical intervention (T1 and T2) (Table 2). As expected, the field operations (chiseling or subsoiling) were more effective than either lime (T3 and T5) or gypsum (T2) applications because those treatments did not affect soil chemical properties (Table 1). Other studies have also shown greater soybean yield response to chiseling (Calonego and Rosolem, 2010; Calonego et al., 2017; Cortez et al., 2017) and subsoiling (Botta et al., 2010; Bobade et al., 2016), even in subsequent years. Similar soil property effects were also observed within wheat and corn fields (Klein et al., 2008; Secco et al., 2009), but results still diverge regarding yield improvement (Izumi et al., 2009; Lozano et al., 2016).

This on-farm evaluation indicated both physical and chemical treatments to ameliorate NT compaction were effective at improving soil physical properties, which in turn increased soybean yield, even when rainfall and therefore water supply were sufficient. Studies quantifying subsoiling and chiseling effects in clay soils under NT management have not reached consensus regarding their effect on crop yield, probably because of interactions with available soil water that can significantly influence the severity of soil compaction (Calonego and Rosolem, 2010; Hakojärvi et al., 2013; Girardello et al., 2014; Cecagno et al., 2016; Calonego et al., 2017). Soil water content is also influenced by changes in pore-size distribution, which in granular oxidic soils (Silva et al., 2015) can result in reduced transmission of soil water to plants (Debiasi et al., 2010) and thus expose them to hydric stress in dry years.

Seasonal rainfall of approximately 1000 mm (Fig. 1) at this on-farm site easily met the crop water requirement for maximum yield, which varies between 450 and 800 mm, depending on other climatic conditions, soil management, and plant characteristics (Farias et al., 2007). Of these 1000 mm rainfall, soybean plants were supplied with approximately 7.5 mm of water per day (Fig. 1), during flowering and grain formation, which is therefore considered ideal for those phases (Farias et al., 2007).

Subsoiling was more effective than chiseling with regard to increasing soybean yield (Table 2). This presumably reflected the larger and thicker shanks and breaking of compacted layers deeper within the soil profile than is feasible with chiseling. Subsoiling was confirmed to be more effective for improving soil physical properties (Botta et al., 2006) than chiseling, which often has a residual effect of only 6 to 30 mo, depending on the soil physical properties (Nunes et al., 2014; Drescher et al., 2011). Subsoiling, however, may have a residual effect lasting from 24 to 48 mo for soils where cereal crops are being grown (Busscher et al., 1995) to as long as 120 mo beneath eucalyptus (Eucalyptus globulus L.) plants (Curi et al., 2017). Therefore, subsoiling, which does require more energy, may be a more effective practice for alleviating NT compaction when evaluated from economic and environmental perspectives.

Table 2. Orthogonal contrasts for soil physical properties and soybean growth and yield variables.†

		Orthogonal contrasts											
		T1 vs. T3, T4, and T5			T1 vs. T2			T3 and T5 vs. T4			T3 vs. T5		
Variable	Depth	×1	×2	*p* value	×1	×2	*p* value	×1	×2	*p* value	×1	×2	*p* value
Yield, Mg ha^{-1}	–	4.02	4.55	**	4.05	3.99	ns‡	4.67	4.30	*	4.75	4.59	ns
Inser1stpod, cm	–	14.65	12.58	***	15.25	14.05	ns	12.47	12.80	ns	12.70	12.25	ns
PHeight, cm	–	88.82	90.57	ns	87.65	90.00	ns	91.22	89.25	ns	90.75	91.70	ns
IE, J kg^{-1}	0.00–0.05	152.88	151.57	ns	150.22	155.55	ns	153.19	148.33	ns	157.36	149.02	ns
	0.20–0.25	157.60	154.56	ns	150.40	164.80	ns	152.89	157.91	ns	149.26	156.51	ns
	0.30–0.35	147.85	138.31	ns	134.15	161.55	*	134.99	144.94	ns	138.26	131.71	ns
	Profile§	152.78	148.15	ns	144.92	160.63	ns	147.02	150.39	ns	148.30	145.75	ns
S	0.00–0.05	0.059	0.088	**	0.069	0.050	ns	0.088	0.086	ns	0.087	0.090	ns
	0.20–0.25	0.050	0.062	*	0.053	0.047	ns	0.067	0.051	*	0.069	0.065	ns
	0.30–0.35	0.058	0.065	ns	0.067	0.049	*	0.068	0.057	ns	0.068	0.069	ns
	Profile	0.056	0.071	**	0.063	0.049	*	0.075	0.065	ns	0.075	0.075	ns
Mic, m^{3} m^{-3}	0.00–0.05	0.413	0.372	ns	0.400	0.425	ns	0.371	0.372	ns	0.370	0.373	ns
	0.20–0.25	0.402	0.368	**	0.409	0.396	ns	0.359	0.388	*	0.361	0.356	ns
	0.30–0.35	0.408	0.385	*	0.401	0.415	ns	0.383	0.391	ns	0.378	0.387	ns
	Profile	0.408	0.375	**	0.403	0.412	ns	0.371	0.383	ns	0.370	0.372	ns
Mac, m^{3} m^{-3}	0.00–0.05	0.145	0.235	**	0.186	0.105	ns	0.242	0.221	ns	0.254	0.230	ns
	0.20–0.25	0.148	0.191	*	0.150	0.147	ns	0.209	0.155	*	0.211	0.207	ns
	0.30–0.35	0.176	0.189	ns	0.185	0.168	ns	0.196	0.173	ns	0.208	0.185	ns
	Profile	0.157	0.205	**	0.174	0.140	ns	0.216	0.183	ns	0.224	0.207	ns
BD, Mg m^{-3}	0.00–0.05	1.05	0.90	*	1.02	1.01	ns	0.90	0.90	ns	0.90	0.90	ns
	0.20–0.25	1.12	1.04	**	1.12	1.12	ns	1.00	1.10	*	1.01	1.00	ns
	0.30–0.35	1.12	1.01	*	1.09	1.15	ns	1.07	1.11	ns	1.08	1.06	ns
	Profile	1.10	1.01	**	1.08	1.12	ns	0.99	1.04	ns	0.99	0.99	ns
TP, m^{3} m^{-3}	0.00–0.05	0.558	0.606	*	0.586	0.530	*	0.613	0.593	ns	0.624	0.603	ns
	0.20–0.25	0.551	0.559	ns	0.559	0.543	ns	0.567	0.543	ns	0.572	0.563	ns
	0.30–0.35	0.585	0.574	ns	0.586	0.583	ns	0.579	0.564	ns	0.586	0.572	ns
	Profile	0.565	0.580	ns	0.577	0.552	ns	0.587	0.567	ns	0.594	0.579	ns
PAWC, m^{3} m^{-3}	0.00–0.05	0.159	0.152	ns	0.154	0.164	ns	0.150	0.155	ns	0.140	0.160	ns
	0.20–0.25	0.143	0.129	*	0.145	0.141	ns	0.128	0.132	ns	0.125	0.131	ns
	0.30–0.35	0.139	0.130	ns	0.144	0.135	ns	0.131	0.128	ns	0.125	0.138	ns

	Profile	0.147	0.137	ns	0.148	0.146	ns	0.137	0.138	ns	0.130	0.143	ns
PORp, m^3 m^{-3}	0.00–0.05	0.069	0.128	ns	0.094	0.045	ns	0.136	0.110	ns	0.160	0.113	ns
	0.20–0.25	0.083	0.108	ns	0.081	0.086	ns	0.119	0.084	ns	0.119	0.120	ns
	0.30–0.35	0.094	0.093	ns	0.087	0.100	ns	0.096	0.086	ns	0.111	0.081	ns
	Profile	0.082	0.109	ns	0.087	0.077	ns	0.117	0.094	ns	0.130	0.104	ns
AC, m^3 m^{-3}	0.00–0.05	0.171	0.261	**	0.213	0.129	ns	0.266	0.249	ns	0.275	0.258	ns
	0.20–0.25	0.178	0.220	*	0.182	0.174	ns	0.238	0.183	*	0.239	0.236	ns
	0.30–0.35	0.204	0.216	ns	0.217	0.191	ns	0.225	0.199	ns	0.235	0.215	ns
	Profile	0.184	0.232	**	0.204	0.165	ns	0.243	0.210	ns	0.250	0.236	ns
RFC	0.00–0.05	0.698	0.573	**	0.641	0.755	ns	0.568	0.583	ns	0.562	0.574	ns
	0.20–0.25	0.679	0.610	*	0.677	0.680	ns	0.583	0.664	*	0.584	0.582	ns
	0.30–0.35	0.652	0.625	ns	0.631	0.673	ns	0.613	0.648	ns	0.601	0.625	ns
	Profile	0.676	0.602	**	0.650	0.703	ns	0.588	0.632	ns	0.582	0.593	ns
ACm, m^3 m^{-3}	0.00–0.05	0.102	0.133	ns	0.119	0.084	ns	0.130	0.139	ns	0.115	0.145	ns
	0.20–0.25	0.094	0.112	ns	0.100	0.088	ns	0.119	0.099	ns	0.121	0.116	ns
	0.30–0.35	0.110	0.123	ns	0.129	0.091	ns	0.129	0.112	ns	0.124	0.134	ns
	Profile	0.102	0.123	*	0.116	0.088	*	0.126	0.117	ns	0.120	0.132	ns
RAW, m^3 m^{-3}	0.00–0.05	0.076	0.069	ns	0.075	0.077	ns	0.069	0.070	ns	0.068	0.070	ns
	0.20–0.25	0.067	0.057	**	0.070	0.064	ns	0.056	0.059	ns	0.057	0.054	ns
	0.30–0.35	0.072	0.070	ns	0.078	0.066	*	0.070	0.068	ns	0.068	0.072	ns
	Profile	0.072	0.065	*	0.075	0.069	ns	0.065	0.066	ns	0.064	0.066	ns
PR, MPa	0.00–0.05	1.23	0.77	***	1.09	1.37	*	0.66	0.98	**	0.69	0.64	ns
	0.20–0.25	2.78	1.80	***	2.76	2.81	ns	1.36	2.68	***	1.50	1.21	ns
	0.30–0.35	2.82	2.39	**	2.96	2.68	ns	2.01	3.14	***	1.89	2.14	ns
	Profile	2.28	1.65	***	2.27	2.29	ns	1.34	2.27	***	1.36	1.33	ns
PAWCip, m^3 m^{-3}	0.00–0.05	0.198	0.253	**	0.222	0.175	ns	0.258	0.244	ns	0.261	0.254	ns
	0.20–0.25	0.192	0.210	ns	0.193	0.191	ns	0.220	0.189	*	0.219	0.222	ns
	0.30–0.35	0.205	0.205	ns	0.210	0.201	ns	0.210	0.195	ns	0.213	0.206	ns
	Profile	0.186	0.191	ns	0.202	0.171	ns	0.188	0.197	ns	0.209	0.167	ns
RAWip, m^3 m^{-3}	0.00–0.05	0.107	0.137	**	0.120	0.094	ns	0.139	0.132	ns	0.141	0.137	ns
	0.20–0.25	0.104	0.113	ns	0.104	0.103	ns	0.119	0.102	*	0.118	0.120	ns
	0.30–0.35	0.111	0.111	ns	0.113	0.108	ns	0.113	0.105	ns	0.115	0.111	ns
	Profile	0.101	0.103	ns	0.109	0.096	ns	0.101	0.106	ns	0.113	0.090	ns

* Statistical significance at the 0.05 level.

** Statistical significance at the 0.01 level.

***Statistical significance at the 0.001 level.

† IE, integral energy; Mic, microporosity; Mac, macroporosity; BD, bulk density; TP, total porosity; PAWC, plant-available water capacity; PORp, porosity of soil macropore domain; AC, air capacity; ACm, air capacity of soil matrix; RFC, relative field capacity; RAW, readily available water; PR, penetration resistance; PAWCip, plant-available water capacity using the inflection point as field capacity; RAWip, readily available water using inflection point as field capacity.

‡ Not significant.

§ Represents the mean value calculated for three depths, representing the 0- to 0.35-m profile.

There were no statistical differences between the treatments that were subsoiled (T3 and T5); thus, the local (~0.60-m depth) or surface application of limestone had no effect on soybean yield. It was already expected to have little or no effect on soybean yield, because some studies have shown that not even the limestone incorporation has improved the subsequent crop yield in NT consolidated areas (Quincke et al., 2007; Rossato et al., 2009; Fidalski et al., 2015). Similarly, application of gypsum (T2) when compared with the NT control (T1) did not increase soybean yield. These results therefore confirm that increases in soybean yield in this on-farm study occurred due to improvements in soil physical properties.

The soil physical properties that were most sensitive to change due to tillage, regardless of depth, were: Mac, Mic, BD, S index, AC, RFC, and PR. On the other hand, IE, TP, PAWC, PAWCip, RAW, RAWip, PORp, and ACm showed significant differences only between the control (T1) and either subsoiling or chiseling (T3, T4, and T5) and/or between subsoiling (T3 and T5) and chiseling (T4) at the 0.20- to 0.25-m depth (Table 2). Among the measured soil physical properties, PR was the most variable within all three depth increments, suggesting it is highly sensitive to chemical and physical manipulations in addition to soil moisture content. The soil physical properties identified in this study as most sensitive to physical, chemical, or combined NT compaction treatments are also those commonly used as soil quality indicators (Arshad et al., 1996; Nortcliff, 2002; Dexter, 2004; Reynolds et al., 2002, 2008).

3.2. Relationship between soil physical properties and soybean yield

3.2.1. Pearson correlation

Among the 15 soil physical properties measured at the 0.00- to 0.05-m depth increment, 73, 20, and 7% significantly correlated with soybean yield, Inser1stpod, and PHeight, respectively (Table 3). There was a reduction in significant correlations with depth, presumably because of differences in root distribution for this cultivar and main soil management effect on topsoil, among others. Gregory (1992) found that approximately 80% of soybean root mass is distributed in the top 0.15 m of the soil profile, especially when rainfall is adequate (Fig. 1) and plants do not need to develop a deeper root system.

Table 3. Pearson correlation coefficients of soil physical properties and yield, insertion of the first pod, and soybean plant height at three depths and in the whole soil profile. *N* = 20.†

	0.0–0.05 m			0.20–0.25 m			0.30–0.35 m			Profile 0.0–0.35 m		
Soil Property	Yield	Inser1stpod	PHeight	Yield	Inser1stpod	PHeight	Yield	Inser1stpod	PHeight	Yield	Inser1stpod	PHeight
IE	-0.10	0.23	0.37	-0.06	0.10	0.52*	-0.23	0.21	0.19	-0.21	0.27	0.53*
S	0.64**	-0.46**	-0.06	0.43	-0.28	-0.26	0.27	-0.27	-0.16	0.62**	-0.46*	-0.17
Mic	-0.49*	0.25	-0.31	-0.42	0.41	-0.08	-0.39	0.27	0.04	-0.57**	0.39	-0.20
Mac	0.67**	-0.35	0.06	0.45*	-0.24	0.03	0.25	-0.17	-0.03	0.64**	-0.35	0.04
BD	-0.53*	0.32	-0.24	-0.41	0.38	<0.01	-0.43	0.40	0.23	-0.60**	0.44	-0.10
TP	0.58**	-0.31**	-0.18	0.38	0.02	-0.04	-0.07	0.05	<-0.01	0.53*	-0.20	-0.14
PAWC	-0.28	-0.08	-0.42	-0.23	0.24	-0.20	-0.33	0.17	0.02	-0.39	0.09	-0.35
PORp	0.58**	-0.26	0.11	0.37	-0.15	0.17	0.08	<0.01	0.02	0.55*	-0.23	0.15
AC	0.67**	-0.37	0.03	0.44	-0.24	-0.02	0.25	-0.18	-0.07	0.63**	-0.36	-0.01
RFC	-0.66**	0.38**	-0.08	-0.44**	0.30	0.00	-0.29	0.22	0.09	-0.63**	0.39	-0.02
ACm	0.30	-0.26	-0.14	0.29	-0.25	-0.30	0.17	-0.19	-0.10	0.34	-0.32	-0.23
RAW	-0.25	-0.06	-0.51*	-0.22	0.21	-0.54*	-0.04	-0.04	-0.18	-0.24	0.02	-0.59**
PR	-0.74**	0.53*	-0.04	-0.66**	0.46*	-0.24	-0.55*	0.32	-0.12	-0.69**	0.46*	-0.18
PAWCip	0.63**	-0.40	-0.05	0.48*	0.20	0.07	0.06	-0.05	0.03	0.61**	-0.35	<-0.01
RAWip	0.63**	-0.40	-0.05	0.48*	-0.20	0.07	0.06	-0.05	0.03	0.61**	-0.35	<-0.01

* Statistical significance at the 0.05 level.

** Statistical significance at the 0.01 level.

† IE, integral energy; Mic, microporosity; Mac, macroporosity; BD, bulk density; TP, total porosity; PAWC, plant-available water capacity; PORp, porosity of soil macropore domain; AC, air capacity; ACm, air capacity of soil matrix; RFC, relative field capacity; RAW, readily available water; PR, penetration resistance; PAWCip, plant-available water capacity using the inflection point as field capacity; RAWip, readily available water using inflection point as field capacity.

The greatest variation in soil physical properties was within the top 0.05 m (Table 4), which is the zone most affected by soil and crop management (i.e., wheel traffic, planting, fertilization, harvest, subsoiling, and chiseling practices) and therefore affected by soil compaction (Batey, 2009; Reichert et al., 2009; Drescher et al., 2011; Nunes et al., 2014, 2015). Furthermore, when the entire 0- to 0.35-m soil profile was analyzed, it was the surface layer that was most responsive to management and was therefore a dominant factor driving the whole profile correlation.

Table 4. Descriptive statistic of soil physical properties, soybean growth, and yield variables. $N = 20$.†

Variable	Depth	Mean	SD	Median	Minimum	Maximum
Yield, Mg ha^{-1}	–	4.34	0.40	4.35	3.59	5.06
Inser1stpod, cm	–	13.41	1.43	13.00	11.20	16.40
PHeight, cm	–	89.87	4.40	90.30	81.40	99.00
IE, J kg^{-1}	0.00–0.05	152.10	16.85	150.68	115.94	188.62
	0.20–0.25	155.78	16.43	156.10	125.55	182.90
	0.30–0.35	142.12	19.33	144.91	103.27	167.60
	Profile‡	150.00	11.62	146.54	135.20	179.71
S	0.00–0.05	0.076	0.024	0.072	0.037	0.113
	0.20–0.25	0.057	0.014	0.055	0.032	0.095
	0.30–0.35	0.062	0.013	0.063	0.042	0.085
	Profile	0.065	0.013	0.065	0.043	0.086
Mic, m^3 m^{-3}	0.00–0.05	0.388	0.042	0.388	0.307	0.465
	0.20–0.25	0.382	0.028	0.380	0.328	0.433
	0.30–0.35	0.394	0.022	0.392	0.351	0.436
	Profile	0.388	0.024	0.388	0.348	0.431
Mac, m^3 m^{-3}	0.00–0.05	0.199	0.073	0.187	0.080	0.337
	0.20–0.25	0.174	0.046	0.172	0.110	0.277
	0.30–0.35	0.184	0.030	0.182	0.141	0.238
	Profile	0.186	0.040	0.184	0.126	0.258
BD, Mg m^{-3}	0.00–0.05	0.961	0.142	0.958	0.657	1.211
	0.20–0.25	1.070	0.076	1.079	0.925	1.229
	0.30–0.35	1.100	0.051	1.092	1.028	1.194
	Profile	1.044	0.072	1.042	0.916	1.167
TP, m^3 m^{-3}	0.00–0.05	0.587	0.048	0.590	0.459	0.663
	0.20–0.25	0.556	0.023	0.550	0.526	0.606
	0.30–0.35	0.578	0.018	0.580	0.544	0.609
	Profile	0.574	0.029	0.573	0.532	0.615
PAWC, m^3 m^{-3}	0.00–0.05	0.154	0.025	0.161	0.098	0.194
	0.20–0.25	0.135	0.013	0.134	0.110	0.163
	0.30–0.35	0.134	0.012	0.133	0.105	0.162
	Profile	0.141	0.012	0.142	0.117	0.160
PORp, m^3 m^{-3}	0.00–0.05	0.104	0.063	0.084	0.027	0.278
	0.20–0.25	0.098	0.036	0.094	0.049	0.187
	0.30–0.35	0.093	0.030	0.096	0.040	0.138
	Profile	0.098	0.032	0.093	0.063	0.167
AC, m^3 m^{-3}	0.00–0.05	0.225	0.072	0.216	0.105	0.348
	0.20–0.25	0.203	0.046	0.199	0.131	0.307
	0.30–0.35	0.211	0.031	0.210	0.164	0.269
	Profile	0.213	0.040	0.213	0.149	0.284

RFC	0.00–0.05	0.623	0.096	0.627	0.460	0.808
	0.20–0.25	0.637	0.068	0.640	0.493	0.751
	0.30–0.35	0.635	0.047	0.639	0.556	0.707
	Profile	0.632	0.057	0.630	0.531	0.728
ACm, $m^3\ m^{-3}$	0.00–0.05	0.120	0.037	0.112	0.046	0.191
	0.20–0.25	0.105	0.024	0.104	0.059	0.153
	0.30–0.35	0.118	0.030	0.115	0.073	0.184
	Profile	0.114	0.022	0.113	0.066	0.142
RAW, $m^3\ m^{-3}$	0.00–0.05	0.072	0.013	0.072	0.042	0.095
	0.20–0.25	0.061	0.008	0.060	0.049	0.078
	0.30–0.35	0.070	0.008	0.069	0.056	0.087
	Profile	0.068	0.007	0.067	0.054	0.082
PR, MPa	0.00–0.05	0.955	0.307	0.981	0.560	1.610
	0.20–0.25	2.192	0.783	2.335	0.837	3.423
	0.30–0.35	2.563	0.541	2.683	1.423	3.303
	Profile	1.903	0.501	2.125	1.031	2.614
PAWCip, $m^3\ m^{-3}$	0.00–0.05	0.231	0.044	0.225	0.151	0.307
	0.20–0.25	0.203	0.023	0.201	0.166	0.249
	0.30–0.35	0.205	0.016	0.205	0.177	0.232
	Profile	0.189	0.050	0.194	0.162	0.247
RAWip, $m^3\ m^{-3}$	0.00–0.05	0.125	0.024	0.121	0.081	0.166
	0.20–0.25	0.110	0.012	0.108	0.090	0.134
	0.30–0.35	0.111	0.009	0.111	0.096	0.125
	Profile	0.102	0.027	0.105	0.088	0.133

† IE, integral energy; Mic, microporosity; Mac, macroporosity; BD, bulk density; TP, total porosity; PAWC, plant-available water capacity; PORp, porosity of soil macropore domain; AC, air capacity; ACm, air capacity of soil matrix; RFC, relative field capacity; RAW, readily available water; PR, penetration resistance; PAWCip, plant-available water capacity using the inflection point as field capacity; RAWip, readily available water using inflection point as field capacity.

‡ Represents the mean value calculated for three depths, representing the 0- to 0.35-cm profile.

At the 0.00- to 0.05-m depth, PR (r = -0.74), which is a reliable indicator of soil mechanical resistance, showed the highest correlation with soybean yield. This was followed by properties associated with soil air capacity: Mac (r = 0.67), AC (r = 0.67), RFC (r = -0.66), and S index (r = 0.64). Those properties are all related to the capacity of a soil to provide air and water throughout the entire distribution of pores. The least sensitive indicators were those associated with retention capacity and potential water availability PAWCip (r = 0.63), RAWip (r = 0.63), and Mic (r = -0.49).

Penetration resistance at all evaluated depths correlated to soybean yield, which was presumably associated with root cell elongation (Bengough et al., 2001) and its effect on plant shoots (Passioura, 2002) and in agreement with other studies (Busscher et al., 2001; Beutler et al., 2006; Koch et al., 2009; Dalchiavon et al., 2011; Ahmad et al., 2010; Bölenius et al., 2017). This result has an important practical aspect, because it suggests that PR can be used as a fast, low-cost indicator to help with decision-making regarding management practices that should be used to address NT compaction or within pedotransfer functions for evaluating more complex indicators. Bölenius et al. (2017) reported that PR could explain crop yield variation and is therefore a good screening tool for areas with poor soil physical conditions or where chemical or physical treatments were imposed to alter the physical state. However, other reports indicate a lack of correlation with yield under consolidated NT, presumably because of biopores created by previous crops and used by the current crop as a pathway for root growth that are not represented by the penetrometer readings (Stirzaker et al., 1996; Bengough et al., 2011).

Positive and significant correlations between soybean yield and Mac, AC, and S index, as well as a negative correlation with RFC, confirm that disrupting soil compaction alters pore-size distribution, often increasing the relative number of larger pores and thus favoring crop yield because macropores provide most of the soil air porosity. Lapen et al. (2004) showed that low air-filled porosity results in low yield and an inefficient plant establishment, thus making it an adequate predictor of biometric properties in agricultural crops. For soybean, lack of soil O_2 may inhibit biological N fixation (Bacanamwo and Purcell, 1999) and the uptake of nutrients. This ultimately decreases root growth and nodulation, most likely, due to the O_2 demand within the biological N fixation process (Amarante and Sodek, 2006).

The treatments with greater soybean yield (T4 and T5) had RFC values of less than 0.6, indicating the crop produced more in the presence of pores responsible for supplying oxygen than water. These results probably reflect the abundant rainfall (Fig. 1) that met crop needs throughout the growing season and especially during flowering and grain formation. There may have even been water excess at some times, which reduced air porosity, since total rainfall was 200 mm greater than the ideal for soybean. Higher RFC values ($RFC > 0.7$) cause a reduction in N fixation, limiting the plant development due to insufficient aeration (Linn and Doran, 1984; Reynolds et al., 2008).

Regarding indicators of plant water availability, PAWCip and RAWip were more sensitive than conventional PAWC and RAW with regard to soybean yield. The latter indicators did not show a significant correlation. Andrade and Stone (2011) reported that when they used a single independent variable to predict the field capacity, the best correlation occurred with the inflection point, which was also in agreement with studies by Ferreira and Marcos (1983), Mello et al. (2002), and Silva et al. (2014). Those authors suggested soil moisture at the inflection point corresponded to field capacity in tropical soils. The PAWC and RAW determined by classic definition are not considered adequate indicators of soil physical quality, especially in intensive agricultural systems with soil compaction problems. However, there are similar implementations using the superior and inferior limits of PAWC and RAW that do not cause a substantial change in those properties (Reynolds et al., 2008). Therefore, use of the inflection point associated with the water retention curve was useful as an indicator of compaction changes caused by soil management.

Among the soil physical properties measured for the 0.00- to 0.05-m depth increment, PR (r = 0.53), S index (r = -0.46), RFC (r = 0.38), and TP (r = -0.31) correlated to Inser1stpod height (Table 3). Penetration resistance also had the highest correlation coefficient at the 0.20- to 0.25-m depth and for the entire soil profile. Plant height was correlated with RAW (r = -0.51 and -0.54) to a depth of 0.25 m and with IE (r = 0.52) correlated at the 0.20- to 0.25-m depth. The treatments that did not use chiseling or subsoiling to disrupt NT compaction had higher Inser1stpod values when compared with those that were chiseled or subsoiled. Plant height was not influenced by soil management.

3.2.2. Principal component analysis

The PCA divided the 18 variables into two groups (PC1 and PC2), making it possible to characterize and quantify the combined importance of variables that were most sensitive to the five on-farm treatments. The quantity of information from the original variables retained by two principal components was 91, 97, 79, and 89% for the 0.00- to 0.05-, 0.20- to 0.25-, and 0.30- to 0.35-m depth increments and the whole soil profile, respectively (Fig. 3). These values are well above the 70% threshold established as adequate PC accuracy (Hair et al., 2009).

Group PC1 explained between 59 and 84% of total variance, whereas PC2 explained between 13 and 21%. Therefore, most variables contributed more with PC1, including soybean yield. For all depth increments, the variables associated with mechanical impediments to root growth (PR and BD) and aeration restrictions (RFC and Mic), which are negatively correlated with soybean yield, were in the left portion of PC1. However, variables related to air and water availability (Mac, ACm, AC, PORp, and RAWip) and soybean yield were more concentrated in the right portion of PC1 (Fig. 3).

For the 0.00- to 0.05-m depth, variables that contributed most to PC1 were Inser1stpod (−0.73), RP (−0.96), Mic (−0.99), BD (−0.98), and RFC (−0.98). Grouping the treatments that did not include chiseling or subsoiling (T1 and T2) are located on the left side of PC1 (negative correlations). On the contrary, ACm (0.80), AC (0.98), RAWpi (0.99), Mac (0.98), TP (0.94), PORp (0.91), and Yield (0.90) associated with chisel (T4) and subsoil treatments (T3 and T5) are located on the right side of PC1 (positive correlations). Within the surface layer (0.00–0.05

m), the control had greater mechanical resistance to root penetration (PR and BD) and water retention (RFC and Mic), decreased pore-size distribution and aeration (AC, S, Mac, PORp, and TP), and lower plant water availability capacity (RAWip). The opposite was observed for treatments that had mechanical disruption of the NT compaction. These results thus show improvement in soil physical conditions for crop yield with mechanical intervention.

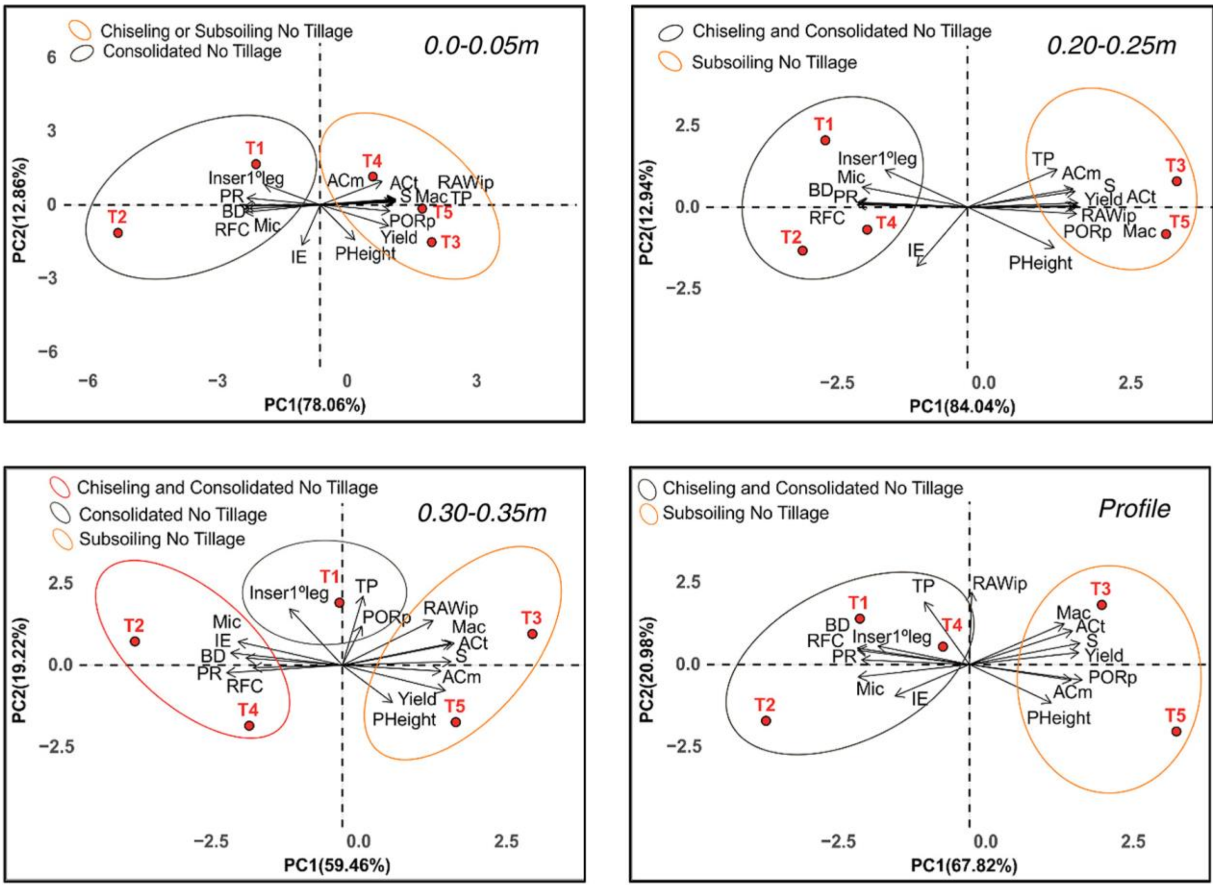

Fig. 3. Principal components analysis of soil physical properties and soybean plant variables in five soil managements. T1, NT for 10 yr (control); T2, NT with surface application of 3.6 Mg ha^{-1} of agricultural gypsum; T3, NT with subsoiling plus 1.44 Mg ha^{-1} of highly reactive limestone (relative power of total neutralization = 180%) applied to a depth of ~0.60 m; T4, NT planting following chisel plowing at a depth of ~0.26 m; and T5, NT with subsoiling to a depth of ~0.60 m plus 1.44 Mg ha^{-1} of surface-applied, highly reactive limestone (relative power of total neutralization = 180%). IE, integral energy; S, S Index; Mic, microporosity; Mac, macroporosity; BD, bulk density; TP, total porosity; PAWC, plant-available water capacity; PORp, porosity of soil macropore domain; AC, air capacity; ACm, air capacity of soil matrix; RFC, relative field capacity; PR, penetration resistance; RAWip, readily available water using inflection point as field capacity; Inser1stpod, height of insertion of the first pod; PHeight, plant height. Ellipses indicate groups of treatments.

At depths greater than 0.20 m and for the entire profile analysis, chiseling was grouped with the treatments that did not disrupt compaction because of the superficial effect of chiseling on soil physical properties. Chiseling simply did not penetrate the entire depth of compaction because it was not effective below 0.26 m. Therefore, considering and confirming the orthogonal contrast results for yield (Table 2), it is possible to affirm that subsoiling treatments (T3 and T5) altered the subsoil physical properties that were important for increasing soybean yield. This is very important for the Cerrado biome because short-term drought is a common occurrence, even during the rainy season.

Variables associated with mechanical resistance to root penetration (i.e., PR), soil aeration (i.e., PORp Mac and RFC), pore size distribution (i.e., S index), and water availability (i.e., RAWip) were highly correlated with soybean yield and therefore formed an acute angle (positive correlation) or angles close to 180° (negative correlation) (Fig. 3). There were no substantial differences in the distribution of variables as a function of soil depth because PCA groups variables as a function of their variance (that is, according to their behavior in the population and that did not change among the sampling depths, despite the decrease in magnitude of correlation coefficients among the variables).

With respect to biometric variables, PHeight was not an effective indicator for a soil management study focused on disrupting NT soil compaction, because there was very little correlation between PHeight and either soil physical properties or soybean yield. Inser1stpod height, however, had a negative correlation with soybean yield, indicating that when the plant delays flowering there is likely a decrease in potential yield. Therefore, Inser1stpod may be a useful indicator to predict the soybean potential yield, making it possible to monitor the soil compaction and make decisions regarding when to use mechanical methods to disrupt soil compaction. For the cultivar used and edaphoclimatic conditions encountered in this study, the greatest yield was associated with Inser1stpod heights between 0.12 and 0.13 m above the soil, whereas the lowest yields had values greater than 0.15 m.

3.2.3. Random Forest Algorithm

The best regression models within this on-farm study were obtained for the 0.00- to 0.05-m depth increment and the whole (0–0.35 m) soil profile as indicated by higher proportion of variance explained (Var_{ex}) values in Table 5. This statistical parameter is an important indicator for comparing the performance of different prediction models (Liaw and Wiener, 2002).

Table 5. Random Forest model performance and validation for predicting soybean yield based on soil physical properties.†

Predict Performance	0.0–0.05 m	0.20–0.25 m	0.30–0.35 m	Profile
	---------------------------- yield, kg ha^{-1}	----------------------------		
Performance indicator				
Var_{ex}, %	23.88	-16.27	-0.78	7.16
Validation parameter				
RMSE, Mg ha^{-1}	0.295	0.354	0.426	0.310
RRMSE, %	6.96	8.20	10.08	7.28
R^2	0.80*	0.76ns‡	0.15ns	0.94**

† Var_{ex}, proportion of variance explained; RMSE, root mean square error; RRMSE, root of the relative mean square error relative to the average yield of the experiment; R^2, coefficient of determination.

* Significant at the 0.05 level of probability.

** Significant at the 0.01 level of probability.

‡ Not significant

To confirm the results for this on-farm study, a validation model was constructed. Through the R 2 and RMSE it confirmed the best adjustment and the least error, respectively, were associated with the 0.00- to 0.05-m depth increment (R^2 = 0.80* and 0.295 Mg ha^{-1}; *Significant at 0.05) and for the whole profile (R^2 = 0.94** and 0.31 Mg ha^{-1}; **Significant at 0.01). Furthermore, the RRMSE shows the RFA error for predicting soybean yield was only 7% of the average experimental yield; a level consistent with excellent accuracy (Li et al., 2013). These results thus demonstrate the potential to predict soybean yield in Brazilian NT fields using soil physical property data and an RFA. Other studies that used RFA models to estimate crop yield based on climatic (Everingham et al., 2016), environmental (Vincenzi et al., 2011), and water (Fukuda et al., 2013) variables also found adequate on-farm accuracy in these respective estimations.

Figure 4 shows the percentage of increase in the mean square error (%IncMSE) of the RF prediction model for soybean yield when each of the soil physical properties is removed. Regardless of depth, PR was the most important indicator for predicting soybean yield. Particularly to the models that were significant and validated, the decreasing ranking of importance for the 0.00- to 0.05-m depth is: PR, Mac, S, RFC, AC, TP, PORp, Mic, and BD, and for the whole profile: PR, RFC, Mac, Mic, S, BD, AC, TP, and PORp. There are subtle differences in the importance of various soil physical indicators when the 0.00 to 0.05 and whole profile (0–0.35 m) are compared (Fig. 4), but PR is consistently the most influential variable for predicting soybean yield. Among the nine measured soil physical property indicators, Mac, the S index, RFC, Mic, and BD are also important.

Our results show the Pearson correlation analysis and RFA assessment are in agreement. Regarding the PCA, some properties that were highly related to yield (e.g., PORp and Mic) did not stand out in the RFA model. The PCA was useful for reducing the number of variables and grouping soil physical properties that were responsive to the treatments.

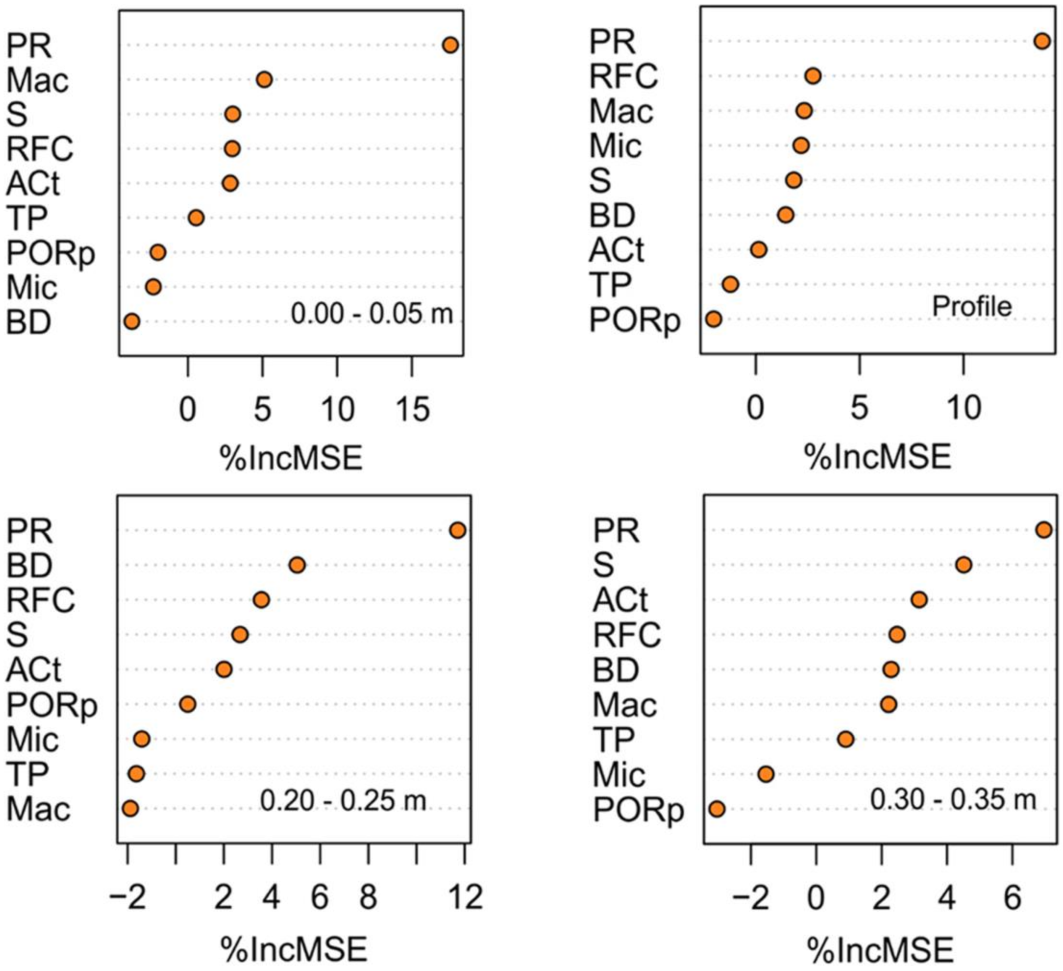

Fig. 4. Importance of soil physical co-variables for predicting soybean yield. S, S Index; Mic, microporosity; Mac, macroporosity; BD, bulk density; TP, total porosity; PORp, porosity of soil macropore domain; AC, air capacity; ACm, air capacity of soil matrix; RFC, relative field capacity; PR, penetration resistance.

The most sensitive soil physical properties for detecting changes due to chemical and/or physical treatments (Table 2) were also the most important for predicting soybean yield (Fig. 4). This includes those reflecting mechanical resistance to root penetration (PR), air capacity (AC and Mac), and pore size distribution (RFC and S index). In contrast, water availability indicators were neither sensitive nor did they influence soybean yield. This likely reflects the suitable supply of water by rainfall during the crop period (Fig. 1). Our recommendation, therefore, is to monitor PR, AC, Mac, RFC, and S index to determine if intervention is needed to correct for NT compaction and thus increase soybean yield potential.

Considering PR as a sensitive property to management practices and soybean yield (Tables 2 and 3; Fig. 4), the linear regression of soybean yield as a function of PR was adjusted

(Fig. 5), being significant ($p < 0.01$). The optimal range for PR was established as a function of the mean value ± standard deviation of treatments T3 and T5, which had higher yields. Thus, PR between 1.15 and 1.54 MPa was the range related to greater soybean yields (Fig. 5). Penetration resistance above 2MPa, considered critical for most crops, was associated to lesser yields.

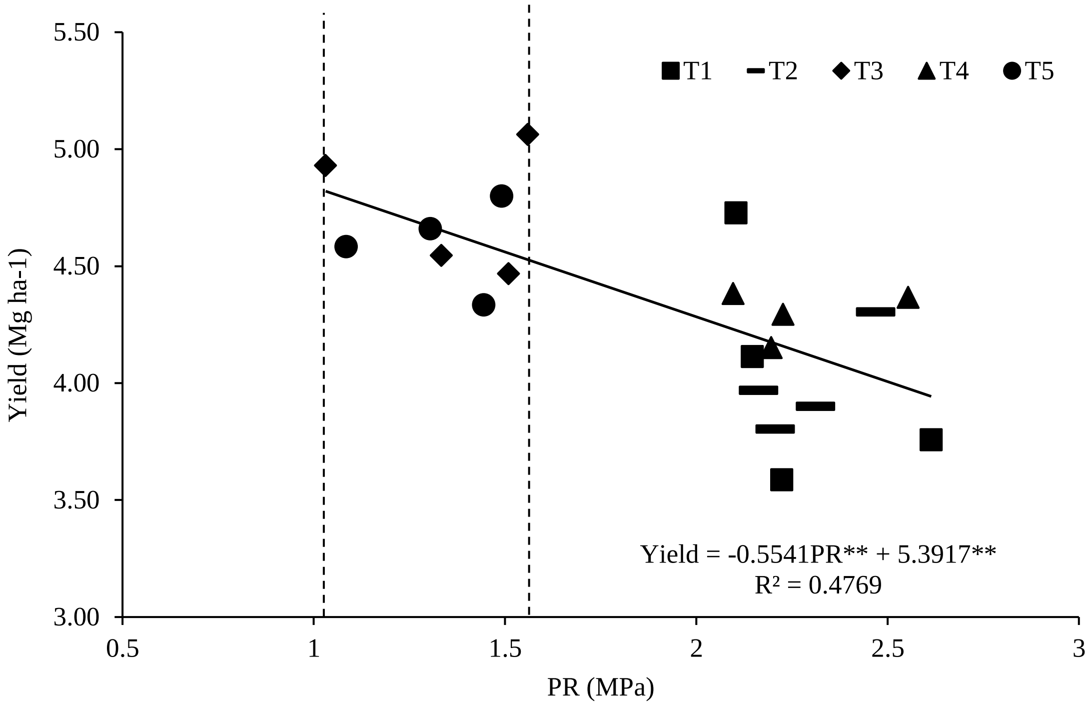

Fig. 5. Regression of yield as a function of penetration resistance (PR), using the profile mean (0.0–0.35 m). Both vertical bars indicate the PR range where soybean yield was at its maximum. **Model parameter statistically significant at the 0.01 level. T1, NT for 10 yr (control); T2, NT with surface application of 3.6 Mg ha^{-1} of agricultural gypsum; T3, NT with subsoiling plus 1.44 Mg ha^{-1} of highly reactive limestone (relative power of total neutralization = 180%) applied to a depth of ~0.60 m; T4, NT planting following chisel plowing at a depth of ~0.26 m; and T5, NT with subsoiling to a depth of ~0.60 m plus 1.44 Mg ha^{-1} of surface-applied, highly reactive limestone (relative power of total neutralization = 180%).

Considering the optimal range of PR, the linear regressions were adjusted with PR and RFC, Mac and S index ($p < 0.01$), similarly as proposed by Reynolds et al. (2008), in order to obtain the optimal ranges for these respective soil physical properties (Fig. 6). Thus, the optimal range for RFC was established between 0.573 and 0.604, Mac was between 0.205 and 0.225 m^3 m^{-3}, and S Index was between 0.070 and 0.077. These values are more restrictive than the ones presented by Reynolds et al. (2008) and the ones specific to soybean crop (Reichert et al., 2009); however, they were obtained in high-yield conditions.

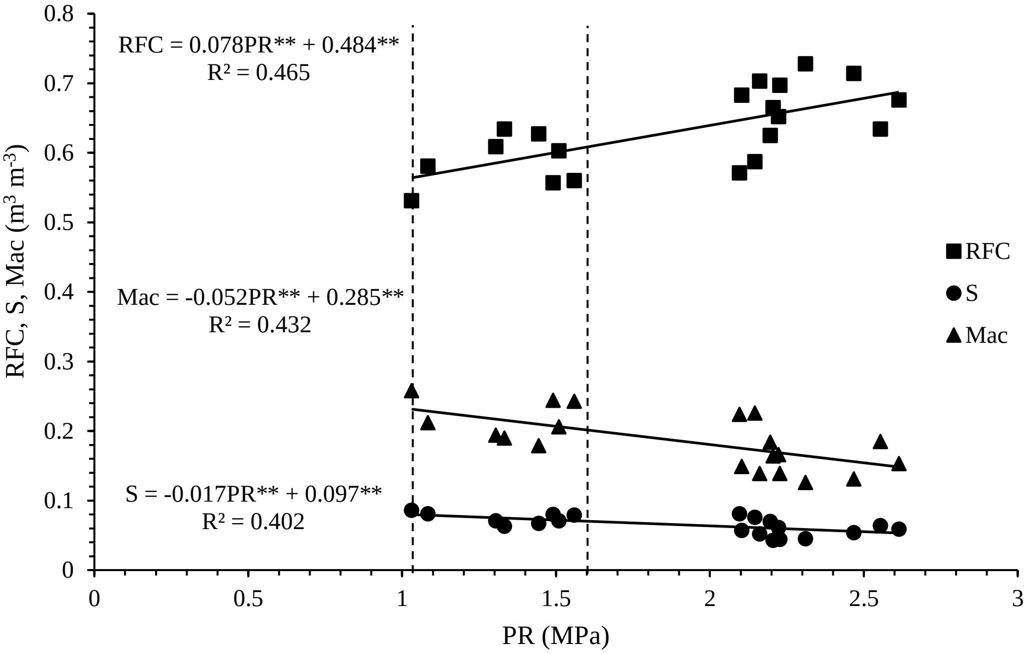

Fig. 6. Regressions of relative field capacity (RFC), S index, and macroporosity (Mac) with penetration resistance (PR), using the profile mean (0.0–0.35 m). Both vertical bars indicate the PR optimal range, considering the maximum yield obtained. **Model parameter statistically significant at the 0.01 level.

4. Conclusions

Mechanical intervention, specifically subsoiling, after long-term NT (10 yr) improved soil physical properties and increased soybean yield during the first crop cycle within this on-farm Brazilian study. Soybean yield response to chiseling was less than for subsoiling, presumably because the depth of soil property alteration was reduced.

Use of an RFA ranked PR, AC, Mac, RFC, and S index as the most important soil physical property indicators with regard to predicting soybean yield. These soil physical indicators were also sensitive to soil structure changes induced by the various treatments imposed to address NT soil compaction. Therefore, we conclude they should be considered key soil physical properties for monitoring soil compaction and deciding when to correct it. We also point out that if time and fiscal resources are limited, PR is the indicator that should be used to guide on-farm decision-making regarding when and how to address NT soil compaction and its effect on soybean yield.

More studies across different soils types, years of NT, and climates are needed to accurately predict effects of occasional tillage on soil physical quality and crop yield in Brazilian NT systems.

5. References

Ahmad, M., H. Abdullah, M. Iqbal, M. Umair, and M. Ghani. 2010. Effect of deep tillage on soil properties and crop (wheat) yield. *Soil Environ*. 29:177–180.

Amarante, L., and L. Sodek. 2006. Waterlogging effect on xylem sap glutamine of nodulated soybean. *Biol. Plant*. 50:405–410. doi:10.1007/s10535-006-0057-6

Andrade, R.S., and L.F. Stone. 2011. Estimativa da umidade na capacidade de campo em solos sob Cerrado. *Rev. Bras. Eng. Agric. Ambient*. 15:111–116. doi:10.1590/S1415-43662011000200001

Arshad, M.A., B. Lowery, and B. Grossman. 1996. Physical tests for monitoring soil quality. In: J.W. Doran and A.J. Jones, editors, *Methods for assessing soil quality*. *SSSA Spec. Publ. 49*. SSSA, Madison, WI. p. 123–141. doi:10.2136/sssaspecpub49.c7

Asgarzadeh, H., M.R. Mosaddeghi, and A.M. Nikbakht. 2014. SAWCal: A user-friendly program for calculating soil available water quantities and physical quality indices. *Comput. Electron. Agric*. 109:86–93. doi:10.1016/j.compag.2014.09.008

Asgarzadeh, H., M.R. Mosaddeghi, A.A. Mahboubi, A. Nosrati, and A.R. Dexter. 2011. Integral energy of conventional available water, least limiting water range and integral water capacity for better characterization of water availability and soil physical quality. *Geoderma* 166:34–42. doi:10.1016/j.geoderma.2011.06.009

Bacanamwo, M., and L.C. Purcell. 1999. Soybean dry matter and N accumulation responses to flooding stress, N sources and hypoxia. *J. Exp. Bot.* 50:689–696. doi:10.1093/jxb/50.334.689

Batey, T. 2009. Soil compaction and soil management: A review. *Soil Use Manage*. 25:335–345. doi:10.1111/j.1475-2743.2009.00236.x

Bengough, A.G., D.J. Campbell, and M.F. O'Sullivan. 2001. Penetrometer techniques in relation to soil compaction and root growth. In: K.A. Smith and C.E. Mullins, editors, *Soil and environmental analysis: Physical methods.* 2nd edition. Marcel Dekker, Edinburgh. p. 377–403.

Bengough, A.G., B.M. McKenzie, P.D. Hallett, and T.A. Valentine. 2011. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. *J. Exp. Bot*. 62:59–68. doi:10.1093/jxb/erq350

Beutler, A.N., J.F. Centurion, A.P. Silva, and J.C. Barbosa. 2006. Intervalo hídrico ótimo e produtividade de cultivares de soja. *Rev. Bras. Eng. Agric. Ambient.* 10:639–645. doi:10.1590/S1415-43662006000300015

Bobade, A.B., S.K. Kshirsagar, and M.R. Deshmukh. 2016. The yield performance and economics under different tillage practices of soybean. *Adv. Life Sci.* 5:2755–2760.

Bölenius, E., B. Stenberg, and J. Arvidsson. 2017. Within field cereal yield variability as affected by soil physical properties and weather variations: A case study in east central Sweden. *Geoderma Reg.* 11:96–103. doi:10.1016/j.geodrs.2017.11.001

Botta, G.F., A. Tolon-Becerra, X. Lastra-Bravo, and M. Tourn. 2010. Tillage and traffic effects (planters and tractors) on soil compaction and soybean (Glycine max L.) yields in Argentinean pampas. *Soil Tillage Res.* 110:167–174. doi:10.1016/j.still.2010.07.001

Botta, G.F., D. Jorajuria, R. Balbuena, M. Ressia, C. Ferrero, H. Rosatto, and M. Tourn. 2006. Deep tillage and traffic effects on subsoil compaction and sunflower (Helianthus annus L.) yields. *Soil Tillage Res.* 91:164-172. doi:10.1016/j.still.2005.12.011

Breiman, L. 2001. Random forests. *Mach. Learn.* 45:5–32. doi:10.1023/A:1010933404324

Busscher, W., J. Frederick, and P. Bauer. 2001. Effect of penetration resistance and timing of rain on grain yield of narrow-row corn in a coastal plain loamy sand. *Soil Tillage Res.* 63:15–24. doi:10.1016/S0167-1987(01)00228-8

Busscher, W.J., J.H. Edwards, M.J. Vepraskas, and D.L. Karlen. 1995. Residual effects of slit tillage and subsoiling in a hardpan soil. *Soil Tillage Res.* 35:115–123. doi:10.1016/0167-1987(95)00488-2

Caires, E.F., G. Barth, and F.J. Garbuio. 2006. Lime application in the establishment of a no-till system for grain crop production in Southern Brazil. *Soil Tillage Res.* 89:3–12. doi:10.1016/j.still.2005.06.006

Calonego, J.C., J.P.A. Raphael, J.P.G. Rigon, L. Oliveira Neto, and C.A. Rosolem. 2017. Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. *Eur. J. Agron.* 85:31–37. doi:10.1016/j.eja.2017.02.001

Calonego, J.C., and C.A. Rosolem. 2010. Soybean root growth and yield in rotation with cover crops under chiseling and no-till. *Eur. J. Agron.* 33:242–249. doi:10.1016/j.eja.2010.06.002

Cecagno, D., S.E.V.G.A. Costa, I. Anghinoni, T.R. Kunrath, A.P. Martins, J.M. Reichert, P.I. Gubiani, F. Balerini, J.R. Fink, and P.C.F. Carvalho. 2016. Least limiting water range and soybean yield in a long-term, no-till, integrated crop-livestock system under different grazing intensities. *Soil Tillage Res.* 156:54–62. doi:10.1016/j.still.2015.10.005

Cortez, J.W., M. Mauad, L.C.F. Souza, M.V. Rufino, and P.H.N. Souza. 2017. Agronomical attributes of soybeans and soil resistance to penetration in no-tillage and chiseled surfaces. *Eng. Agric.* 37:98–105. doi:10.1590/1809-4430-eng.agric.v37n1p98-105/2017

Curi, N., J.C. Ker, R.F. Novais, P. Vidal-Torrado, and C.E.G.R. Schaefer. 2017. *Pedologia: Solos dos Biomas Brasileiros*. Sociedade Brasileira de Ciência do Solo, Viçosa.

Cutler, R.D., T.C. Edwards, K.H. Beard, K.T. Cutler, H.J. Gibson, and J.J. Lawler. 2007. Random forests for classification in ecology. *Ecology* 88:2783–2792. doi:10.1890/07-0539.1

Dalchiavon, F.C., M.P. Carvalho, D.C. Nogueira, D. Romano, F.L. Abrantes, J.T. Assis, and M.S. Oliveira. 2011. Produtividade da soja e resistência mecânica à penetração do solo sob sistema plantio direto no cerrado brasileiro. *Agric. Res. Tropics* 41:8–19.

Debiasi, H., R. Levien, C.R. Trein, O. Conte, and K.M. Kamimura. 2010. Produtividade de soja e milho após coberturas de inverno e descompactação mecânica do solo. *Pesq. Agropec. Bras*. 45:603–612. doi:10.1590/S0100-204X2010000600010

Derpsch, R., T. Friedrich, A. Kassam, and H.W. Li. 2010. Current status of adoption of no-till farming in the world and some of its main benefits. *Int. J. Agric. Biol. Eng.* 3:1–25. doi:10.3965/j.issn.1934-6344.2010.01.0-0

Dexter, A.R. 2004. Soil physical quality. Part I. Theory, effects of soil texture, density and organic matter, and effects on root growth. *Geoderma* 120:201–214. doi:10.1016/j.geoderma.2003.09.004

Drescher, M.S., F.L.F. Eltz, J.E. Denardin, and A. Faganello. 2011. Persistência do efeito de intervenções mecânicas para a descompactação de solos sob plantio direto. *Braz. J. Soil Sci.* 35:1713–1722. doi:10.1590/S0100-06832011000500026

Everingham, Y., J. Sexton, D. Skocaj, and G. Inman-Bamber. 2016. Accurate prediction of sugarcane yield using a random forest algorithm. *Agron. Sustain. Dev.* 36:27. doi:10.1007/s13593-016-0364-z

FAO. 2016. *AQUASTAT: FAO's Global Information System on Water and Agriculture.* Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/nr/aquastat/ (accessed 4 Feb. 2018).

Farias, J.R.B., A.L. Nepomuceno, and N. Neumaier. 2007. *Ecofisiologia da soja.* Circular Técnica 48. Embrapa, Londrina.

Ferreira, M.M., and Z.Z. Marcos. 1983. Estimativa da capacidade de campo de Latossolo Roxo distrófico e regossolo através do ponto de inflexão da curva característica de umidade. *Ciência e Prática* 7:96–101.

Fidalski, J., R. Yagi, and C.A. Tormena. 2015. Revolvimento ocasional e calagem em Latossolo muito argiloso em sistema plantio direto consolidado. *Braz. J. Soil Sci.* 39:1483–1489. doi:10.1590/01000683rbcs20140428

Flint, A.L., and L.E. Flint. 2002. Particle density. In: J.H. Dane and G.C. Topp, editors, *Methods of soil analysis. Part 4.* SSSA Book Ser. 5. SSSA, Madison. p. 229–240. doi:10.2136/sssabookser5.4.c10

Flowers, M.D., and R. Lal. 1998. Axle load and tillage effects on soil physical properties and soybean grain yield on a mollic ochraqualf in northwest Ohio. *Soil Tillage Res.* 48:21–35. doi:10.1016/S0167-1987(98)00095-6

Fukuda, S., W. Spreer, E. Yasunaga, K. Yuge, V. Sardsud, and J. Müller. 2013. Random forests modelling for the estimation of mango (*Mangifera indica* L. cv. Chok Anan) fruit yields under different irrigation regimes. *Agric. Water Manage*. 116:142–150. doi:10.1016/j.agwat.2012.07.003

Girardello, V.C., T.J.C. Amado, A.L. Santi, M.R. Cherubin, J. Kunz, and T.G. Teixeira. 2014. Resistência à penetração, eficiência de escarificadores mecânicos e produtividade da soja em Latossolo argiloso manejado sob plantio direto de longa duração. *Braz. J. Soil Sci.* 38:1234–1244. doi:10.1590/S0100-06832014000400020

Grandy, A.S., G.P. Robertson, and K.D. Thelen. 2006. Do productivity and environmental trade-offs justify periodically cultivating no-till cropping systems? *Agron. J.* 98:1377–1382. doi:10.2134/agronj2006.0137

Gregory, P.J. 1992. Crecimiento y funcionamiento de las raíces. In: A. Wild, editor, *Condiciones del suelo y desarrollo de las plantas según Russel*. Mundi-Prensa, Madrid. p. 121–175.

Grossman, R.B., and T.G. Reinsch. 2002. Bulk density and linear extensibility. In: J.H. Dane and G.C. Topp, editors, *Methods of soil analysis. Part 4.* SSSA Book Ser. 5. SSSA, Madison. p. 201–228. doi:10.2136/sssabookser5.4.c9

Hair, J.F., Jr., B. William, B. Babin, and R.E. Anderson. 2009. *Multivariate data analysis*. 6th edition. Bookman, Porto Alegre.

Hakojärvi, M., M. Hautala, A. Ristolainen, and L. Alakukku. 2013. Yield variation of spring cereals in relation to selected soil physical properties on three clay soil fields. *Eur. J. Agron.* 49:1–11. doi:10.1016/j.eja.2013.03.003

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil Tillage Res.* 82:121–145. doi:10.1016/j.still.2004.08.009

Izumi, Y., T. Yoshida, and M. Iijima. 2009. Effects of subsoiling to the non-tilled field of wheat-soybean rotation on the root system development, water uptake, and yield. *Plant Prod. Sci.* 12:327–335. doi:10.1626/pps.12.327

Klein, V.A., and R.K. Camara. 2007. Rendimento da soja e intervalo hídrico ótimo em Latossolo Vermelho sob plantio direto escarificado. *Braz. J. Soil Sci.* 31:221–227. doi:10.1590/S0100-06832007000200004

Klein, V.A., M.L. Vieira, F.F. Durigon, J.P. Massing, and F. Fávero. 2008. Porosidade de aeração de um Latossolo Vermelho e rendimento de trigo em plantio direto escarificado. *Cienc. Rural* 38:365–371. doi:10.1590/S0103-84782008000200011

Klute, A. 1986. Water retention: Laboratory methods. In: A. Klute, editor, *Methods of soil analysis. Part 1.* SSSA Book Ser. 5.1. SSSA and ASA, Madison, WI. p. 635–662. doi:10.2136/sssabookser5.1.2ed.c26

Koch, H.J., J. Dieckmann, A. Büchse, and B. Märländer. 2009. Yield decrease in sugar beet caused by reduced tillage and direct drilling. *Eur. J. Agron.* 30:101–109. doi:10.1016/j.eja.2008.08.001

Lal, R., D.C. Reicosky, and J.D. Hanson. 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. *Soil Tillage Res.* 93:1–12. doi:10.1016/j.still.2006.11.004

Lapen, D.R., G.C. Topp, E.G. Gregorich, and W.E. Curnoe. 2004. Least limiting water range indicators of soil quality and corn production, eastern Ontario, Canada. *Soil Tillage Res.* 78:151–170. doi:10.1016/j.still.2004.02.004

Lê, S., J. Josse, and F. Husson. 2008. FactoMineR: An R Package for multivariate analysis. *J. Stat. Softw.* 25:1–18. doi:10.18637/jss.v025.i01

Letey, J. 1985. Relationship between soil physical properties and crop production. *Adv. Soil Sci.* 1:277–294. doi:10.1007/978-1-4612-5046-3_8

Li, M.F., X.P. Tang, W. Wu, and H.B. Liu. 2013. General models for estimating daily global solar radiation for different solar radiation zones in mainland China. *Energy Convers. Manage.* 70:139–148. doi:10.1016/j.enconman.2013.03.004

Liaw, A., and M. Wiener. 2002. Classification and regression by randomForest. *R News* 2/3:18–22.

Linn, D.M., and J.W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci. Soc. Am. J.* 48:1267–1272. doi:10.2136/sssaj1984.03615995004800060013x

Lipiec, J., R. Horn, J. Pietrusiewicz, and A. Siczek. 2012. Effects of soil compaction on root elongation and anatomy of different cereal plant species. *Soil Tillage Res.* 121:74–81. doi:10.1016/j.still.2012.01.013

Lipiec, J., and W. Stepniewski. 1995. Effects of soil compaction and tillage systems on uptake and losses of nutrients. *Soil Tillage Res.* 35:37–52. doi:10.1016/0167-1987(95)00474-7

Lozano, L.A., C.G. Soracco, R. Villarreal, J.M. Ressia, G.O. Sarli, and R.R. Filgueira. 2016. Soil physical quality and soybean yield as affected by chiseling and subsoiling of a no-till soil. *Braz. J. Soil Sci.* 40:1–12. doi:10.1590/18069657rbcs20150160

Mello, C.R., G.C. Oliveira, D.V.S. Resck, J.M. Lima, and M.S. Dias Júnior. 2002. Estimativa da capacidade de campo baseada no ponto de inflexão da curva característica. *Cienc. Agrotec.* 26:835–841.

Montanari, R., M.P. Carvalho, M. Andreotti, F.C. Dalchiavon, L.H. Lovera, and M.A.O. Honorato. 2010. Aspectos da produtividade do feijão correlacionados com atributos físicos do solo sob elevado nível tecnológico de manejo. *Braz. J. Soil Sci.* 34:1811–1822. doi:10.1590/S0100-06832010000600005

Nortcliff, S. 2002. Standardisation of soil quality attributes. *Agric. Ecosyst. Environ.* 88:161–168. doi:10.1016/S0167-8809(01)00253-5

Novais, R.F. 1999. Soja. In: A.C. Ribeiro, P.T.G. Guimarães, and V.H. Alvarez, editors, *Recomendação para o uso de corretivos e fertilizantes em Minas Gerais*. CFSEMG, Viçosa, MG.

Nunes, M.R., J.E. Denardin, E.A. Pauletto, A. Faganello, and L.F.S. Pinto. 2015. Mitigation of clayey soil compaction managed under no-tillage. *Soil Tillage Res.* 148:119–126. doi:10.1016/j.still.2014.12.007

Nunes, M.R., E.A. Pauletto, J.E. Denardin, A. Faganello, L.F.S. Pinto, and T. Scheunemann. 2014. Persistence of chiseling effects on the compaction of a Nitosol under no-till in a humid subtropical region. *Pesq. Agropec. Bras.* 49:531–539. doi:10.1590/S0100-204X2014000700005

Passioura, J.B. 2002. Soils conditions and plant growth. *Plant Cell Environ.* 25:311–318. doi:10.1046/j.0016-8025.2001.00802.x

Pittelkow, C.M., B.A. Linquist, M.E. Lundy, X. Liang, K. Jan van Groenigen, J. Lee, N. van Gestel, J. Six, R.T. Venterea, and C. van Kessel. 2015. When does no-till yield more? A global meta-analysis. *Field Crops Res.* 183:156–168. doi:10.1016/j.fcr.2015.07.020

Quincke, J.A., C.S. Wotmann, M. Mamo, R. Franti, R.A. Drijber, and J.P. Garcia. 2007. One-time tillage of no-till systems: Soil physical properties, phosphorus runoff, and crop yield. *Agron. J.* 99:1104–1110. doi:10.2134/agronj2006.0321

R Development Core Team. 2017. *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. https://www.Rproject.org (accessed 2 Feb. 2018).

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

Reynolds, W.D., B.T. Bowman, C.F. Drury, C.S. Tan, and X. Lu. 2002. Indicators of good soil physical quality: Density and storage parameters. *Geoderma* 110:131–146. doi:10.1016/S0016-7061(02)00228-8

Reynolds, W.D., C.F. Drury, C.S. Tan, C.A. Fox, and X.M. Yang. 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. *Geoderma* 152:252–263. doi:10.1016/j.geoderma.2009.06.009

Reynolds, W.D., C.F. Drury, X.M. Yang, and C.S. Tan. 2008. Optimal soil physical quality inferred through structural regression and parameter interactions. *Geoderma* 146:466–474. doi:10.1016/j.geoderma.2008.06.017

Rossato, O.B., C.A. Ceretta, L.S. Silva, G. Brunetto, J.C. Adorna, E. Girotto, and C.R. Lourenzi. 2009. Correction of soil acidity in the subsurface of an Oxisol with sandy loam texture under no-tillage. *Braz. J. Soil Sci.* 33:659–667. doi:10.1590/S0100-06832009000300018

Santi, A.L., T.J.C. Amado, M.R. Cherubin, T.N. Martin, J.L. Pires, L.P.D. Flora, and C.J. Basso. 2012. Análise de componentes principais de atributos químicos e físicos do solo limitantes à produtividade de grãos. *Pesq. Agropec. Bras.* 47:1346–1357. doi:10.1590/S0100-204X2012000900020

Secco, D., D.J. Reinert, J.M. Reichert, and C.O. da Ros. 2004. Produtividade de soja e propriedades físicas de um Latossolo submetido a sistemas de manejo e compactação. *Braz. J. Soil Sci.* 28:797–804. doi:10.1590/S0100-06832004000500001

Secco, D., D.J. Reinert, J.M. Reichert, and V.R. Silva. 2009. Atributos físicos e rendimento de grãos de trigo, soja e milho em dois Latossolos compactados e escarificados. *Cienc. Rural* 39:58–64. doi:10.1590/S0103-84782009000100010

Shukla, M.K., and R. Lal. 2005. Erosional effects on soil organic carbon stock in an on-farm study on Alfisols in west central Ohio. *Soil Tillage Res.* 81:173–181. doi:10.1016/j.still.2004.09.006

Shukla, M.K., R. Lal, and M. Ebinger. 2004. Principal component analysis for predicting corn biomass and grain yields. *Soil Sci.* 169:215–224. doi:10.1097/01.ss.0000122521.03492.eb

Silva, B.M., G.C. Oliveira, M.E. Serafim, E.A. Silva, M.M. Ferreira, L.D. Norton, and N. Curi. 2015. Critical soil moisture range for a coffee crop in an oxidic latosol as affected by soil management. *Soil Tillage Res.* 154:103–113. doi:10.1016/j.still.2015.06.013

Silva, B.M., E.A. Silva, G.C. Oliveira, M.M. Ferreira, and M.E. Serafim. 2014. Plant-available soil water capacity: Estimation methods and implications. *Braz. J. Soil Sci.* 38:464–475. doi:10.1590/S0100-06832014000200011

Silva, M.C.C., M. Andreotti, N.R. Costa, C.G.R. Lima, and C.M. Pariz. 2017. Soil physical attributes and yield of winter common bean crop under a no-till system in the Brazilian Cerrado. *Rev. Caatinga* 30:155–163. doi:10.1590/1983-21252017v30n117rc

Smidt, E.R., S.P. Conley, J. Zhu, and F.J. Arriaga. 2016. Identifying field attributes that predict soybean yield using random forest analysis. *Agron. J.* 108:637–646. doi:10.2134/agronj2015.0222

Soane, B.D., B.C. Ball, J. Arvidsson, G. Basch, F. Moreno, and J. Roger-Estrade. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil Tillage Res.* 118:66–87. doi:10.1016/j.still.2011.10.015

Soil Survey Staff. 2014. *Keys to soil taxonomy*. 12th ed. USDA, Washington, DC.

Sparks, D.L., A.L. Page, P.A. Helmke, and R.H. Loeppert, editors. 1996. *Methods of soil analysis. Part 3*. SSSA Book Ser. 5.3. SSSA and ASA, Madison, WI.

Stavi, I., R. Lal, and L.B. Owens. 2011. On-farm effects of no-till versus occasional tillage on soil quality and crop yields in eastern Ohio. *Agron. Sustain. Dev.* 31:475–482. doi:10.1007/s13593-011-0006-4

Stirzaker, R.J., J.B. Passioura, and Y. Wilms. 1996. Soil structure and plant growth: Impact of bulk density and biopores. *Plant Soil* 185:151–162. doi:10.1007/BF02257571

Stolf, R. 1991. Teoria e teste experimental de fórmulas de transformação dos dados de penetrômetro de impacto em resistência do solo. *Braz. J. Soil Sci.* 15:229–235.

Tullberg, J.N. 1990. Why control field traffic. In: M.N. Hunter, C.J. Paull, and G.D. Smith, editors, *Proceedings of Queensland Department of Primary Industries Soil Compaction Workshop, Toowoomba, Australi*a. 28, p. 13–25.

van Genuchten, M.T. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892–898. doi:10.2136/sssaj1980.03615995004400050002x

Vincenzi, S., M. Zucchetta, P. Franzoi, M. Pellizzato, F. Pranovi, G.A. De Leo, and P. Torricelli. 2011. Application of a Random Forest algorithm to predict spatial distribution of the potential yield of Ruditapes philippinarum in the Venice lagoon, Italy. *Ecol. Modell.* 222:1471–1478. doi:10.1016/j.ecolmodel.2011.02.007

Walkley, A., and L.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 37:29–38. doi:10.1097/00010694-193401000-00003

Wang, Q., C. Lu, H. Li, J. He, K.K. Sarker, R.G. Rasaily, Z. Liang, X. Qiao, H. Li, and A.D.J. Mchungh. 2014. The effects of no-tillage with subsoiling on soil properties and maize yield: 12-year experiment on alkaline soils of Northeast China. *Soil Tillage Res.* 137:43–49. doi:10.1016/j.still.2013.11.006

Zhang, Y., R. Wang, S. Wang, H. Wang, Z. Xu, G. Jia, X. Wang, and J. Li. 2017. Effects of different sub-soiling frequencies incorporated into no-tillage systems on soil properties and crop yield in dryland wheat-maize rotation system. *Field Crops Res.* 209:151–158. doi:10.1016/j.fcr.2017.05.002

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PAPER 3 – A SOIL COMPACTION DIAGNOSIS METHOD FOR OCCASIONAL TILLAGE RECOMMENDATION UNDER CONTINUOUS NO TILLAGE SYSTEM IN BRAZIL

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Highlights

- Occasional tillage increases crop production in continuous NTS.
- A method for diagnosing compaction and recommend occasional tillage was proposed.
- PR models were validated to base compaction and yield response prediction.
- The PR should be evaluated under drier moisture conditions than FC.

Abstract

Soil compaction has reduced crop yield under continuous no-tillage systems (NTS), and occasional tillage has been suggested as a mitigating measure. The aim of this study was to suggest a moisture content range ideal for diagnosing and monitoring soil compaction and propose a criterion based on PR for making decisions regarding recommendation of occasional tillage. After 10 years of cultivation under NTS, soil management practices were tested for mitigating soil compaction, combining occasional tillage (subsoiling or chisel plowing) and chemical soil conditioning (limestone or agricultural gypsum). Undisturbed soil samples were collected at three depths, and PR was measured at seven soil matric potentials at 1.5 years after the installation of the experiment. Five PR models were tested in accordance with soil moisture content and validated for each treatment and soil depth. The yields of soybean (2015/2016 and 2017/2018 crop seasons), maize (2016/2017 crop season), common bean (2017 second crop), and wheat (2018 second crop) were evaluated. Occasional tillage with subsoiling or chisel plowing under continuous NTS led to an increase in grain yield in the three subsequent years. An ideal range of soil water content for diagnosis of compaction (IRDC) in a continuous NTS area between the matric potentials of -0.03 and -0.50 MPa, preferentially -0.10 MPa, was suggested, unlike the value of field capacity suggested in the literature. Based on the IRDC, a method was proposed for diagnosis and monitoring of soil compaction in continuous NTS areas exhibiting restricted grain yield for the purpose of making decisions regarding occasional tillage. An example of application of this method was tested and was successful.

Keywords: Penetration resistance; Deep tillage methods; Soil moisture.

1. Introduction

Soil compaction due to agricultural use is a serious threat to crop yield (Schjønning et al., 2015) and to the ecological functions of the soil (Hamza and Anderson, 2005; Schjønning et al., 2015), with considerable economic impact (Batey, 2009; Chamen et al., 2015). Soil compaction limits plant root development (Bengough et al., 2011; Lipiec et al., 2012; Szatanik-Kloc et al., 2018) due to greater soil bulk density and resistance to root penetration and lower permeability to air and water (Hamza and Anderson, 2005). This hinders gas exchanges and water and nutrient uptake by roots (Lipiec and Stepniewski, 1995).

In Brazil, more than 32 million hectares of land are under the no-tillage system (NTS). Soybean and maize are the main crops grown under this system. In spite of the numerous benefits of NTS reported in the literature in comparison to conventional tillage (plowing and disking), such as improvement in soil aggregate structure and stability, greater capacity for water retention and availability, an increase in the biodiversity and content of organic matter, and reduced production costs (for example, labor costs, use of agricultural equipment, and fuel use) (Tebrügge and Düring, 1999; Holland, 2004; Lal et al., 2007; Derpsch et al., 2010; Blanco-Canqui and Ruis, 2018), some challenges have arisen over its years of use. Challenges include an increase in herbicide-resistant weeds, proliferation of pests and diseases, stratification of the soil at depth, and exaggerated accumulation of nutrients in the soil surface layer (Blanco-Canqui and Ruis, 2018), as well as compaction problems due to lack of soil mobilization, especially in clayey soils (Batey, 2009; Reichert et al., 2009a; Farooq et al., 2011; Severiano et al., 2013; Nunes et al., 2014a, 2015; Blanco-Canqui and Ruis, 2018). In this context, occasional tillage in continuous NTS has been proposed to meet these challenges (Blanco-Canqui and Ruis, 2018). The few studies on occasional tillage in continuous NTS have indicated little or no negative effect on soil physical properties (Quincke et al., 2007; Wortmann et al., 2010; Crawford et al., 2015; Liu et al., 2016). Nevertheless, occasional tillage may expose the soil to the action of rain and to the erosive forces of wind, which can increase erosion, losses of nutrients, and greenhouse gas emissions, especially if intense rains occur soon after this operation (Melland et al., 2017).

One of the methods most used for diagnosis of soil compaction is measuring penetration resistance (PR) with a cone penetrometer (Masaddeghi et al., 2000; Herrick and Jones, 2002; Lampurlanés and Cantero-Martinez, 2003; Jung et al., 2010; Beckett et al., 2018). This method is simple, with fast and easy determination in the field, at low cost (Hartge et al., 1985). It exhibits correlation with plant variables, such as root growth (Dexter, 1987; Bengough et al., 2011; Otto et al., 2011) and yield (Busscher et al., 2001; Whalley et al., 2008; Weber and Biskupski, 2008; Koch et al., 2009; Ahmad et al., 2010; Bölenius et al., 2017). However, PR is strongly affected by soil moisture content (Reichert et al., 2010; Vaz et al., 2011) and generally shows an exponential increase as soil moisture decreases (Busscher et al., 1997; Vaz et al., 2011; Moraes et al., 2012; Mome Filho et al., 2014). This may hinder diagnosis of soil compaction.

To isolate the effect of soil moisture content and increase accuracy in detection of the compacted layer, determination of soil PR with moisture at field capacity has been recommended (Arshad et al., 1996; Lowery and Morrison, 2002; Vaz et al., 2011). The explanation for this is based on friction at the soil-metal interface, which tends to be significantly greater (from two to eight times) compared to the friction between the soil and the plant roots (Bengough et al., 1997). In addition, the penetrometer, unlike the plant root, cannot change its trajectory to advance when there is a particularly resistant aggregate (Arshad et al., 1996) or rockiness in its route. Thus, when the soil is in dry conditions, the forces of friction are higher than under moist conditions, reducing the correlation between the impedance confronted by the roots and that measured by the penetrometer, lending support to the idea of carrying out measurements of PR between 0.00 and -0.01 MPa (Vaz et al., 2011). Furthermore, the condition of moisture content at field capacity is repeatable from season to season of crop development and from one time to another within a given season (Lowery and Morrison, 2002) since climate conditions that promote changes in moisture content in the soil will strengthen or weaken the effect of compaction on the roots (Unger and Kaspar, 1994).

Nevertheless, previous studies have shown that PR determined with moister soil (field capacity) might not have sensitivity to evaluate the level of soil compaction, especially in evaluations of the effect of machine traffic and of the methods of mitigating soil compaction (Reinert et al., 2001; Assis et al., 2009; Moraes et al., 2012, 2013; Bölenius et al., 2018; Catania et al., 2018). Considering that PR is more dependent on soil bulk density under drier conditions and that it might not be affected by bulk density under high moisture content conditions (Fulton et al., 1996; Mulqueen et al., 1977), determination of PR when the soil is at field capacity might not be the best approach in attempting to identify areas that are potentially limiting to crop yield (Bölenius et al., 2018). Thus, questions have arisen regarding the ability of the penetrometer to identify compacted areas under both dry and moist conditions (Bölenius et al., 2018).

The PR value of 2 MPa has been indicated as a sign of restrictions to root growth (Soil Survey Staff, 1993; Arshad et al., 1996; Bengough et al., 2006, 2011) and, therefore, of compaction or densification of the soil. PR higher than 2.0 MPa severely reduces root growth of the cotton plant (Taylor et al., 1966) and, in the absence of water stress, it reduces the root elongation rate in maize and peanut to half (Bengough et al., 2011). However, there is no consensus on this value, due to the specificities of crops, cultivars, experimental conditions, management systems, and the presence or lack of alternatives routes (channel and fissure network) for the roots to exploit (Bengough et al., 2011), routes which are frequently found in conservationist systems (Tormena et al., 2007; Betioli Júnior et al., 2012; Moraes et al., 2014a; Calonego et al., 2017; Blanco-Canqui and Ruis, 2018). In addition, there is evidence that reduction in root elongation is the result of the combination of the increase in mechanical resistance and water deficit. Bengough et al. (2011) evaluated 19 soils with different textures and found that upon raising water deficit from -0.01 MPa to-0.20 MPa, there was an increase from 10% to 50% in the number of situations in which PR was greater than 2 MPa. This shows that change in moisture content under which PR was measured affects the result of diagnosis of soil compaction.

To contribute toward improving the quality of diagnosis of soil compaction in the field, considering the problematic of the effect of moisture content on PR in the context of conservationist systems for cultivation of grain crops, the hypothesis of this study is that PR should be determined at a matric potential lower than -0.01 MPa (adopted as field capacity) to favor distinction among soil management practices and allow greater assurance in making decisions concerning occasional tillage to mitigate soil compaction under continuous NTS. The aims of this study were to suggest a range of soil water content ideal for performing diagnosis and monitoring of soil compaction; and to propose a criterion based on PR for making decisions on occasional tillage to mitigate soil compaction in NTS.

2. Materials and methods

2.1. Location and characterization of the area

The experiment was set up in October 2015 on the Santa Helena Farm at 21° 15′ 39″ S and 44° 31′ 04″ W, at 1020 m AMSL in the municipality of Nazareno, in the Campo das Vertentes mesoregion of the state of Minas Gerais, Brazil. Climate is type Cwa (Köppen classification), with cold and dry winters and hot and humid summers. Mean annual rainfall and temperature are 1300 mm and 19.7 °C, respectively. The soil was classified as a Typic

Hapludox according to Soil Taxonomy (Soil Survey Staff, 2014) or “Latossolo Vermelho Amarelo Distrófico típico” according to Brazilian Soil Classification System (Santos et al., 2013). The mean distribution of clay, silt, and sand in the soil profile of the experimental area was 530, 250, and 220 g kg^{-1}, respectively.

The experiment was conducted in strips, with 5 treatments and 4 replications. The strips were set up with dimensions of 18 m width and 80 m length (1440 m^{2}) and subdivided into 4 experimental plots of 360 m^{2} (Fig. 1). The treatments consisted of soil management practices to mitigate compaction, combining physical and chemical soil conditioning. The diagnosis of compaction in the experimental area was indicated by the time since the NTS was set up (since 2005) and was confirmed by morphological analysis of the soil profile in 2015. The following treatments were used: (T1) continuous NTS since establishment in 2005 (control); (T2) NTS with surface application of 3600 kg ha^{-1} of agricultural gypsum according to van Raij et al. (1997); (T3) NTS with the use of a fertilizing subsoiler (KAMAQ®) with incorporation of 1440 kg ha^{-1} of additional limestone (in addition to the chemical application recommended by soil analysis) of high reactivity [total neutralizing power (TNP) = 180%] making application to a depth of 0.60 m, with spacing of 0.75 m between shanks; (T4) NTS with the use of a chisel plow with shanks of 0.26 m length; (T5) NTS with use of a subsoiler (Ikeda®) with a 0.60 m length shank and application of 1440 kg ha^{-1} of additional limestone (in addition to the application of the recommended by the Soil Fertility Commission of the State of Minas (1999), taking into account the maximum dose as indicated by Sá (1999) (2500 kg ha^{-1}; limestone TNP = 100%) of high reactivity (TNP = 180%) on the surface. An area of native forest vegetation, beside the experiment, was used as a reference.

Annual crops were fertilized based on soil analysis and also on the amounts of nutrients exported by each crop. Operations for management of weeds, pests, and diseases in the experiment were the same as those adopted by the producer. The production system used on the farm consists of rotation and succession of soybean (*Glycine max* (L.) Merrill) and maize (*Zea mays* L.) in the spring-summer crop and common bean (*Phaseolus vulgaris* L.) and wheat (*Triticum aestivun* L.) in the fall-winter crop. When the soil moisture conditions allow, oats (*Avena sativa* L.) are grown after the fall-winter crop season as a soil cover plant and for straw production.

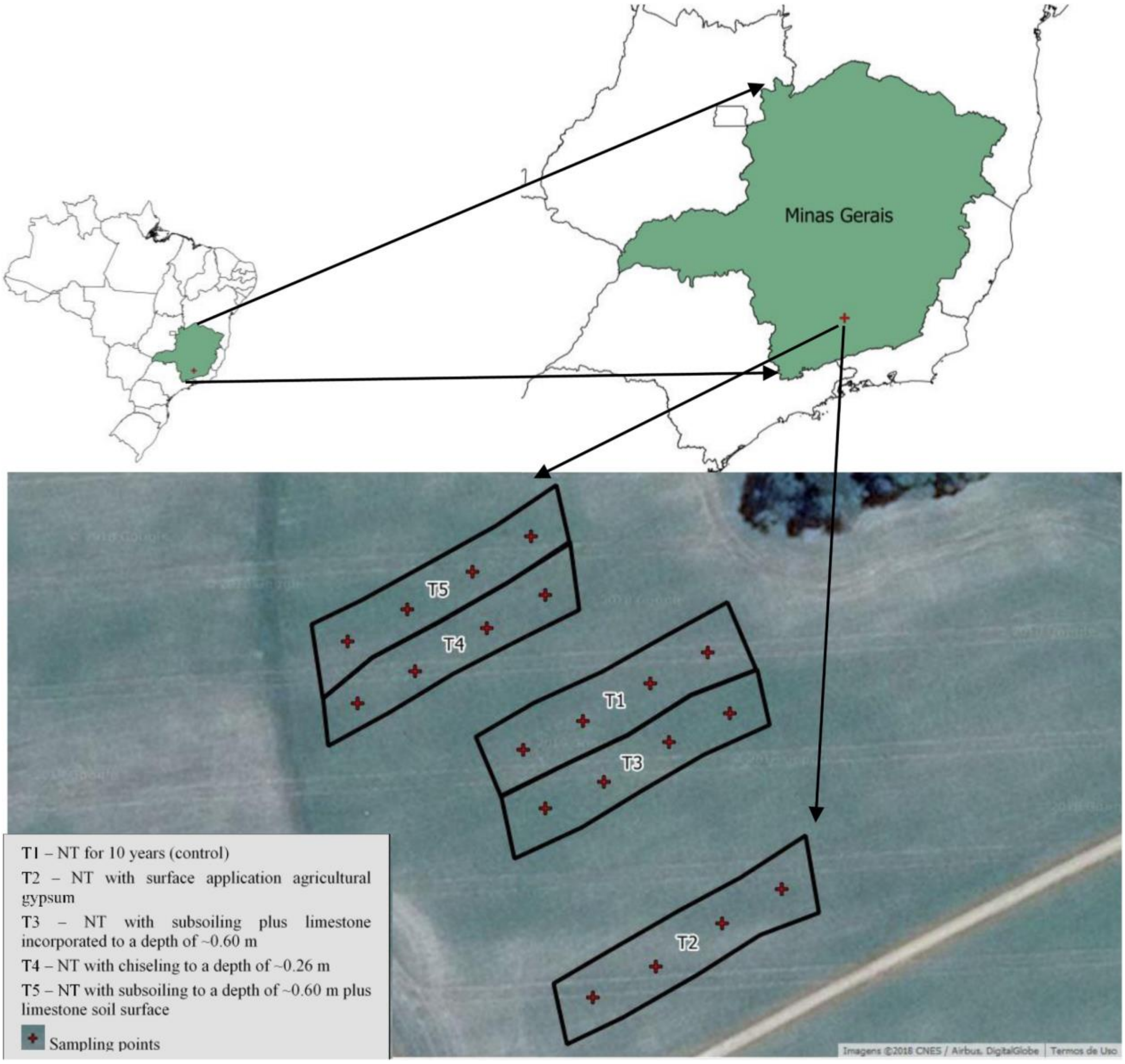


Fig. 1. Experimental layout for evaluation of mitigation strategies of soil compaction in no tillage.

The agricultural machinery used in the farm for sowing, harvesting and application of agrochemicals and fertilizers are: a John Deere® 4730 Self-Propelled Sprayer; a combined harvester New Holland® CR6080 with grain tank capacity of 9000 L; a tractor John Deere® with peak rated power of 230 hp and maximum weight of 12,650 kg; and a seeder Stara®, Princesa model, with 14 rows and two fertilizer reservoirs of 3000 kg and two seed reservoirs of 1100 kg.

The machinery used for occasional tillage were: Ikeda® subsoiler of 4 shanks with winged tips and leveling roller. Winged tips have the function to fracture the soil uniformly without lifting or furrowing the surface in excess. SAK 4 Kamaq® fertilizer subsoiler of 4 shanks with wedge shaped tip (conventional) and leveling roller. The shanks have 3 outlets for fertilizer, 0.20, 0.40 and 0.60 m. In this experiment, only the 0.60 m output was opened. Stara®

Fox chisel plowing with 5 shanks and leveling roller. The shanks have a thickness of 30 mm and maximum depth of 0.26 m.

2.2. Soil sampling and PR evaluation

For determination of PR, in March 2017 (at 1.5 years after the implantation of the treatments) soil sample rings with dimensions of 0.06 x 0.025 m (diameter and height) were collected at the depths of 0.0-0.05 m, 0.25-0.30 m, and 0.45-0.50 m in each experimental plot. Definition of these depths was made based on an initial evaluation with a dynamic penetrometer in the field, where the depth of 0.30 m proved to be physically more restrictive to the crops. The other depths were selected to make an inference regarding initial growth of the plant (0.0-0.05 m) and the effects of use of the subsoiler (0.45-0.50 m). For each experimental plot, seven undisturbed samples per depth evaluated were collected, for a total of 420 samples for the experimental area plus 21 samples for the native vegetation area, totaling 441 samples. The samples were initially prepared by removing excess soil and were then gradually saturated by capillarity. After reaching saturation, they were subjected to seven matric potentials: -0.004, -0.006, -0.010, and -0.033 MPa on an automated tension table (Ecotek®) and -0.10, -0.50, and -1.50 MPa in a Richards chamber (Klute, 1986).

After reaching equilibrium at each matric potential (-0.004, -0.006, -0.01, -0.033, -0.10, -0.50, and -1.5 MPa), the samples were weighed and tested for penetration resistance using a benchtop digital penetrometer (Marconi, MA 933), with a straight circular cone tip of 45° and 3.84 mm diameter and constant speed of 10 mm min^{-1}. The evaluation time was 2 min per sample, corresponding to a depth of 2 cm. The penetrograph stores the results of applied force (kgf) which were transformed to pressure (MPa) based on the straight circular cone dimensions. The mean PR of the middle third of the sample depth (0.66–1.33 cm) was used. Finally, the samples were oven dried at 105–110 °C for 48 h for quantification of soil water content (kg kg^{-1}).

2.3.Crop yield

In the spring-summer crop season of 2015/2016, soybean (*Glycine max* (L.) Merrill) conventional cv. VTOP was grown, and in the fall-winter season, wheat (*Triticum spp.* L.) cv. BRS 264. In the spring-summer crop season of 2016/2017, maize (*Zea mays* L.) hybrid DKB 230 PRO3 was grown, followed by common bean (*Phaseolus vulgaris* L.) cv. IPR Tuiuiú in the fall-winter crop season. Finally, soybean cv. MONSOY 5719 IPRO was grown in the spring-summer of the 2017/2018 crop season and wheat cv. BRS 264 in the fall-winter. The wheat yield in the 2016 crop season was not determined for some treatments due to loss of information from two treatments, which was thus not used in this study.

To estimate crop yield, the grain from three plant rows (length of five meters) was sampled at random from each experimental plot for soybean, maize, and common bean, and from five rows (length of five meters) for wheat. For soybean of the 2017/2018 crop season, two rows (length of five meters) were harvested. The estimated yield was corrected to 13% grain moisture and extrapolated to an area of one hectare.

2.4. Data and statistical analysis

Penetration resistance (PR) was modeled in accordance with soil water content (wc), testing five models. The models described by Eqs. (1) and (2) were proposed by Mielke et al. (1994), and model (3) was used by Busscher et al. (1997). The linear model (4) was tested due to behavior of the data of some treatments that showed little variation in PR in accordance with wc. Model (5) was selected using the software TableCurve 2D® v5.01.

$$PR = a*wc^{b} \tag{1}$$

$$PR = a*(1 - wc)^{b} \tag{2}$$

$$PR = a*exp^{bwc} \tag{3}$$

$$PR = a + b*wc \tag{4}$$

$$PR = a + b*wc*ln*wc \tag{5}$$

where PR is penetration resistance (MPa); wc is soil water content (kg kg^{-1}); and “a” and “b” are empirical parameters of fitting the models.

All the models were fitted using the “nlstools” package (Baty et al., 2015) with the R software (R Development Core Team, 2018). The Akaike Information Criterion (AIC) was used to compare the models regarding accuracy. The models were validated by the cross-validation method of “leave-one-out” using the “nlsJack” function of the “nlstools” package. The function uses the resampling procedure without reposition by the Jackknife method. Each observation was sequentially removed from the initial dataset using the leave-one-out strategy. The dataset with *n* observations provides a new resampled dataset of *n*-1 observations. After that, the residual standard error was calculated for the resampled set *n*-1 (Baty et al., 2015). The choice of the model was based on three criteria: significance of the empirical parameters of the model, lowest residual standard error using cross validation, and the lowest AIC.

After definition of the model for each treatment and depth, the confidence interval was defined using the non-parametric bootstrap resampling method. The bootstrap method does not require as many assumptions for estimation of parameters of the distributions of interest; it generally provides more accurate responses; and it does not depend on the original distribution of the data (Efron and Tibshirani, 1986). Analysis was performed using the “nlsBoot” function of the “nlstools” package. The bootstrap confidence interval was estimated by fitting each one of the 1000 resampled datasets from the original dataset to the model. When there is not convergence of at least 50% of the cases, the procedure is interrupted and no result is provided (Baty et al., 2015). In the fits made in this study, no convergence problems were detected.

To estimate the root elongation rate in accordance with PR at the matric potentials of -0.01, -0.03, -0.10, and -0.50 MPa, the empirical linear equation (Eq. 6) was used, which was developed for maize by Veen and Boone (1990) and used by Bengough et al. (2011).

$$Er = 48 + 28*\psi - 12*PR \tag{6}$$

where Er is the elongation rate (relative to the highest value found) (%), ψ is the matric potential (MPa), and PR is penetration resistance (MPa). Er was tested up to the water condition of ψ = -0.50 MPa because, according to Bengough et al. (2011), under conditions drier than this value, stress by water deficit is greater than by mechanical impedance. For ψ = -0.50 MPa, the Er values were negative for all the experimental plots. For that reason, only the Er relative to the matric potentials of -0.01, -0.03, and -0.10 MPa was plotted on the graph.

For to evaluate the soil depth that was more physically restrictive for crop development, in each treatment except native vegetation, an analysis of variance (ANOVA), using linear mixed-effects model (“lmer” function in R software), of PR was performed as a function of soil depth and treatments in each matric potential separately. The plot was included in the model as a random effect, since in the same plot samples were collected at 3 soil depths to determine PR.

The yield of the soybean (2016 and 2018), maize (2017), wheat (2018), and common bean (2017) crops were relativized based on the plot of highest yield for each crop/season. Relative grain yield was analyzed together, considering all the crops/seasons. For this, it was used the “lme4″ package through the “lmer” function in the R software. This function was used to make a linear fit with a mixed effect model, in order to obtain a combined analysis of the crop yields over the years. To do so, the crop/season was treated as the random effect, and the treatments for mitigation of soil compaction as the fixed effect.

The experimental area has soil homogeneity (Typic Hapludox), similar slope gradient, and equal cropping and management history, so a completely randomized design was used for analysis of variance. A similar statistical approach, using pseudo-replicates, was successfully used in prior studies (Shukla and Lal, 2005; Stavi et al., 2011; Cecagno et al., 2016).

We proposed a methodology for the diagnosis of soil compaction in continuous no-tillage system, aiming at the decision making for occasional tillage (chisel plowing or subsoiling, depending on the soil compacted layer depth). For this we present a definition of an ideal range of soil water content for diagnosis of compaction (IRDC), to improve penetration resistance accuracy in compaction diagnosis, introducing an Optimal Model of Penetration Resistance (OMPR). The method steps are: 1) Definition of the area of reference (AOR) in which the adopted cropping system has proved to render high yields; 2) sampling and modeling of PR ~ wc (OMPR) for the AOR; 3) evaluation of PR in the area of interest (AOI) with suspected as compacted, it must be conducted with soil moisture within the IRDC; 4) comparison of the PR values of the AOI with the OMPR as a basis for making decisions regarding occasional tillage.

3. Results and discussion

3.1. Crop yield

Relative grain yield, determined by combined analysis of four crops (soybean, maize, common bean, and wheat) in three years of crop production, for a total of five yield evaluations, is shown in Fig. 2. The no-tillage system involving subsoiling and application of additional limestone on the surface (T5) and the treatment with chisel plowing (T4) led to higher crop yields over the 3 years of evaluation in comparison to the no-tillage system without mechanical intervention (T1) and with application of gypsum (T2). The treatment with subsoiling and limestone application at the depth of 0.60 m (T3) did not differ from the other treatments. Thus, the results indicate that occasional tillage promotes improvement of soil physical conditions, possibly by increasing soil porosity and reducing bulk density and penetration resistance (Blanco-Canqui and Ruis, 2018), alleviating soil structural conditions, and that may provide conditions for increasing crop yields. Subsoiling did not differ from the treatment involving chisel plowing, even though subsoiling was associated with the application of additional limestone, on the surface or at depth.

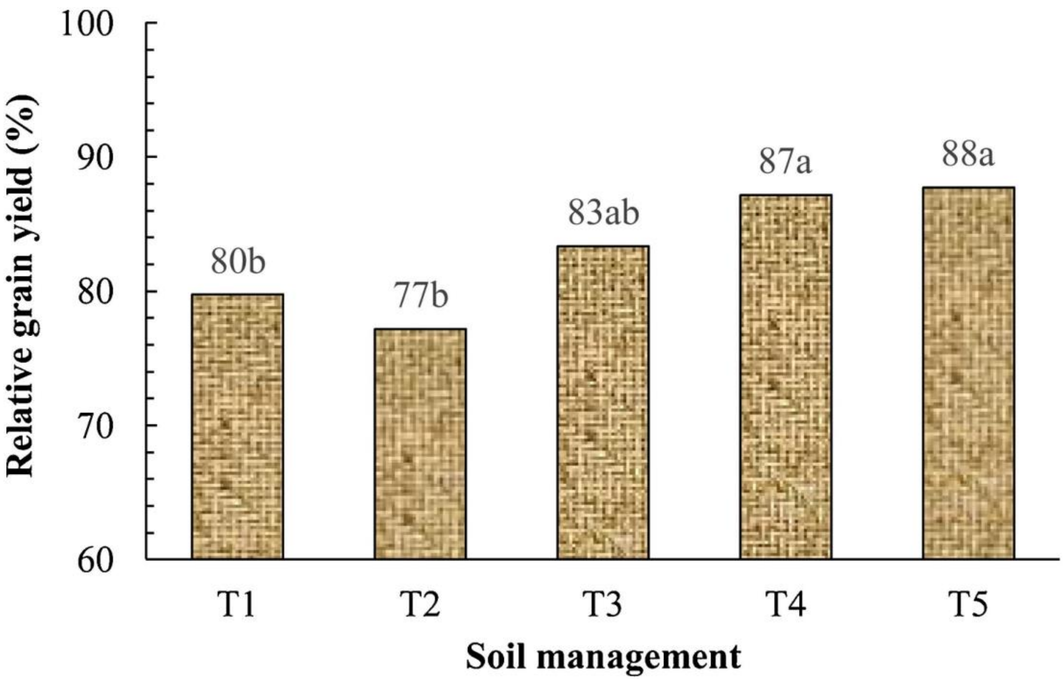


Fig. 2. Relative grain yield (yield/yield max) due to soil management aiming to ameliorate soil compaction. Four crops (soybean, corn, wheat and dry beans) in three years of evaluation, totaling five grain harvests ($n = 112$). Mean values followed by the same letter do not differ from each other according to Tukey's test ($p \leq 0.05$). T1 – NT for 10 years (control); T2 – NT with surface application gypsum; T3 – NT subsoiling plus limestone incorporated to a depth of 0.60 m; T4 – NT planting following chisel plowing at a depth of ~0.26 m; and T5 – NT subsoiling to a depth of 0.60 m plus limestone applied on surface.

Among the treatments with use of subsoiling, the greater yield in the treatment with application of additional limestone on the surface in relation to the control might have the following explanations. Differences between the subsoilers (T3 – Kamaq© fertilizing subsoiler – wedge shaped tip; T5 – Tandem Ikeda© subsoiler – winged tips) regarding mechanical action on the soil. Additional application of limestone on the surface when acidity in the surface layer is already lower promotes an increase in pH and reduction in Al3+ in deeper soil layers (Caires et al., 2008) (Table A, supplementary material). The limestone applied at depth (0.60 m) had not yet completely solubilized after 3 years, and vestiges of it at the depth it was applied could be observed, this is because the limestone needs to be mixed into the soil to speed up its reaction, which does not happen when it is placed in deep layers of soil. Under an adequate water supply, plant root growth is concentrated in the soil surface layer (Hoogenboom et al., 1987; Merrill et al., 2002), a condition observed in the three years of crop production in this experiment (Fig. 3). Furthermore, it was found that, on average, around 70% of the root length of wheat (Caires et al., 2008) and maize (Caires et al., 2002) and 90% of the root length of soybean (Pivetta et al., 2011) occur in the 0.0-0.20 m soil layer, and the rest in the subsoil layers (0.20-0.6 m) in areas of the no-tillage system.

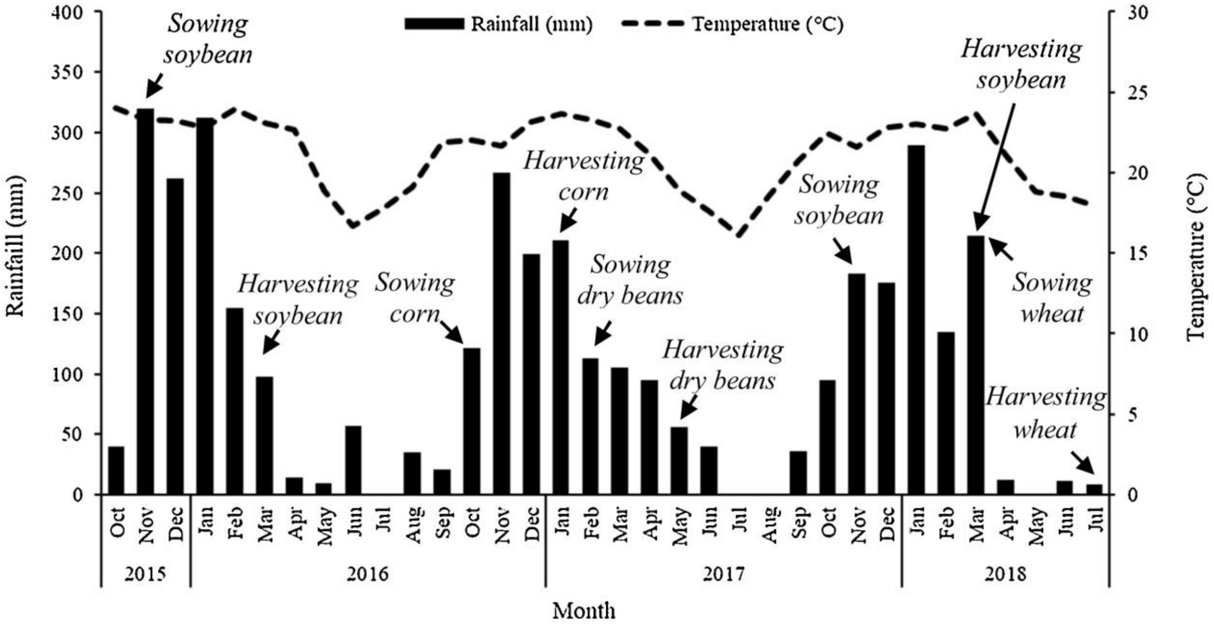


Fig. 3. Monthly average rainfall and temperature for the 2016/2017/2018 period.

The mean soybean yield in the 2015/2016 crop season for the treatments with occasional tillage (T3, T4, and T5) was 4548 kg ha^{-1}; without occasional tillage (T1 and T2), the yield was 3906 kg ha^{-1}. In the 2017/2018 crop season, the treatments with occasional tillage had a mean yield of 4978 kg ha^{-1}, and those without this tillage yielded 4704 kg ha^{-1}. These yields were much higher than the Brazilian average of the 2016/2017 crop season, 3364 kg ha^{-1} (Conab, 2018). Maize had a mean yield of 14,560 kg ha^{-1} in the treatments with occasional tillage and 13,604 kg ha^{-1} without this tillage in the 2016/2017 crop season. These values are nearly triple the mean Brazilian yield for that period, 5556 kg ha^{-1} (Conab, 2018). Black common bean showed similar yield under the two conditions, 1851 kg ha^{-1} in the treatment without occasional tillage and 1863 kg ha^{-1} with occasional tillage, values a little higher than the mean Brazilian average for 2017, which was 1338 kg ha^{-1} (Conab, 2018). Wheat in the 2018 season had a yield of 2169 kg ha^{-1} in the area without occasional tillage and 2656 kg ha^{-1} in the area with occasional tillage, higher than the Brazilian average, which was 2225 kg ha^{-1}. These results confirm that, in general, there was compaction in the area of continuous NTS, which limited grain yield. The occasional tillage performed in 2015 resulted in improved yield considering the combined effect on the five subsequent harvests.

There was no significant effect of the additional application of limestone and gypsum on Ca and Mg contents, base saturation, pH and Al (Table A, supplementary material). Therefore, the increase in crop yield was due to improved soil physical conditions. Therefore, adequate diagnosis of compaction must be clarified as a basis for decision making for the future.

3.2. Penetration resistance in the soil profile

In general, PR was greater in the 0.25 – 0.30 m, followed by the 0.00 – 0.05 m layer, and the lowest PR occurred in the 0.45 – 0.50 m layer, regardless of matric potential (Table 1), and especially for the control treatment (T1). There were some differences for the other treatments, due to the alleviation of the soil structure in soil depth by the occasional tillage. The depth of the soil compaction under continuous NTS varied with the history of soil use and management, and, for clayey soils, it has been noted from around a 0.07 to 0.20 m depth (Reichert et al., 2009a; Farooq et al., 2011; Nunes et al., 2014a, 2015). Soil compaction is characterized by high PR and soil bulk density and low permeability to air and to water. In the experimental area, for setting up the NTS, the soil was tilled twice with a heavy disk to incorporate limestone to a depth of 0.30 m, which helps explain the greater compaction in this layer. This compaction is associated with machine traffic over the years, which exercises pressure on the soil surface layer. Pressures measured in the area of tire/soil contact can be transmitted, nearly completely, to a depth of 0.30 m (Lamandé and Schjønning, 2011).

Table 1. Penetration resistance as a function of treatments and soil depth in each matric potential in Oxisol after methods to ameliorate soil compaction under continuous no-tillage system.

Depth (m)	Treatments T1	T2	T3	T4	T5
			Matric Potential -0.004 MPa		
0.00 – 0.05	0.72 bB	0.42 aA	0.23 aA	0.54 bA	0.58 bA
0.25 – 0.30	0.91 bB	0.51 aA	0.68 bB	0.54 aA	0.64 aA
0.45 – 0.50	0.34 aA	0.44 aA	0.44 aA	0.45 aA	0.46 aA
			Matric Potential -0.006 MPa		
0.00 – 0.05	0.58 aA	0.31 aA	0.40 aA	0.72 aA	0.35 aA
0.25 – 0.30	0.61 aA	1.18 bB	0.82 aB	0.34 aA	0.66 aA
0.45 – 0.50	0.63 aA	0.54 aA	0.32 aA	0.45 aA	0.51 aA
			Matric Potential -0.01[†] MPa		
0.00 – 0.05	0.63 aA	0.43 aA	0.42 aA	0.55 aA	0.81 aB
0.25 – 0.30	1.57 bB	1.18 bB	1.10 bB	0.99 aB	0.91 aB
0.45 – 0.50	0.76 aA	0.65 aA	0.50 aA	0.49 aA	0.48 aA
			Matric Potential -0.033 MPa		
0.00 – 0.05	1.36 bA	0.94 aA	0.81 aA	0.65 aA	2.20 aB
0.25 – 0.30	2.39 bB	0.91 aA	1.14 aB	1.47 aB	1.82 bB
0.45 – 0.50	0.66 aA	0.88 aA	0.64 aA	0.74 aA	0.88 aA
			Matric Potential -0.10 MPa		
0.00 – 0.05	2.11 bA	2.04 bB	0.59 aA	1.86 bA	1.87 bA
0.25 – 0.30	3.14 bB	1.50 aB	1.92 aB	1.73 aA	2.20 aA
0.45 – 0.50	1.15 aA	0.55 aA	0.75 aA	1.31 aA	1.35 aA
			Matric Potential -0.50 MPa		
0.00 – 0.05	1.85 aA	1.39 aA	1.14 aA	1.33 aA	2.12 aA
0.25 – 0.30	3.51 bB	3.80 bB	2.48 bA	2.12 aA	2.74 bA
0.45 – 0.50	1.73 aA	1.34 aA	1.59 aA	0.92 aA	1.75 aA
			Matric Potential -1.50 MPa		

0.00 – 0.05	2.20 aA	2.11 aA	1.03 aA	2.11 aA	2.04 aA
0.25 – 0.30	3.39 bB	3.80 bB	2.17 aA	3.39 bB	2.13 aA
0.45 – 0.50	1.42 aA	1.89 aA	1.34 aA	2.12 aA	1.23 aA

Means followed by the same lowercase letter in the line do not differ significantly from the control (T1) according to Dunnett test ($p < 0.05$) and same capital letter in column do not differ significantly from the soil depth (0.25 – 0.30 m), considered control, according to Dunnett test ($p < 0.05$). N = 360. † soil matric potential at field capacity. The matric potential was not used as a factor in the linear mixed-effects model.

Lower PR in the 0.0-0.05 m layer compared to the 0.025-0.030 m layer is related to depositing and maintaining straw from crop residue on the surface, especially when the crop has greater population density, as in wheat, culminating in greater organic matter content in the first centimeters of the soil (Table A, supplementary material). Soil mobilization (0.0-0.10 m) also occurs in this layer due to sowing operations (Santos et al., 2008; Nunes et al., 2014b). Increases in soil organic matter can reduce soil compactibility by increasing resistance to deformation and/or by increasing elasticity (rebound effects), even in response to small increases in the amount of organic matter (Soane, 1990; Ekwue and Stone, 1995; Zhang et al., 1997). This happens because living or dead roots provide a filamentous network which resists compactive loads. Fungal hyphae have a similar action, especially within aggregates. Highly humified organic matter increases the stability and strength of aggregates, and hence decreases compactibility (Soane, 1990).

At the 0.45-0.50 m depth, the lower PR under all evaluated conditions is related to the lower transmission of pressures to deeper layers (Dexter et al., 1988; Lamandé and Schjønning, 2011) and to the microgranular structure of this soil (Ajayi et al., 2009a, b; Lamandé and Schjønning, 2011; Mazurana et al., 2017) due to the higher content of aluminum and iron oxides (gibbsite, hematite and goethite), which favor the formation of highly stable aggregates.

Except for the matric potential of -0.006 MPa, the control treatment (T1) presented higher PR at the soil depth of 0.25-0.30 m. PR is only considered restrictive to root development of crops (> 2.0 MPa) when evaluated at a matric potential ≤ -0.033 MPa (Table 1). Furthermore, the greatest differences between treatments with and without occasional tillage occur in the matric potential range of -0.033 and -0.50 MPa. Thus, it is important to evaluate PR at a moisture condition drier than the field capacity, highlighting differences between treatments and improving the soil compaction diagnosis in continuous no-tillage systems.

However, due to the great influence of the soil water content in PR, even at the same matric potential, it is suggested to correct PR for the same water content in order to compare treatments (Busscher et al., 1997; Vaz et al., 2011). Nevertheless, the best way is to model PR as a function of the soil water content and to perform the comparison of treatments by the confidence interval of the respective models, as presented in the next section. This allows comparison of PR between treatments in any chosen soil water content (Imhoff et al., 2000).

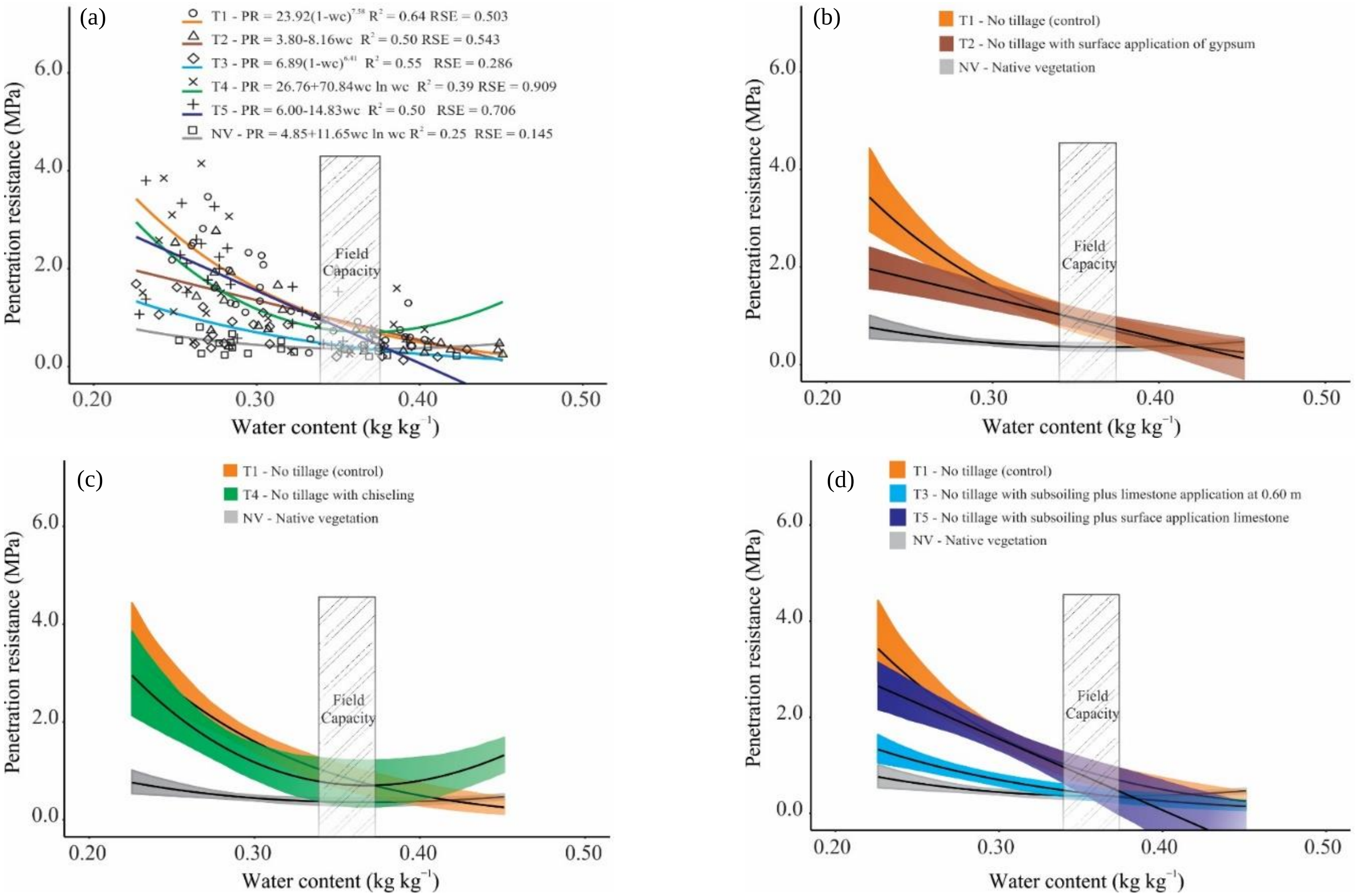
3.3. Modeling penetration resistance in accordance with soil water content

The models fitted for PR in accordance with soil water content and their respective confidence intervals are shown in Fig. 4. Based on the criteria chosen, three models exhibited best fit for each treatment and depth. In the 0.0-0.05 m layer, model (2) fit the data from T1 and T3, model (4) fit the data from T2 and T5, and model (5) fit the data from T4 and the reference area with native vegetation. For the 0.25-0.30 m layer, model (5) best fit the data from T1, T2, T4, and native vegetation. Models (4) and (5) fit the data from T3 e T5, respectively. Model (2) exhibited the best fit for all the treatments in the 0.45-0.50 m layer. The indicators of accuracy (R2) and of validation (RSE) of the best models are shown in Fig. 4a, e, and i, and Table B (supplementary material).

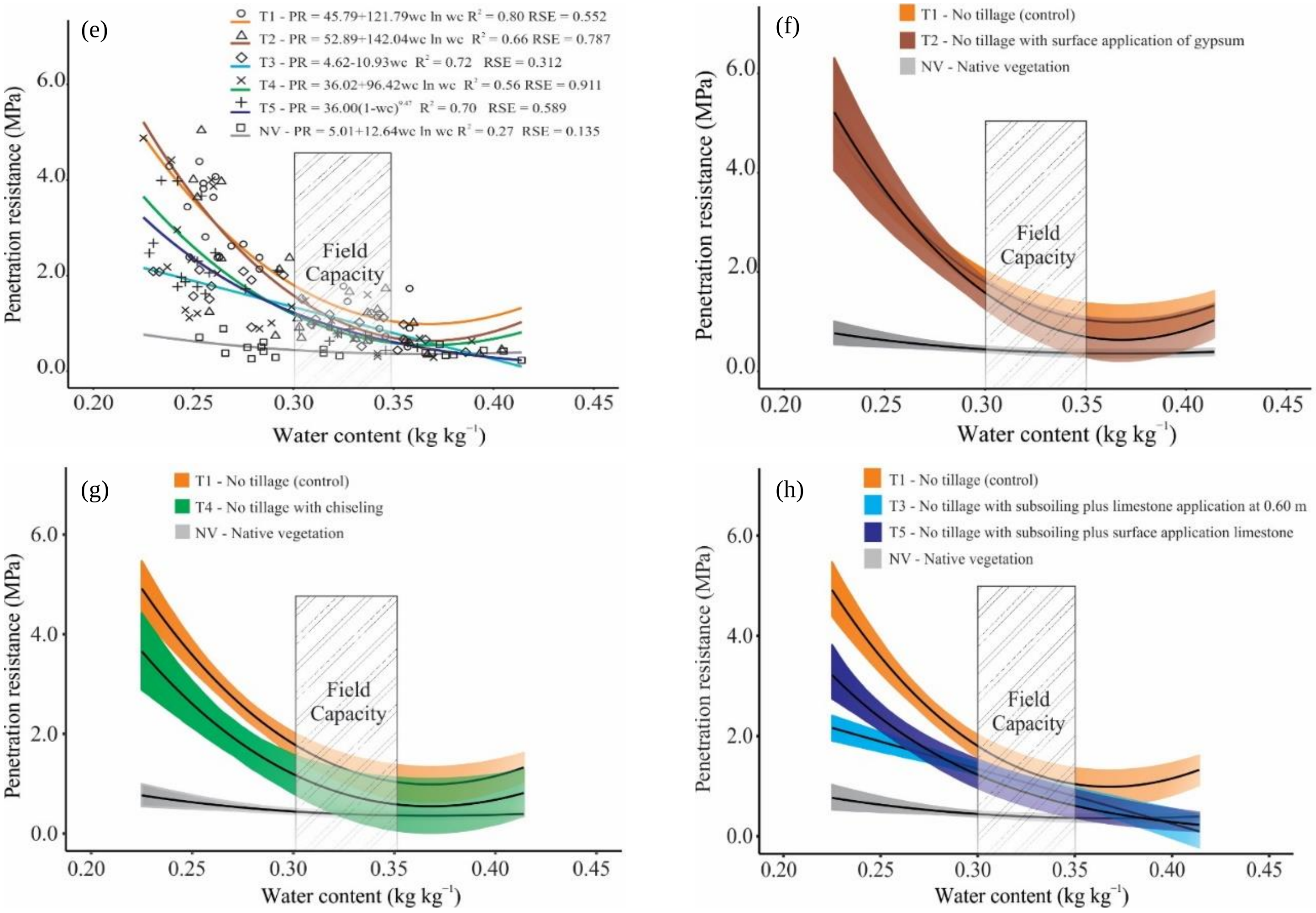
The different behaviors of the models for fit among treatments indicate that the soil management system modifies the relationship between PR and the soil water content. Therefore, it was not possible to obtain only one model for this relationship. This is explained by the adoption of empirical models in which not all the factors associated with PR are considered. Therefore, due to the impossibility of comparing the coefficients of the models in some cases, the models were compared by bootstrap confidence interval. The reference area with native vegetation exhibited the lowest increase in PR from reduction in soil water content (Fig. 4a, e, i). In contrast, the management practices that promoted the greatest soil compaction (T1 and T2) exhibited a greater increase in PR from reduction in soil water content, especially in the most compacted layer, 0.25-0.30 m.

The greater the soil water content, the smaller the differences in PR were among treatments, including for the cropped areas in relation to the native vegetation area. In soil water content at field capacity, the condition recommended for measurements of PR for the purpose of diagnosing soil compaction (Arshad et al., 1996; Lowery and Morrison, 2002; Vaz et al., 2011), differences did not occur among treatments, which indicates the absence of compaction in the continuous NTS. Nevertheless, as shown before, occasional tillage (T4 and T5) led to a significant increase in grain yield (Fig. 2) in relation to continuous NTS (T1 and T2), showing that compaction was present and was mitigated.

Depth of 0.0 – 0.05 m



Depth of 0.25 – 0.30 m



Depth of 0.45 – 0.50 m

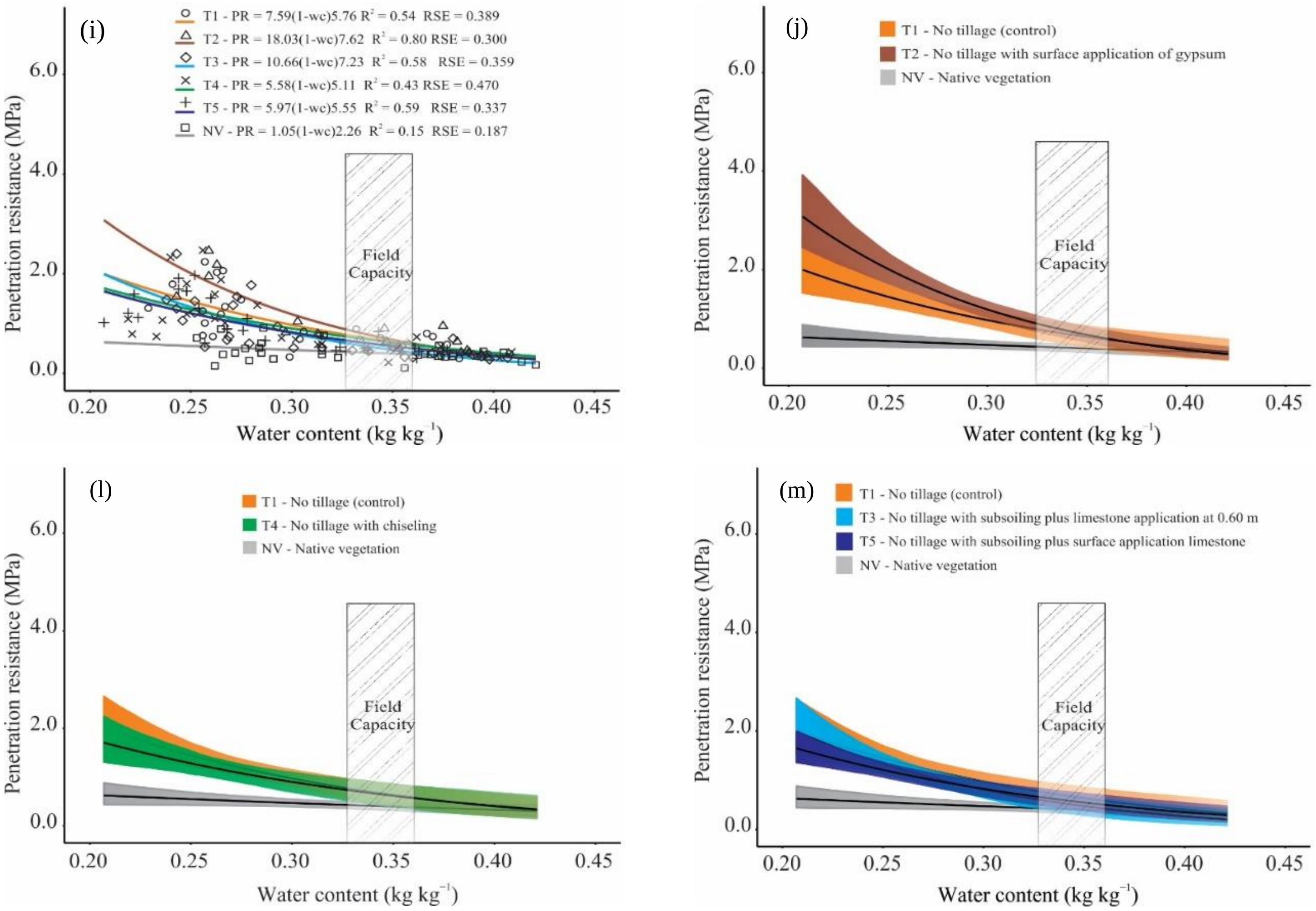


Fig. 4. Penetration resistance models as a function of soil water content for three soil layers managed with soil compaction mitigation methods in a continuous no-tillage area. The colored area represents the 95% bootstrap confidence interval. The field capacity (estimated by the soil moisture retained at -0.01 MPa) was plotted using the mean ± standard deviation.

Determination of PR at field capacity has been recommended due to the penetrometer overestimating the resistance offered by the soil to root elongation by two to eight times, explained by greater friction at the soil-metal interface in relation to friction between the soil and the plant roots (Bengough et al., 1997). Thus, the PR determined under dry conditions, where the forces of friction are high, would have little significance for studies on crop production, supporting the idea of conducting measurements of PR from 0 to -0.01 MPa (Vaz et al., 2011). Nevertheless, the differences in PR among the management practices that led to the highest crop yields (T4 and T5) and to the lowest (T1 and T2) only occurred at soil water content below field capacity (Fig. 4).

Previous studies have corroborated our results, showing that the PR determined in soil with water content near field capacity is not adequate as an indicator of the degree of soil compaction, especially in comparison among management systems (Reinert et al., 2001; Assis et al., 2009; Moraes et al., 2012, 2013; Bölenius et al., 2018; Catania et al., 2018). Moraes et al. (2013) suggested making measurements of PR under the friable soil condition, and Assis et al. (2009) under the condition of soil with low soil water content; however, they did not establish values. Bölenius et al. (2018) suggested that for studies that aim at identifying areas with problems of limitation of crop yield using PR, measurements should be made at soil water content drier than field capacity.

Studies on the use of PR in diagnosis of the physical conditions of the soil at different phases of the crop growing season (Reichert et al., 2009b; Reinert et al., 2001; Moraes et al., 2013; Catania et al., 2018) highlight that only under low soil water content conditions was it possible to observe the effects of soil management (below field capacity), which is also in agreement with our results. Therefore, the diagnosis of soil compaction by means of PR considering soil water content requires deeper study.

3.4. Proposal of an ideal range of soil water content in diagnosis of compaction under continuous NTS

Estimation of the root elongation rate in accordance with PR at the matric potentials of -0.01, -0.03, and -0.10 MPa is shown in Fig. 5a. The elongation rate at the matric potential corresponding to field capacity (-0.01 MPa) was reduced from 10% to 20% depending on the treatment, with the PR ranging from 0.8 to 1.1 MPa. From the matric potential of -0.03 MPa on in the T1 treatment, the PR was higher than 2 MPa and the root elongation rate decreased to half. At the potential of -0.10 MPa, the T1, T4, and T5 treatments led to reduction from 60% to

95% in the root elongation rate, with PR values from 2.3 to 3.6 MPa. At matric potential ≥ -0.50 MPa, there was no root growth. Thus, only in conditions drier than field capacity was PR greater than 2.0 MPa, the value frequently used as an indicator of compaction (Arshad et al., 1996; Bengough et al., 2006) through bringing about large (50% to 70%) mechanical impedance to root elongation (Taylor et al., 1966; Bengough et al., 2011).

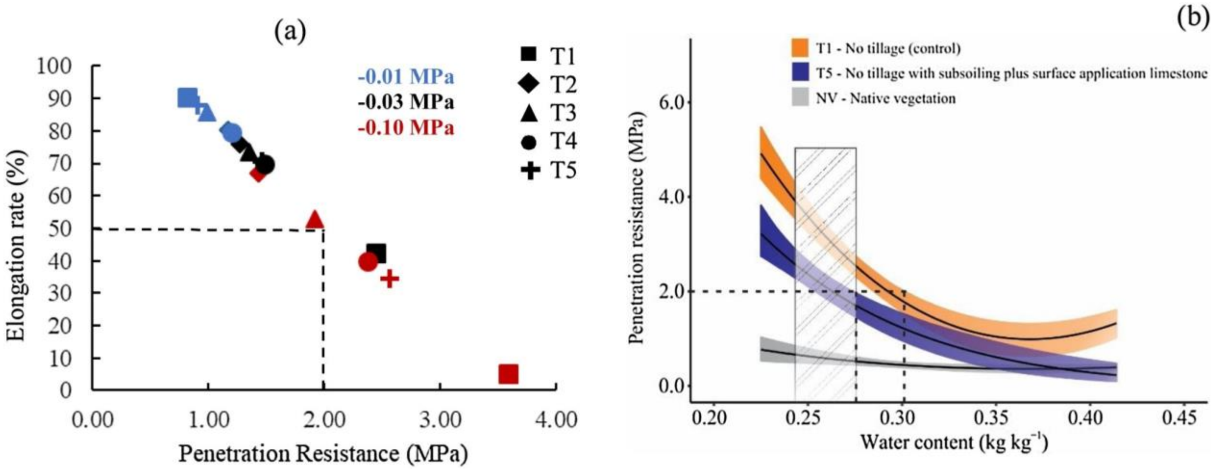


Fig. 5. a) Estimation of the elongation rate (relative to the maximum value) as a function of the penetration resistance (matric potentials of -0.01, -0.03 and -0.10 MPa). b) Ideal range of moisture content for diagnosis of soil compaction diagnosis (IRDC), comparing treatments with contrasting yields.

Several observations were made considering soil with soil water content drier than field capacity. There was significant reduction in root elongation for PR =2 MPa (Fig. 5a). Soil with lower moisture content allowed greater distinction of management practices through PR (Fig. 4), in agreement with previous observations in the literature already reported above. Mechanical impedance can lead to considerable limitation for root growth at a matric potential close to -0.10 MPa, due to the increase in effective tension among the soil particles (Whalley et al., 2005). Root elongation is reduced to half at soil water content lower than -0.50 MPa in the absence of mechanical impedance (Bengough et al., 2011). All these considerations lead to a proposal for definition of an ideal range of soil water content for diagnosis of compaction (IRDC) in soils under a continuous no-till system (Fig. 5b). The IRDC should comprise soil water content corresponding to the matric potential range from -0.03 to -0.5 MPa, preferentially with measurement of PR near -0.10 MPa as an initial suggestion, corroborating previous use of this criterion (Grant et al., 2001; Melo Filho et al., 2007, 2009).

Comparison of the PR models in accordance with soil water content for the treatments that exhibited contrasting grain yields, T1 and T5, showed that in the IRDC the PR in T1 ranged from 2.4 to 4.2 MPa, whereas in T5, it ranged from 2.0 to 2.5 MPa (Fig. 5b). The statistical differences in the models allowed diagnosis of compaction, a diagnosis that is not possible at field capacity. Regarding the use of the critical value of RP =2 MPa, this was exceeded in the continuous NTS when analyzing the IRDC, which is consistent with that suggested in the literature for the diagnosis of compaction. Nevertheless, this critical value varies considerably according to soil water content (as shown in Fig. 5b). Furthermore, in continuous NTS, the presence of biopores provides alternative routes for root growth, reducing stress by mechanical impedance (Lampurlanés and Cantero-Martinez, 2003; Bengough et al., 2011; Moraes et al., 2014a; Calonego et al., 2017; Blanco-Canqui and Ruis, 2018), and each plant has specific features for example, cereals are less sensitive to soil compaction under reduced tillage than dicotyledons (Arvidsson et al., 2014), mainly due to the differences in their root system, nutrient uptake and water use efficiency. Therefore, consideration of this critical value requires further investigation, which was not the aim of this study.

3.5. Proposal of a methodology for diagnosis of compaction in continuous NTS

Diagnosis and monitoring of soil compaction should consider a reference area with high yield and the yield history of crops on the property. In addition, analysis must be made if low yield in relation to the reference area might be related to problems of climate, pests and/or diseases, soil fertility, and requirements of specific cultivars, among others. If these possibilities are excluded, the PR can be used for diagnosis of a possible compaction problem, assisting in decision making regarding occasional tillage.

In a study conducted by the Brazil Strategic Soybean Committee (Comitê Estratégico Soja Brasil - CESB) evaluating 47 agricultural areas in the states of GO, MG, MT, PR, RG, and SP, the locations with soybean yields greater than 70 bag ha^{-1} or 4200 kg ha^{-1} (49% of the total evaluated), considered as high yielding, exhibited PR from 0.9 to 1.7 MPa up to a depth of 0.40 m, evaluated at field capacity (Sako et al., 2015). Thus, diagnosis and monitoring of soil compaction with use of PR aiming at making decisions regarding application of mitigating measures should consider the conditions of soil impedance of areas or fields that have high yields as a reference.

The methodological proposal of diagnosis of soil compaction in a continuous NTS area should consist of the following steps: 1) definition of the area or field of reference; 2) sampling and determination of the model of PR ~ wc (Optimal Model of Penetration Resistance - OMPR) for the reference area; 3) sampling of PR in the area suspected as compacted; 4) comparison of the PR values of the area suspected as compacted with the OMPR as a basis for making decisions regarding occasional tillage.

The reference area should be high yielding for the production system of the property or of the experimental area, and the PR of these areas should be lower than 2 MPa to a depth of 0.40 m, evaluated at field capacity, since there are no standard values of PR for soil water content within the IRDC in high yield areas.

In the reference area, the PR should be modeled in accordance with soil water content for the layer that exhibits highest PR, establishing the confidence interval of the model. Sampling can be performed in situ, for example, with the use of a dynamic penetrometer and concomitant determination of soil water content, or in the laboratory, by collecting undisturbed samples and placing the samples under different matric potentials and determining PR. In the case of in situ sampling, this should be performed in soil from high water content (soon after an intense rain) up to the driest condition possible, near the permanent wilting point (matric potential of -1.5 MPa). In this case, the soil water retention curve of the study area should be available to evaluate the range of matric potential that the sampling was able to encompass. For determination of PR in the laboratory, undisturbed samples should be collected in the soil layer that an initial analysis with a field penetrometer diagnoses as having the highest PR, and then these samples should be taken to be subjected to variation of matric potential from -0.004 to -1.50 MPa, determining the PR and the soil water content at each matric potential.

The literature shows that the minimum number of samples for determination of PR necessary to create the model for a homogeneous area or field, adopting a mean error of 10%, would be from 15 to 20 (Tavares Filho and Ribon, 2008; Molin et al., 2012; Storck et al., 2016). However, this may vary, depending on the type of soil, tillage practices, and type of penetrometer used (Alesso et al., 2017). The model that best fits the data should be supported by statistical parameters, such as lowest AIC and residual standard error (RSE) and the highest coefficient of determination (R^2). The confidence interval can be determined by different methods; however, due to the advantages already reported, the bootstrap confidence interval is suggested.

The survey of PR and concomitant soil water content in the soils suspected as compacted can be performed in situ or in the laboratory, as described for creating the OMPR. Nevertheless, this survey should be performed with soil water content within the IRDC, preferentially near the matric potential of -0.10 MPa. Monitoring of soil water content to define the suitable time for surveying the PR, i.e., within the IRDC, can be carried out by use of a soil probe and later determination by the laboratory oven method, or through the use of tensiometers and soil moisture sensors (the latter being duly calibrated). A minimum of 15–20 determinations is suggested, analogous to that used for the OMPR. The area to be diagnosed and the reference area should be in the same soil class.

After modeling and definition of the confidence interval in the reference area and surveying in the areas suspected as compacted, the criterion for making a decision regarding occasional tillage should be based on the OMPR (Fig. 6). The criteria and the model presented here were conceived based on the model of load bearing capacity proposed by Dias Junior et al. (2005). The model is divided into three regions: (a) Compacted: region where more than 70% of the surveys of PR of the area suspected as compacted are greater than those of the upper confidence interval of the OMPR, with PR higher than that considered optimal for high crop yields – therefore, where there are soil compaction problems with a possible negative effect on yield, with occasional tillage being recommended in the area. (b) Non-compacted: region where more than 70% of the surveys of PR are within the lower and upper confidence interval of the OMPR, with optimal PR for high crop yields, without soil compaction, and therefore where occasional tillage would not be recommended. (c) Non-compacted: region where more than 70% of the surveys of PR are below the lower confidence interval, indicating a non-compacted area.

The definition that more than 70% of the surveys of the area suspected as compacted be in one of the three regions of the OMPR for classification and making decisions regarding occasional tillage was based on mean spatial variability (12% < CV < 60%) (Warrick and Nielsen, 1980) of the PR in areas of continuous no-till (Souza et al., 2001; Silva et al., 2004). Compiling the results of spatial variability of the PR of these studies, a coefficient of variation between 15% and 44% and a mean value of 28% were observed.

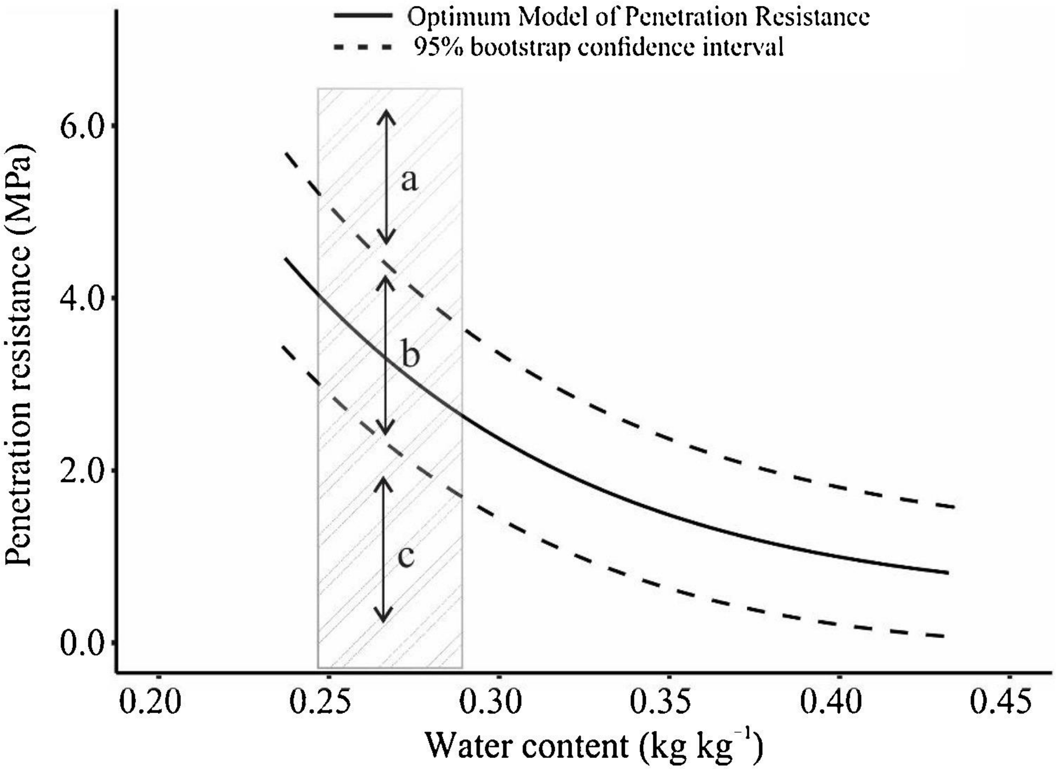


Fig. 6. Optimum Model of Penetration Resistance showing regions (a), (b) and (c) used as criteria for decision making on mechanical intervention to mitigate compaction in no-tillage system. The hatching area represents the ideal range of soil water content for the diagnosis of compaction (IRDC) using the penetration resistance. Adapted from Dias Junior et al. (2005).

3.6.Application of the compaction diagnosis method in continuous NTS

An example of application of the method proposed is presented in Fig. 7, in which the treatment of highest yield (T5) was used as a reference model (OMPR) and the treatment under continuous NTS (T1) as the area to be diagnosed. The PR at the soil water content corresponding to the IRDC at the depth of greatest PR (0.25 – 0.30 m) was used. Of the results of PR in accordance with soil water content for T1, only 12 values were within the IRDC and were used in application of the model. Eleven values (92%) of PR fell in region (a) and only one (8%) in region (b) (Fig. 7). Thus, the area in reference to T1 is compacted and occasional tillage, subsoiling (T5), or chisel plowing (T4) would thus be recommended to reduce compaction and increase crop yield (Fig. 2).

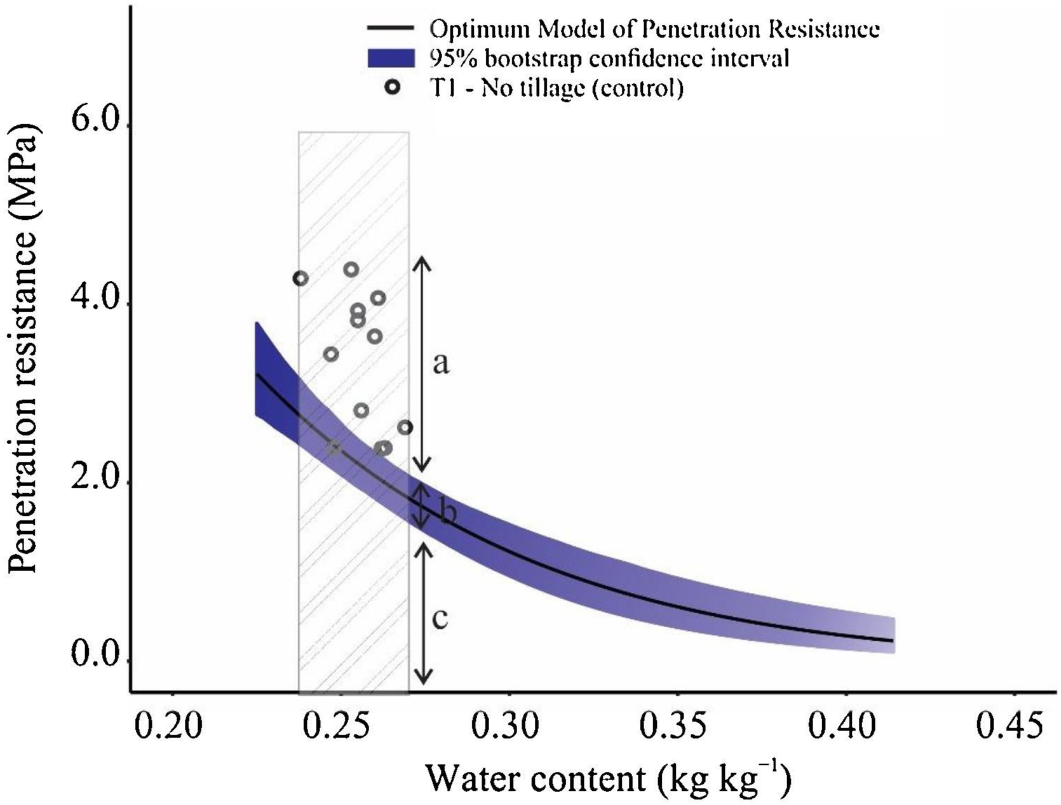


Fig. 7. Soil compaction status in no-tillage area, aiming at decision making on the use of mitigation methods applying the optimum model of penetration resistance (MRPO). The hatching area represents the soil water content range ideal for the diagnosis of compaction using PR (IRDC).

4. Considerations concerning the proposed method

- The use of the same piece of equipment for modeling the reference area and for surveying the area suspected as compacted is recommended. The angle of the cone, the diameter and roughness, and the penetration rate of the penetrometer are factors that affect determination of PR (Lowery and Morrison, 2002; ASABE, 2006). Use of the dynamic penetrometer is suggested, since studies have shown greater correlation of PR with soil bulk density when this apparatus is used compared to the static penetrometer (Roboredo et al., 2010; Molin et al., 2012; Vogel et al., 2017), indicating that the dynamic penetrometer may be more sensitive for diagnosis of compacted layers (Moraes et al., 2014b).

- The proposed method may be carried out using only field evaluations. Thus, future studies are suggested with the aim of obtaining OMPR with a dynamic penetrometer and moisture sensor or tensiometer. In an analogous manner, soil monitoring aiming to identify IRDC and use of probing for diagnosis of compaction need to be evaluated. For that purpose, the use of tensiometers may increase the ease and speed of diagnosis.

- The proposed method does not assume a critical PR value as a criterion for diagnosis of compaction and assistance in making decisions regarding occasional tillage. Crops have specific levels of susceptibility to soil compaction, and greater sensitivity of dicotyledonous species has been reported (Arvidsson et al., 2014). PR lower than 2.0 MPa was used as a critical limit in definition of the reference area; however, crop yield, the specific aspects of soils, the climate, and local management practices were also considered because they are factors that affect the PR value and, consequently, the diagnosis of compaction.
- Studies using the method under different conditions of soil types, management practices, and climate conditions are recommended to validate the proposal.

5. Conclusions

Occasional tillage with subsoiling or chisel plowing in continuous NTS led to an increase in grain yield in 3 years of subsequent harvests in a soybean/maize crop rotation in the spring-summer season followed by common bean/wheat in the fall-winter season. Given this information, areas under continuous NTS and those with occasional tillage were investigated regarding penetration resistance, modeled in accordance with soil water content through the use of different equations, which led to the conclusion that use of a single model for the different conditions was not feasible. The best models showed that the ideal range of soil water content for diagnosis of soil compaction (IRDC) in an area of continuous no-tillage should be between the matric potentials of -0.03 and -0.50 MPa, preferentially -0.10 MPa as an initial suggestion, and not at field capacity as is currently suggested.

A method was proposed for diagnosis and monitoring of soil compaction in areas of continuous NTS with restricted grain yield with the aim of making decisions regarding occasional tillage. In this method, a model of PR in accordance with soil water content and its respective confidence interval should be developed for a reference area with high yield (OMPR). Surveys (in the areas suspected as compacted) through PR determined within the IRDC are compared to the OMPR for diagnosis of compaction and as support for making decisions regarding the use of mitigation methods, with the expectation of increasing yield in subsequent crops. An example using the data of the present study was tested and was successful.

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7. References

Ahmad, M., Abdullah, H., Iqbal, M., Umair, M., and Ghani, M., 2010. Effect of deep tillage on soil properties and crop (wheat) yield. Soil Environ. 29, 177-180.

Ajayi, A.E., Dias Júnior, M.S., Curi, N., Araújo Júnior, C.F., Souza, T.T.T., Inda Júnior, A.V., 2009a. Strength attributes and compaction susceptibility of Brazilian Latosols. Soil Tillage Res. 105, 122-127. https://doi.org/10.1016/j.still.2009.06.004

Ajayi, A.E., Dias Júnior, M.S., Curi, N., Gontijo, I., Araújo Júnior, C.F., Inda Júnior, A.V., 2009b. Relation of strength and mineralogical attributes in Brazilian Latosols. Soil Tillage Res. 102, 14-18. https://doi.org/10.1016/j.still.2008.05.013

Alesso, C.A., Masola, M.J., Carrizo, M.E., Imhoff, S.C., 2017. Estimating sample size of soil cone index profiles by bootstrapping. Rev. Bras. Cienc. Solo. 41, e0160464. https://doi.org/10.1590/18069657rbcs20160464

Arshad, M.A., Lowery, B., Grossman, B., 1996. Physical tests for monitoring soil quality. In: Doran, J.W., Jones, A.J. (Eds.), Methods for assessing soil quality. Soil Science Society of America, Madison, pp. 123-141 (SSSA Special Publication 49).

Arvidsson, J., Etana, A., Rydberg, T., 2014. Crop yield in Swedish experiments with shallow tillage and no-tillage 1983–2012. Europ. J. Agronomy. 52, 307-315. https://doi.org/10.1016/j.eja.2013.08.002

ASABE. American Society of Agricultural and Biological Engineers., 2006. Procedures for using and reporting data obtained with the soil cone penetrometer. Saint Joseph, pp. 1052-1055. (ASABE standard: ASAE EP542 FEB99).

Assis, R.L., Lazarini, G.D., Lancas, K.P., Cargnelutti Filho, A., 2009. Avaliação da resistência do solo à penetração em diferentes solos com a variação do teor de água. Eng. Agríc. 29, 558-568. https://doi.org/10.1590/S0100-69162009000400006

Batey, T., 2009. Soil compaction and soil management – a review. Soil Use Manage. 25, 335-345. https://doi.org/10.1111/j.1475-2743.2009.00236.x

Baty, F., Ritz, C., Charles, S., Brutsche, M., Flandrois, J.P., Delignette-Muller, M.L., 2015. A Toolbox for Nonlinear Regression in R: The Package nlstools. J. Stat. Soft. 66, 1-21. https://doi.org/10.18637/jss.v066.i05

Beckett, C.T.S., Bewsher, S., Guzzomi, A.L., Lehane, B.M., Fourie, A.B., Riethmuller, G., 2018. Evaluation of the dynamic cone penetrometer to detect compaction in ripped soils. Soil Tillage Res. 175, 150-157. https://doi.org/10.1016/j.still.2017.09.009

Bengough, A.G., Bransby, M.F., Hans, J., MacKenna, S.J., Roberts, T.J., Valentine, T.A., 2006. Root responses to soil physical conditions; growth dynamics from field to cell. J. Exp. Bot. 57, 437-447. https://doi.org/10.1093/jxb/erj003

Bengough, A.G., McKenzie, B.M., Hallett, P.D., Valentine, T.A., 2011. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. J. Exper. Bot. 62, 59-68. https://doi.org/10.1093/jxb/erq350

Bengough, A.G., Mullins, C.E., Wilson, G., 1997. Estimating soil frictional resistance to metal probes and its relevance to the penetration of soil by roots. Eur. J. Soil Sci. 48, 603-612. https://doi.org/10.1111/j.1365-2389.1997.tb00560.x

Betioli Júnior, E., Moreira, W.H., Tormena, C.A., Ferreira, C.J.B., Silva, A.P., Giarola, N.F.B., 2012. Intervalo hídrico ótimo e grau de compactação de um Latossolo Vermelho após 30 anos sob plantio direto. Rev. Bras. Cienc. Solo, 36, 971-982. https://doi.org/10.1590/S0100-06832012000300027

Blanco-Canqui, H., Ruis, S.J., 2018. No-tillage and soil physical environment. Geoderma. 326, 164-200. https://doi.org/10.1016/j.geoderma.2018.03.011.

Bölenius, E., Stenberg, B., and Arvidsson, J., 2017. Within field cereal yield variability as affected by soil physical properties and weather variations – a case study in east central Sweden. Geoderma Regional. 11, 96-103. https://doi.org/10.1016/j.geodrs.2017.11.001

Bölenius, E., Wetterlind, J., Keller, T., 2018. Can within field yield variation be explained using horizontal penetrometer resistance and electrical conductivity measurements? Results from three Swedish fields. Acta Agri. Scand. B. 68, 690-700. https://doi.org/10.1080/09064710.2018.1464201

Busscher, W., Frederick, J., Bauer, P., 2001. Effect of penetration resistance and timing of rain on grain yield of narrow-row corn in a coastal plain loamy sand. Soil Tillage Res. 63, 15–24. https://doi.org/10.1016/S0167-1987(01)00228-8

Busscher, W.J., Bauer, P.J., Camp, C.R., Sojka, R.E., 1997. Correction of cone index for soil water content differences in a coastal plain soil. Soil Tillage Res. 43, 205–217. https://doi.org/10.1016/S0167-1987(97)00015-9

Caires, E.F., Barth, G., Garbuio, F.J., Kusman, M.T., 2002. Correção da acidez do solo, crescimento radicular e nutrição do milho de acordo com a calagem na superfície em sistema plantio direto. Rev. Bras. Cienc. Solo. 26, 1011-1022. https://doi.org/10.1590/S0100-06832002000400019

Caires, E.F., Garbuio, F.J., Churka, S., Barth, G., Corrêa, J.C.L., 2008. Effects of soil acidity amelioration by surface liming on no-till corn, soybean, and wheat root growth and yield. Eur. J. Agronomy. 28, 57-64. https://doi.org/10.1016/j.eja.2007.05.002

Calonego, J.C., Raphael, J.P.A., Rigon, J.P.C., Oliveira Neto, L., Rosolem, C.A., 2017. Soil compaction management and soybean yields with cover cropsunder no-till and occasional chiseling. Eur. J. Agronomy. 85, 31-37. https://doi.org/10.1016/j.eja.2017.02.001

Catania, P., Badalucco, L., Laudicina, V.A., Vallone, M., 2018. Effects of tilling methods on soil penetration resistance, organic carbon and water stable aggregates in a vineyard of semiarid Mediterranean environment. Environ. Earth Sci. 77, 348-356. https://doi.org/10.1007/s12665-018-7520-5

Cecagno, D., Costa, S.E.V.G.A., Anghinoni, I., Kunrath, T.R., Martins, A.P., Reichert, J.M., Gubiani, P.I., Balerini, F., Fink, J.R., Carvalho, P.C.F., 2016. Least limiting water range and soybean yield in a long-term, no-till, integrated crop-livestock system under different grazing intensities. Soil Tillage Res. 156, 54-62. https://doi.org/10.1016/j.still.2015.10.005

Chamen, W.C.T., Moxey, A.P., Towers, W., Balana, B., Hallett, P.D., 2015. Mitigating arable soil compaction: A review and analysis of available cost and benefit data. Soil Tillage Res. 146, 10-25. https://doi.org/10.1016/j.still.2014.09.011

Conab – Companhia Nacional de Abastecimento., 2018. Acompanhamento da safra brasileira de grãos. Brasília: Conab. ISNN 2318-6852.

Crawford, M.H., Rincon-Florez, V., Balzer, A., Dang, Y.P., Carvalhais, L.C., Liu, H., Schenk, P.M., 2015. Changes in the soil quality attributes of continuous no-till farming systems following a strategic tillage. Soil Res. 53, 263–273. https://doi.org/10.1071/SR14216

Derpsch, R., Friedrich, T., Kassam, A., and Li, H.W., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. Int. J. Agric. Biol. Eng. 3, 1-25. https://doi.org/10.3965/j.issn.1934-6344.2010.01.0-0

Dexter, A.R., 1987. Mechanics of root growth. Plant Soil. 98, 303–312. https://doi.org/10.1007/BF02378351

Dexter, A.R., Horn, R., Holloway, R., Jakobsen, B.F., 1988. Pressure transmission beneath wheels in soils on the Eyre peninsula of South Australia. J. Terramechanics. 25, 135-147. https://doi.org/10.1016/0022-4898(88)90020-1

Dias Junior, M.S., Leite, F.P., Lasmar Junior, E., Araujo Junior, C.F., 2005. Traffic effects on the soil preconsolidation pressure due to Eucalyptus harvest operations. Sci. Agric. 62, 248-255. https://doi.org/10.1590/S0103-90162005000300008

Efron, B., Tibshirani, R., 1986. Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. Stat. Sci, 1, 55–77.

Ekwue, E.I., Stone, R.J., 1995. Organic matter effects on the strength properties of compacted agricultural soils. Trans ASAE. 38, 357-365. https://doi.org/10.13031/2013.27804

Farooq, M., Flower, K.C., Jabran, K., Wahid, A., and Siddique, K.H.M., 2011. Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res. 117, 172-183. https://doi.org/10.1016/j.still.2011.10.001

Fulton, J., L.G. Wells, Shearer, S.A., Barnhisel R.I., 1996. Spatial variation of soil physical properties. A precursor to Precision Tillage. ASAE paper Nº 961002 International Meeting, Phoenix, Arizona, July 14 -18.

Grant, C.D., Angers, D.A., Murray, R.S., Chantigny, M.H., Hasanah, U., 2001. On the nature of soil aggregate coalescence in an irrigated swelling clay. Aust. J. Soil Res. 39, 565-575. https://doi.org/10.1071/SR99073

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: A review of nature, causes and possible solutions. Soil Tillage Res. 82, 121–145. https://doi.org/10.1016/j.still.2004.08.009

Hartge, K.H., Bohne, H., Schrey, H.P., Extra, H., 1985. Penetrometer measurements for screening soil physical variability. Soil Tillage Res. 5, 343-350. https://doi.org/10.1016/S0167-1987(85)80002-7

Herrick, J.E., Jones, T.L., 2002. A dynamic cone penetrometer for measuring soil penetration resistance. Soil Sci. Soc. Am. J. 66, 1320-1324. https://doi.org/10.2136/sssaj2002.1320

Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ. 103, 1-25. https://doi.org/10.1016/j.agee.2003.12.018.

Hoogenboom, G., Huck, M.G., Peterson, C.M., 1987. Root growth rate of soybean as affected by drought stress. Agron. J. 79, 607–614. https://doi.org/10.2134/agronj1987.00021962007900040004x

Imhoff, S., Silva, A.P., Tormena, C.A., 2000. Applications of the resistance curve in the control of the physical quality of soils under grass. Pes. Agropec. Bras. 35, 1493-1500. http://dx.doi.org/10.1590/S0100-204X2000000700025

Jung, K.Y., Kitchen, N.R., Sudduth, K.A., Lee, K.S., Chung, S.O., 2010. Soil compaction varies by crop management system over a claypan soil landscape. Soil Tillage Res. 107, 1–10. https://doi.org/10.1016/j.still.2009.12.007

Klute, A., 1986. Water retention: laboratory methods. In: Klute, A. (Ed.), Methods of soil analysis. American Society of Agronomy, Madison, pp.563-596.

Koch, H.J., Dieckmann, J., Büchse, A., Märländer, B., 2009. Yield decrease in sugar beet caused by reduced tillage and direct drilling. Eur. J. Agron. 30, 101–109. https://doi.org/10.1016/j.eja.2008.08.001

Lal, R., Reicosky, D.C., Hanson, J.D., 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res. 93, 1-12. https://doi.org/10.1016/j.still.2006.11.004.

Lamandé, M., Schjønning, P., 2011. Transmission of vertical stress in a real soil profile. Part I: Site description, evaluation of the Söhne model, and the effect of topsoil tillage. Soil Tillage Res. 114, 57-70. https://doi.org/10.1016/j.still.2011.05.004

Lampurlanés, J., Cantero-Martinez, C., 2003. Soil bulk density and penetration resistance under different tillage and crop management systems and their relationship with barley root growth. Agron. J. 95, 526–536. https://doi.org/10.2134/agronj2003.5260

Lipiec, J., Stepniewski, W., 1995. Effects of soil compaction and tillage systems on uptake and losses of nutrients. Soil Tillage Res. 35, 37-52. https://doi.org/10.1016/0167-1987(95)00474-7.

Lipiec, J., Horn, R., Pietrusiewicz, J., Siczek, A., 2012. Effects of soil compaction on root elongation and anatomy of different cereal plant species. Soil Tillage Res. 121, 74–81. https://doi.org/10.1016/j.still.2012.01.013

Liu, H., Crawford, M., Carvalhais, L.C., Dang, Y.P., Dennis, P.G., Schenk, P.M., 2016. Strategic tillage on a Grey Vertosol after fifteen years of no-till management had no short-term impact on soil properties and agronomic productivity. Geoderma 267, 146–155. https://doi.org/10.1016/j.geoderma.2016.01.002

Lowery, B., Morrison, J.E., 2002. Soil Penetrometers and Penetrability. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis Part 4, Physical Methods. Soil Science Society of America. Book Series, Madison, WI, pp. 363-385.

Masaddeghi, M.R., Hajabbasi, M.A., Hemmat, A., Afyni, M., 2000. Soil compactibility as affected by soil moisture content and farmyard manure in central Iran. Soil Tillage Res. 55, 87–97. https://doi.org/10.1016/S0167-1987(00)00102-1

Mazurana, M., Levien, R., Inda Júnior, A.V., Conte, O., Bressani, L.A., Müller, J., 2017. Soil susceptibility to compaction under use conditions in southern Brazil. Ciênc. agrotec. 41, 60-71. https://doi.org/10.1590/1413-70542017411027216

Melland, A.R., Antille, D.L., Dang, Y.P., 2017. Effects of strategic tillage on short-term erosion, nutrient loss in runoff and greenhouse gas emissions. Soil Res. 55, 201–214. https://doi.org/10.1071/SR16136

Melo Filho, J.F., Carvalho, L.L., Silveira, D.C., Sacramento, J.A.A.S., Silveira, E.C.P., 2009. Índice de qualidade em um latossolo amarelo coeso cultivado com citros. Rev. Bras. Frutic. 31, 1168-1177. https://doi.org/10.1590/S0100-29452009000400034

Melo Filho, J.F., Souza, A.L.V., Souza, L.S., 2007. Determinação do índice de qualidade subsuperficial em um Latossolo Amarelo Coeso dos Tabuleiros Costeiros, sob floresta natural. Rev. Bras. Cienc. Solo. 31,1599-1608. https://doi.org/10.1590/S0100-06832007000600036.

Merrill, S.D., Tanaka, D.L., Hanson, J.D., 2002. Root Length Growth of Eight Crop Species in Haplustoll Soils. Soil Sci. Soc. Am. J. 66, 913–923. https://doi.org/10.2136/sssaj2002.9130

Mielke, L.N., Powers, W.L., Badri, S., Jones, A.J., 1994. Estimating soil water content from soil strength. Soil Tillage Res. 31, 199-209. https://doi.org/10.1016/0167-1987(94)90080-9

Molin, J.P., Dias, C.T.S., Carbonera, L., 2012. Estudos com penetrometria: novos equipamentos e amostragem correta. Rev. Bras. Eng. Agric. Ambient. 16, 584-90. https://doi.org/10.1590/S1415-43662012000500015

Mome Filho, E.A., Silva, A.P., Figueiredo, G.C., Gimenes, F.H.S., Vitti, A.C., 2014. Compared performance of penetrometers and effect of soil water content on penetration resistance measurements. Rev. Bras. Cienc. Solo. 38, 744-754. https://doi.org/10.1590/S0100-06832014000300006

Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.R., 2014a. Critical limits of soil penetration resistance in a Rhodic Eutrudox. Rev. Bras. Cienc. Solo. 38,288-298. https://doi.org/10.1590/S0100-06832014000100029

Moraes, M.T., Debiasi, H., Franchini, J.C., Silva, V.R., 2012. Correction of resistance to penetration by pedofunctions and a reference soil water content. Rev. Bras. Cienc. Solo. 36, 1704-1713. https://doi.org/10.1590/S0100-06832012000600004

Moraes, M.T., Debiasi, H., Franchini, J.C., Silva, V.R., 2013. Soil penetration resistance in a rhodic eutrudox affected by machinery traffic and soil water content. Eng. Agríc. 33, 748-757. https://doi.org/10.1590/S0100-69162013000400014

Moraes, M.T., Silva, V.R., Zwirtes, A.L., Carlesso, R., 2014b. Use of penetrometers in agriculture: a review. Eng. Agríc. 34, 179-193. https://doi.org/10.1590/S0100-69162014000100019

Mulqueen, J., Stafford, J. V., Tanner, D.W., 1977. Evaluation of penetrometers for measuring soil strength. J. Terramechanics. 14, 137-151. https://doi.org/10.1016/0022-4898(77)90012-X

Nunes, M.R., Denardin, J.E., Faganello, A., Pauletto, E.A., Pinto, L.F.S., 2014b. Efeito de semeadura com haste sulcadora para ação profunda em solo manejado com plantio direto. Rev. Bras. Cienc. Solo. 38, 627-638. https://doi.org/10.1590/S0100-06832014000200027

Nunes, M.R., Denardin, J.E., Pauletto, E.A., Faganello, A., Pinto, L.F.S., 2015. Mitigation of clayey soil compaction managed under no-tillage. Soil Tillage Res. 148, 119-126. https://doi.org/10.1016/j.still.2014.12.007

Nunes, M.R., Pauletto, E.A., Denardin, J.E., Faganello, A., Pinto, L.F.S., Scheunemann, T., 2014a. Persistence of chiseling effects on the compaction of a Nitosol under no-till in a humid subtropical region. Pesq. agropec. bras. 49, 531-539. https://doi.org/10.1590/S0100-204X2014000700005

Otto, R., Silva, A.P., Franco, H.C.J., Oliveira, E.C.A., Trivelin, P.C.O., 2011. High soil penetration resistance reduces sugarcane root system development. Soil Tillage Res. 117, 201-210. https://doi.org/10.1016/j.still.2011.10.005

Pivetta, L.A., Castoldi, G., Santos, G.P., Rosolem, C.A., 2011. Crescimento e atividade de raízes de soja em função do sistema de produção. Pesq. agropec. bras. 46, 1547-1554. http://doi.org/10.1590/S0100-204X2011001100017

Quincke, J.A., Wortman, C.S., Mamo, M., Franti, T., Drijber, R.A., Garcia, J.P., 2007. Onetime tillage of no-till systems: soil physical properties, phosphorus runoff, and crop yield. Agron. J. 99, 1104–1110. http://doi.org/10.2134/agronj2006.0321

R Development Core Team, 2018. R: A Language and Environment for Statistical Computing R Foundation for Statistical Computing, Vienna, Austria. https://www.Rproject.org.

Raij, B. van., Cantarella, H., Quaggio, J.A., Furlani, A.M.C., 1997. Recomendações de adubação e calagem para o Estado de São Paulo. 2.ed. rev. e atual. Campinas: Instituto Agronômico/Fundação IAC, 285p. (Boletim Técnico, 100).

Reichert, J.M., Kaiser, D.R., Reinert, D.J., Riquelme, U.F.B., 2009b. Variação temporal de propriedades físicas do solo e crescimento radicular de feijoeiro em quatro sistemas de manejo. Pesq. agropec. bras. 44, 310-319. http://doi.org/10.1590/S0100-204X2009000300013

Reichert, J.M., Reinert, D.J., Suzuki, L.E.A.S., Horn, R., 2010. Mecânica do solo. In: van Lier, Q.J. (Ed.), Física do solo. Sociedade Brasileira de Ciência do Solo, Viçosa, MG, p.30-102.

Reichert, J.M., Suzuki, L.E.A.S., Reinert, D.J., Horn, R., Håkansson, I., 2009a. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res. 102, 242-254. http://doi.org/10.1016/j.still.2008.07.002

Reinert, D.J., Wolkowski, R.P., Lowery, B., Arriaga, F.J., 2001. Compaction effects on plant water use. Proc. 2001 Fertilizer, Aglime and Pest Mgmt. Conf. 40, 222–232. Madison, WI.

Roboredo, D., Maia, J.C.S., Oliveira, O.J., Roque, C.G., 2010. Uso de dois penetrômetros na avaliação da resistência mecânica de um Latossolo Vermelho Distrófico. Eng. Agríc. 30, 308-314. http://doi.org/10.1590/S0100-69162010000200013

Sá, J.C., 1999. Manejo da fertilidade do solo no Sistema Plantio Direto. In: Siqueira, J.O., Moreira, F. M. S., Lopes, A. S., Guilherme, L. R. G., Faquim, V., Furtini Neto, A. E., Carvalho, J.G. (Eds.). Inter-relações fertilidade, biologia do solo e nutrição de plantas. Lavras: Sociedade Brasileira de Ciência do Solo, p. 267-319.

Sako, H., Soares, J.E., Silva, L.A., Balardin, R., 2015. Relação de enraizamento e cálcio no solo para alta produtividade da safra 15/16. CESB – Comitê Estratégico Soja Brasil, Sorocaba – SP. (Boletim Técnico 1).

Santos, A.P., Volpato, C.E.S., Tourino, M.C.C., 2008. Desempenho de três semeadoras-adubadoras de plantio direto para a cultura do milho. Ciênc. agrotec. 32, 540-546. http://doi.org/10.1590/S1413-70542008000200030

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lubreras, J.F., Coelho, M.R., Almeida, J.A., Cunha, T.J.F., Oliveira, J.B. (Eds.)., 2013. Sistema brasileiro de classificação de solos. 3.ed. Embrapa, Brasília, DF. 353p.

Schjønning, P., van den Akker, J.J.H., Keller, T., Greve, M.H., Lamandé, M., Simojoki, A., 2015. Driver–pressure–state–impact–response (DPSIR) analysis and risk assessment for soil compaction: A European perspective. Adv. Agron. 133, 183–237. http://doi.org/10.1016/bs.agron.2015.06.001

Severiano, E.C., Oliveira, G.C., Dias Júnior, M.D., Curi, N., Costa, K.A.P., Carducci, C.E., 2013. Preconsolidation pressure, soil water retention characteristics, and texture of Latosols in the Brazilian Cerrado. Soil Res. 51, 193-202. http://doi.org/10.1071/SR12366

Shukla, M.K., Lal R., 2005. Erosional effects on soil organic carbon stock in an on-farm study on Alfisols in west central Ohio. Soil Tillage Res. 81, 173–181. http://doi.org/10.1016/j.still.2004.09.006.

Silva, V.R., Reichert, J.M., Reinert, D.J., 2004. Variabilidade espacial da resistência do solo à penetração em plantio direto. Cienc. Rural. 34, 399-406. http://doi.org/10.1590/S0103-84782004000200010

Soane, B.D., 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil Tillage Res. 16, 179-201. http://doi.org/10.1016/0167-1987(90)90029-D

Soil Fertility Commission of the State of Minas Gerais, 1999. Recomendações para o uso de corretivos e fertilizantes em Minas Gerais. – 5ª aproximação. CFSEMG. 359p.

Soil Survey Staff., 1993. Soil survey manual. Washington, USDA- SCS. U.S. Gov. Print. Office, 437p. (Handbook, 18).

Soil Survey Staff., 2014. Keys to Soil Taxonomy (12th edition). United States Department of Agriculture, Washington. D.C. USA.

Souza, Z.M., Silva, M.L.S., Guimarães, G.L., Campos, D.T.S., Carvalho, M.P., Pereira, G.T., 2001. Variabilidade espacial de atributos físicos em um Latossolo Vermelho distrófico sob semeadura direta em Selvíria (MS). Rev. Bras. Cienc. Solo. 25, 699-707. http://doi.org/10.1590/S0100-06832001000300019

Stavi, I., Lal, R., Owens, L.B., 2011. On-farm effects of no-till versus occasional tillage on soil quality and crop yields in eastern Ohio. Agronomy Sust. Developm. 31, 475-482. http://doi.org/10.1007/s13593-011-0006-4

Storck, L., Kobata, S.G.K., Brum, B., Soares, A.B., Modolo, A.J., Assmann, T.S., 2016. Sampling plan for using a motorized penetrometer in soil compaction evaluation. Rev. Bras. Eng. Agríc. Ambient. 20, 250-255. http://doi.org/10.1590/1807-1929/agriambi.v20n3p250-255

Szatanik-Kloc, A., Horn, R., Lipiec, J., Siczek, A., Szerement, J., 2018. Soil compaction-induced changes of physicochemical properties of cereal roots. Soil Tillage Res. 175, 226-233. http://doi.org/10.1016/j.still.2017.08.016

Tavares Filho, J., Ribon, A.A., 2008. Resistência do solo à penetração em resposta ao número de amostras e tipo de amostragem. Rev. Bras. Cienc. Solo. 32, 487-94. http://doi.org/10.1590/S0100-06832008000200003

Taylor, H.M., Roberson, G.M., Parker Jr., J.J.. 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102, 18-22.

Tebrügge, F., Düring, R.A., 1999. Reducing tillage intensity — a review of results from a long-term study in Germany. Soil Tillage Res. 53, 15-28. http://doi.org/10.1016/S0167-1987(99)00073-2.

Tormena, C.A., Araújo, M.A., Fidalski, J., Costa, J.M., 2007. Variação temporal do intervalo hídrico ótimo de um Latossolo Vermelho Distroférrico sob sistemas de plantio direto. Rev. Bras. Cienc. Solo. 31, 211-219. http://doi.org/10.1590/S0100-06832007000200003

Unger, P.W., Kaspar, T.C., 1994. Soil compaction and root growth: a review. Agron. J. 86, 759-766. http://doi.org/10.2134/agronj1994.00021962008600050004x

Vaz, C.M.P., Manieri, J.M., Maria, I.C., Tuller, M., 2011. Modeling and correction of soil penetration resistance for varying soil water content. Geoderma. 166, 92-101. http://doi.org/10.1016/j.geoderma.2011.07.016

Veen, B.W., Boone, F.R., 1990. The influence of mechanical resistance and soil-water on the growth of seminal roots of maize. Soil Tillage Res. 16, 219–226. http://doi.org/10.1016/0167-1987(90)90031-8

Vogel, G.F., Martinkoski, L., Grillo, J.F., Michalovicz, L., Fey, R., 2017. Avaliação dos penetrômetros de impacto e eletrônico na determinação da resistência mecânica a penetração do solo. Scientia Agraria. 18, 30-36. http://doi.org/10.5380/rsa.v18i3.52220

Warrick, A.W., Nielsen, D.R., 1980. Spatial variability of soil physical properties in the field. In: Hillel, D. (Ed.), Applications of soil physics. Academic Press, New York, 350p.

Weber, R., Biskupski, A., 2008. Effect of penetration resistance, bulk density and moisture content of soil on selected yield components of winter triticale in relation to method of cultivation. Int. Agrophys. 22, 171-177.

Whalley, W.R., Leeds-Harrison, P.B., Clark, L.J. Gowing, D.J.G., 2005. Use of effective stress to predict the penetrometer resistance of unsaturated agricultural soils. Soil Tillage Res. 84, 18-27. http://doi.org/10.1016/j.still.2004.08.003

Whalley, W.R, Watts, C.W., Gregory, A.S., Mooney, S.J., Clark, L.J., Whitmore, A.P., 2008. The effect of soil strength on the yield of wheat. Plant Soil 306, 237-247. http://doi.org/10.1007/s11104-008-9577-5

Wortmann, C.S., Drijber, R.A., Franti, T.G., 2010. One-time tillage of no-till crop land five years post-tillage. Agron. J. 102, 1302–1307. http://doi.org/10.2134/agronj2010.0051

Zhang, H., Hartge, K.H., Ringe, H., 1997. Effectiveness of organic matter incorporation in reducing soil compactibility. Soil Sci. Soc. Am. J. 61, 239-245. http://doi.org/10.2136/sssaj1997.03615995006100010033x

8. Appendix A – Supplementary data

Table A. Soil fertility characterization of the experimental area in three years of cultivation.

Soil Management	**pH**	**SOM**	**BS**	**Ca^{2+}**	**Mg^{2+}**	**T**	**Al^{3+}**	**K^{+}**	**P**
		g kg^{-1}	%	------------ $cmol_c$ dm^{-3} -----------				--- mg dm^{-3} -	
2016									
0.00 – 0.20 m									
T1	4.74	37.2	54.30	2.70	0.55	6.38	0.10	75.50	3.24
T2	4.46	39.2	43.69	2.08	0.55	6.53	0.03	87.00	6.20
T3	4.80	34.5	51.75	2.19	0.61	5.76	0.00	76.00	3.11
T4	4.61	36.1	48.61	2.11	0.53	6.02	0.02	97.25	6.05
T5	4.35	38.8	42.75	1.95	0.56	6.44	0.05	97.00	9.08
0.20 – 0.40 m									
T1	4.83	33.8	41.43	1.58	0.38	5.06	0.09	59.00	0.91
T2	4.60	35.6	33.10	1.30	0.35	5.58	0.01	73.00	1.13
T3	4.75	33.1	40.40	1.48	0.38	5.05	0.00	54.00	0.99
T4	4.95	33.8	38.39	1.23	0.30	4.31	0.01	55.00	0.85
T5	5.15	34.9	39.03	1.50	0.45	5.13	0.03	60.00	1.66
2017									
0.00 – 0.20 m									
T1	5.34	30.3	58.51	3.09	0.58	6.70	0.02	85.05	3.43
T2	4.46	29.5	28.53	1.71	0.28	7.57	0.09	55.06	2.80
T3	5.01	30.0	49.76	2.55	0.61	6.74	0.03	66.71	4.45
T4	4.79	29.8	44.08	2.31	0.50	7.02	0.04	94.44	6.60
T5	4.73	31.0	39.68	2.00	0.58	7.19	0.01	80.27	4.65
0.20 – 0.40 m									
T1	5.13	25.50	42.52	1.73	0.40	5.30	0.03	42.84	1.06
T2	4.62	26.30	29.66	1.41	0.29	6.29	0.05	45.19	0.84
T3	5.13	22.50	45.96	1.88	0.47	5.37	0.03	31.64	0.70
T4	4.83	27.30	33.20	1.35	0.35	5.63	0.01	51.74	1.63
T5	4.74	27.30	33.63	1.33	0.37	5.59	0.01	56.17	1.23
2018									
0.00 – 0.20 m									
T1	5.34	25.80	41.66	1.98	0.34	6.02	0.06	75.55	4.58
T2	5.06	25.60	25.34	1.27	0.12	6.11	0.46	66.04	4.89
T3	5.40	26.20	59.23	2.80	0.57	5.93	0.03	76.32	10.32
T4	5.21	24.90	27.50	1.18	0.20	5.72	0.15	84.50	7.62
T5	4.95	26.20	43.30	1.90	0.52	6.13	0.07	103.30	6.64
0.20 – 0.40 m									
T1	4.85	22.50	33.48	1.24	0.25	4.96	0.06	70.81	1.09
T2	4.53	22.80	26.80	1.15	0.12	5.39	0.11	59.15	1.35
T3	5.15	22.00	45.22	1.35	0.36	4.70	0.04	47.59	1.41
T4	4.70	21.90	26.28	0.90	0.16	4.62	0.09	62.63	0.85
T5	4.90	23.70	36.07	1.29	0.35	4.96	0.06	59.05	0.85

pH in $CaCl_2$; SOM – soil organic matter; BS – base saturation; T – potential cation exchange capacity. T1 – NT for 10 years (control); T2 – NT with surface application of 3,600 kg ha^{-1} of agricultural gypsum; T3 – NT subsoiling plus 1,440 kg ha^{-1} of highly reactive limestone (Total Neutralizing Power = 180%) incorporated to a depth of 0.60 m; T4 – NT planting following chisel plowing at a depth of ~0.26 m; and T5 – NT subsoiling to a depth of 0.60 m plus 1,440 kg ha^{-1} of highly reactive limestone applied on surface (Total Neutralizing Power = 180%).

Table B. Penetration resistance models as a function of soil water content in a continuous no - tillage system and submitted to occasional tillage

Treat	Model	"a" parameter	"b" parameter	RSE	AIC	R^2
		Depth 0.00 – 0.05 m				
T1	$PR = a*(1-wc)^{b}$	23.62*	7.58***	0.503	44.94	0.64
	$PR = a*wc^{b}$	0.029ns	-3.29***	0.504	45.05	0.64
	$PR = a*exp^{bwc}$	42.25ns	-10.95***	0.502	44.83	0.65
	PR = a+b*wc*ln*wc	38.85***	103.57***	0.504	45.04	0.64
	PR = a+b*wc	5.68***	-13.26***	0.537	48.59	0.60
T2	$PR = a*(1-wc)^{b}$	12.52ns	6.36**	0.528	43.01	0.52
	$PR = a*wc^{b}$	0.03ns	-3.06***	0.527	42.85	0.53
	$PR = a*exp^{bwc}$	22.07ns	-9.50***	0.527	42.93	0.53
	PR = a+b*wc*ln*wc	26.17**	69.65**	0.642	52.70	0.30
	PR = a+b*wc	3.80***	-8.16***	0.543	44.33	0.50
T3	$PR = a*(1-wc)^{b}$	6.89*	6.41***	0.286	12.65	0.55
	$PR = a*wc^{b}$	0.02ns	-2.79***	0.278	11.24	0.57
	$PR = a*exp^{bwc}$	11.21ns	-9.30***	0.283	12.20	0.56
	PR = a+b*wc*ln*wc	13.18***	34.84***	0.292	13.67	0.53
	PR = a+b*wc	2.29***	-5.10***	0.301	15.29	0.50
T4	$PR = a*(1-wc)^{b}$	14.14ns	6.49**	0.912	67.64	0.39
	$PR = a*wc^{b}$	0.05ns	-2.69**	0.915	67.83	0.38
	$PR = a*exp^{bwc}$	22.13ns	-9.26**	0.912	67.64	0.39
	PR = a+b*wc*ln*wc	26.76***	70.84**	0.909	67.49	0.39
	PR = a+b*wc	4.96***	-11.38**	0.928	68.46	0.36
T5	$PR = a*(1-wc)^{b}$	14.01ns	6.33***	0.731	65.92	0.47
	$PR = a*wc^{b}$	0.08ns	-2.41***	0.757	67.89	0.43
	$PR = a*exp^{bwc}$	20.40ns	-8.81***	0.738	66.45	0.46
	PR = a+b*wc*ln*wc	24.68***	64.67***	0.768	68.72	0.41
	PR = a+b*wc	6.00***	-14.83***	0.706	63.93	0.50
NV	$PR = a*(1-wc)^{b}$	1.01*	2.13*	0.141	-18.55	0.20
	$PR = a*wc^{b}$	0.12ns	-1.10*	0.139	-19.18	0.23
	$PR = a*exp^{bwc}$	1.25*	-3.25*	0.141	-18.73	0.21
	PR = a+b*wc*ln*wc	5.01**	12.64*	0.135	-20.37	0.27
	PR = a+b*wc	0.87***	-1.31*	0.142	-18.38	0.20
Depth – 0.25 – 0.30 m						
T1	$PR = a*(1-wc)^{b}$	47.12*	8.99***	0.555	45.46	0.80
	$PR = a*wc^{b}$	0.02ns	-3.63***	0.557	45.63	0.80
	$PR = a*exp^{bwc}$	84.88*	-12.69***	0.554	45.41	0.80
	PR = a+b*wc*ln*wc	45.79***	121.79***	0.552	45.20	0.80
	PR = a+b*wc	9.69***	-25.09***	0.586	48.20	0.78
T2	$PR = a*(1-wc)^{b}$	109.54ns	11.79***	0.780	60.17	0.66
	$PR = a*wc^{b}$	0.004ns	-4.90***	0.762	59.05	0.68
	$PR = a*exp^{bwc}$	244.54ns	-16.74***	0.773	59.80	0.67
	PR = a+b*wc*ln*wc	52.89***	142.04***	0.787	60.58	0.66
	PR = a+b*wc	8.52***	-21.82***	0.888	66.40	0.56
T3	$PR = a*(1-wc)^{b}$	9.74**	5.69***	0.324	17.95	0.70
	$PR = a*wc^{b}$	0.08*	-2.27***	0.339	20.05	0.67
	$PR = a*exp^{bwc}$	14.02**	-8.02***	0.328	18.51	0.69
	PR = a+b*wc*ln*wc	18.75***	48.64***	0.360	23.00	0.63
	PR = a+b*wc	4.62***	-10.93***	0.312	16.15	0.72
T4	$PR = a*(1-wc)^{b}$	63.79ns	11.13***	0.910	67.55	0.57
	$PR = a*wc^{b}$	0.007ns	-4.29***	0.897	66.83	0.58
	$PR = a*exp^{bwc}$	124.10ns	-15.49***	0.906	67.34	0.57
	PR = a+b*wc*ln*wc	36.02***	96.42***	0.911	67.60	0.56

	PR = a+b*wc	7.49***	-19.74***	0.975	70.82	0.50
T5	PR = a*(1-wc)^{b}	36.00*	9.47***	0.589	52.06	0.70
	PR = a*wc^{b}	0.02ns	-3.58***	0.600	53.05	0.68
	PR = a*exp^{bwc}	62.27ns	-13.11***	0.592	52.28	0.69
	PR = a+b*wc*ln*wc	30.85***	82.20***	0.592	52.29	0.69
	PR = a+b*wc	7.41***	-20.01***	0.596	52.61	0.69
NV	PR = a*(1-wc)^{b}	1.02*	2.14*	0.142	-18.55	0.20
	PR = a*wc^{b}	0.13ns	-1.11*	0.139	-19.18	0.23
	PR = a*exp^{bwc}	1.26*	-3.26*	0.140	-18.73	0.21
	PR = a+b*wc*ln*wc	5.01**	12.64*	0.136	-20.37	0.27
	PR = a+b*wc	0.86***	-1.30*	0.142	-18.38	0.19
Depth 0.45 – 0.50 m						
T1	PR = a*(1-wc)^{b}	7.59*	5.76***	0.389	29.56	0.54
	PR = a*wc^{b}	0.05ns	-2.42***	0.394	30.24	0.52
	PR = a*exp^{bwc}	11.45ns	-8.26***	0.389	29.67	0.53
	PR = a+b*wc*ln*wc	16.47***	43.26***	0.405	31.80	0.50
	PR = a+b*wc	3.22***	-7.27***	0.392	30.04	0.53
T2	PR = a*(1-wc)^{b}	18.03*	7.62***	0.300	12.27	0.80
	PR = a*wc^{b}	0.02ns	-3.30***	0.306	13.17	0.79
	PR = a*exp^{bwc}	31.74*	-11.01***	0.300	12.36	0.80
	PR = a+b*wc*ln*wc	27.58***	73.55***	0.316	14.36	0.77
	PR = a+b*wc	4.57***	-10.84***	0.326	15.30	0.76
T3	PR = a*(1-wc)^{b}	10.66*	7.23***	0.359	26.08	0.58
	PR = a*wc^{b}	0.019ns	-3.08***	0.355	25.46	0.59
	PR = a*exp^{bwc}	17.93ns	-10.39***	0.357	25.83	0.58
	PR = a+b*wc*ln*wc	16.90***	44.85***	0.358	25.92	0.58
	PR = a+b*wc	3.02***	-7.06***	0.376	28.68	0.53
T4	PR = a*(1-wc)^{b}	5.58*	5.11**	0.468	38.00	0.43
	PR = a*wc^{b}	0.08ns	-1.94**	0.484	41.46	0.39
	PR = a*exp^{bwc}	7.55ns	-7.12**	0.472	40.03	0.42
	PR = a+b*wc*ln*wc	12.10***	31.32**	0.497	42.84	0.36
	PR = a+b*wc	3.04***	-6.93***	0.459	38.58	0.43
T5	PR = a*(1-wc)^{b}	5.97**	5.55***	0.328	20.40	0.59
	PR = a*wc^{b}	0.07ns	-2.01***	0.356	24.79	0.54
	PR = a*exp^{bwc}	8.08*	-7.64***	0.342	22.59	0.58
	PR = a+b*wc*ln*wc	11.25***	29.11***	0.357	25.06	0.54
	PR = a+b*wc	3.09***	-7.38***	0.337	21.91	0.59
NV	PR = a*(1-wc)^{b}	1.05*	2.26*	0.186	-10.49	0.15
	PR = a*wc^{b}	0.12ns	-1.08*	0.187	-10.36	0.15
	PR = a*exp^{bwc}	1.29ns	-3.37*	0.187	-10.45	0.15
	PR = a+b*wc*ln*wc	4.06ns	10.02ns	0.192	-8.94	0.10
	PR = a+b*wc	0.91***	-1.45*	0.187	-10.54	0.15

Treat = treatments; RSE = residual standard error; AIC = Akaike Information Criterion; R^2 = coefficient of determination

This paper was submitted and is under review at the Geoderma.

PAPER 4 – LINKING AGRICULTURAL MACHINERY TRAFFIC, SOIL COMPRESSIBILITY, AND LEAST LIMITING WATER RANGE IN TROPICAL CONDITIONS

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Highlights

- Vertical stress applied, load bearing capacity and soil physical quality were integrated.
- Occasional tillage improves the soil physical quality but reduces the load-bearing capacity
- An indicator the least limiting water range to plant growth and traffic does not cause soil compaction was proposed.

Abstract

Soil compaction management is one of the primary challenges of modern agriculture. Occasional tillage (OT), which includes the use of chisel plows and subsoilers, has been widely applied as a mitigation method for soil compaction. Furthermore, integrating the concepts of vertical stress applied by the agricultural machinery, load-bearing capacity, and soil physical quality needed to plant growth may assist in the preventive management of soil compaction. Thus, this study aimed to evaluate the OT residual effects on soil physical and mechanical properties 18 months after soil tillage. Moreover, we aimed to establish a soil moisture value in which the traffic of agricultural machinery does not cause additional compaction and does not limit plant root growth by integrating the concepts of vertical stress applied by agricultural machinery, pre-compression pressure (σ_p), and least limiting water range (LLWR). For this, a field experiment was set up in 2015, in a clayey-textured Typic Hapludox, with three OT treatments and one continuous no-tillage (NT) control treatment. Soil physical and mechanical properties were evaluated 18 months after the initiation of the experiment. The model of soil load-bearing capacity (σ_p x moisture) and the LLWR showed that OT reduced the soil physical restrictions to plant growth, remarkably in the subsurface and using subsoilers. Here, we proposed the least limiting water range to plant growth and resistance to additional compaction (LLWRσ_p) – a concept that integrates the applied vertical stress, σ_p, and LLWR – as a soil physical-mechanical indicator. The LLWRσ_p is a soil moisture range in which physical limitations to plant growth are minimal, and agricultural machinery traffic does not cause soil compaction. The indicator was tested using the vertical stress applied by a maize harvester. The results can benefit the decision-making process regarding the proper moment to perform mechanized operations in grain production areas without reducing the soil physical quality.

Keywords: soil physical quality; no-tillage; occasional tillage; chiseling; subsoiling.

1. Introduction

Soil compaction is the principal process of soil physical degradation in agricultural soils (Hamza and Anderson, 2005; Keller et al., 2019; Nawaz et al., 2013) and may reduce up to 75% crop yield (Correa et al., 2019). It is a process of increasing soil bulk density and subsequent porosity reduction owing to the application of mechanical forces to the soil (Soil Science Glossary Terms Committee, 2008). Compaction increases soil mechanical resistance and load-bearing capacity, thus restricting plant root growth, exchange of gases, and water and nutrients absorption by the plants' roots (Bengough et al., 2006; Correa et al., 2019; Lipiec et al., 2012; Lipiec and Stępniewski, 1995; Szatanik-Kloc et al., 2018). Further, compaction increases the soil susceptibility to water erosion (Prats et al., 2019).

Studies in several countries have reported problems with soil compaction in no-tillage (NT) areas (Blanco-Canqui and Ruis, 2018; Blanco-Canqui and Wortmann, 2020; Nunes et al., 2015; Peixoto et al., 2020, 2019a, 2019b; Reichert et al., 2009b). In Brazil, the estimative is that more than 32 million hectares cultivated with grains are under NT systems (FEBRAPD, 2019; Kassam et al., 2018). This area corresponds to half of the area cultivated with grains in the whole country, and soybean and maize are the primary cropping systems under NT (Companhia Nacional de Abastecimento, 2019). To mitigate the adverse effects of soil compaction in NT systems, farmers and researchers have used occasional tillage (OT), particularly chiseling and subsoiling (Nunes et al., 2015, 2014; Peixoto et al., 2019a, 2019b; Tian et al., 2016). However, OT may lead to losses of soil and nutrients by erosion (Deuschle et al., 2019; Melland et al., 2017) and reduce the soil organic carbon contents (Melero et al., 2011; Peixoto et al., 2020). Even when improving the soil physical properties, OT has not increased crop yields (Blanco-Canqui and Wortmann, 2020; Peixoto et al., 2020).

The leading causes of soil compaction in NT systems are associated with the intensification of agricultural management. Intensively managed systems often have increased machinery traffic in inadequate soil moisture conditions, inefficient crop rotation or succession with little or no use of cover crops, and lately, low inputs of crop residue and organic matter (Denardin et al., 2008; Drescher et al., 2011; Moreira, 2019). Among these factors, machinery traffic is regarded as the principal cause of increasing soil compaction in agricultural areas (Hamza and Anderson, 2005; Keller et al., 2019) due to the vertical stress transmitted in the tire-soil interface (Lamandé and Schjønning, 2011a), particularly with the increasing weight of agricultural machinery over time (Keller et al., 2019). Strategies to mitigate the impacts of agricultural traffic include knowing and characterizing the applied vertical stresses (Keller et al., 2019, 2007; Lamandé and Schjønning, 2011b) and the soil compressive behavior as a function of the stress applied and the soil water content (Dias Júnior and Pierce, 1996; O'Sullivan et al., 1999).

The vertical stress transmitted to the soil by the agricultural machinery tires can be estimated by soil compaction models, based on calculations of tire-soil contact area and distribution of the vertical stresses on the contact area (Keller et al., 2015, 2007). The soil compressive behavior may be characterized by the soil pre-compression pressure (σ_p), defining its load-bearing capacity as a function of the soil water content (Ajayi et al., 2010; Dias Júnior, 1994; Dias Junior and Pierce, 1995; Veiga et al., 2007). Soils with increased σ_p are more resistant to compaction (Dias Júnior, 1994; Dias Júnior and Pierce, 1996); however, they are more prone to present physical limitations to the growth of plants' roots (Imhoff et al., 2001; Römkens and Miller, 1971).

Aeration, water supply, and mechanical resistance are the primary physical factors that influence plant growth. These factors were integrated into a water content range non-limiting (Letey, 1985) and then into an indicator of structural quality – the least liming water range (LLWR) (Silva et al. 1994). The LLWR defines a range of soil water content as a function of soil bulk density (Bd). In this range, the limitations to root growth concerning aeration, air-filled porosity, and penetration resistance are minimal (Silva et al., 1994). This indicator has been amended in recent studies (Benevenute et al., 2020; Mohammadi et al., 2010; Silva et al., 2015, 2021) and is efficient to show the effects of soil compaction (Ferreira et al., 2020; Li et al., 2020; Moura et al., 2021b). Moreover, it is a suitable soil physical indicator for crop biomass production (Rabot et al., 2018).

In this regard, the integrated evaluation of the vertical stresses applied by agricultural machinery, load-bearing capacity (σ_p), and structural quality to plant growth (LLWR) may help mitigate the effects of soil compaction and benefit the conservational soil management. One attempt to integrate σ_p and LLWR was made by Imhoff et al. (2001). These authors developed the concept of critical pressures to plant growth. The critical pressure is the maximum pressure that can be applied to the soil, and that does not restrict root growth and cause additional deformation in the soil. However, this estimate is limited, as it considers the soil's critical density (LLWR = 0). In the critical density, soil physical limitations are already severe. Keller et al. (2015) integrated the model of soil compaction (Keller et al., 2007) with the LLWR concept (Silva et al., 1994). The objective was to create a model (*SoilFlex-LLWR*) to quantify the impacts of soil compaction on root growth. The model predicts Bd changes due to agricultural traffic, and since Bd is used to identify the LLWR limit values, the resulting LLWR variation is then estimated. In practical terms, estimating the impacts of soil compaction on LLWR guides the decision-making process regarding the right moment to perform mechanized operations.

Considering the previous initiatives, there is a need for studies that contribute towards determining the limits of the soil water range in which a particular agricultural machine can operate without causing additional compaction to soil and LLWR reduction. Additionally, alterations in soil structure, particularly those caused by OT and related to mechanical properties, need to be assessed to support the evaluation of the effectiveness of this compaction management strategy over time. Thus, the objectives of this study were: i) evaluate the residual effect of OT on soil mechanical properties and LLWR 18 months after the installation of the experiment; ii) establish a range of soil water content in which agricultural machine traffic does not lead to additional soil compaction nor limits the root growth of the plants, by integrating the concepts of vertical stresses applied by the agricultural machinery, σ_p, and LLWR.

2. Material and Methods

2.1.Experimental area and characterization of the experiment

The experiment was set up in October 2015 at Fazenda Santa Helena (21º 15’ 39’’ S and 44º 31’ 04” W, 1,020 m a.s.l), located in Nazareno, Minas Gerais, Brazil. The climate is CwA (Koppen classification), with cold and dry winters and hot and humid summers. Mean annual precipitation and temperature are 1,300 mm and 19.7ºC, respectively. The soil was classified as “Latossolo Vermelho-Amarelo Distrófico típico” according to the Brazilian Soil Classification System (Santos et al., 2018), corresponding to a Typic Hapludox according to the U.S. Soil Taxonomy (Soil Survey Staff, 2014). The mean distribution of soil particle-size fractions (clay, silt, and sand) at the 0-0.50 m soil depth in the experimental area was 530, 250, and 220 g kg^{-1}, respectively.

The experiment was designed in strips, with four treatments and four replications. The strips were 18 m-width and 80 m-length (1,440 m^2) and were subdivided into four 360 m^2-plots. The treatments consisted of soil management systems to mitigate the compaction effects, combining OT and lime application. The treatments were: continuous no-till initiated in 2005 (NT); NT with chiseling (Stara Fox chisel plow with seven 0.26 m length shanks spaced 0.30 m) (NTC); NT with subsoiling [Kamaq fertilizing subsoiler with four 0.60 m length shanks and application of 1440 kg ha^{-1} of dolomitic lime (TNP 180%) at the 0.40-0.60 m depth and 0.75 m spacing between shanks] (NTSDL); NT with subsoiling [Ikeda subsoiler with four 0.60 m length shanks and application of 1440 kg ha^{-1} of dolomitic lime (TNP 180%) on the soil surface and 0.75 m spacing between shanks] (NTSSL).

2.2.Soil sampling and analysis

Soil samples were collected in March 2017 (18 months after the installation of the experiment) from two soil layers (0-0.05 and 0.25-0.30 m), using volumetric rings of 0.064 m-diameter and 0.025 m-height. The 0-0.05 m layer was selected as it is greatly influenced by the management of annual crops. The 0.25-0.30 m was selected as it is the most limiting layer in physical terms. This limitation was evaluated by a penetrometer before installing the experiment. Fourteen soil samples were collected in each experimental plot, seven from the 0-0.05 m ad seven from the 0.25-0.30 m, totaling 224 samples.

Samples were initially prepared by removing the excess soil and were gradually saturated by capillarity. Each sample, within the seven samples collected in each plot/soil layer, was submitted to the following matric potentials: -0.004, -0.006, -0.010, and -0.033 MPa on an automated tension table (Ecotech, Germany), and -0.10, -0.50, and -1.50 MPa in a Richards chamber (Soil Moisture, USA). Each treatment included four soil samples submitted to the matric potentials described above.

After reaching the moisture equilibrium at each potential, the samples were weighed and tested for penetration resistance using a benchtop digital penetrometer (Marconi, MA 933, Brazil), with a cone tip of 45°, 3.84 mm diameter, and constant speed of 10 mm min^{-1}. The mean penetration resistance (PR) of the middle third of the sample depth (0.08 – 0.17 m) was used. After the penetrometer test, each sample was submitted to the uniaxial compression test using a consolidometer (Durham GeoEnterprises, S-450 Terraload Consolidometer, USA). The following pressures were applied to each sample: 25, 50, 100, 200, 400, 800, and 1600 kPa. These pressures were successive and cumulative, and were applied up to 90% of the maximum deformation in each pressure, totaling 8 min of testing. Then, the samples were oven-dried at 105-110 º C until constant weight. Details on the procedure used in the uniaxial compression test are described in Dias Júnior and Martins (2017).

2.3.Soil compressibility

The compression curves were based on data obtained from the uniaxial compression test. The x-axis in the compression curves represents the vertical stress applied, and the y-axis is the soil bulk density. Based on the compression curves, we obtained the soil pre-compression pressure (σ_P), degree of compaction (DC) using the soil bulk density at 1600 kPa as the reference value (Reichert et al., 2009b), compressibility coefficient (Cc), total porosity (TP) at σ_P (TPσ_P), TP reduction with the σ_P application (Red TPσ_P), soil bulk density (Bd) at σ_P (Bdσ_P), and Bd reduction with the σ_P application (Red Bdσ_P). All variables were obtained using the electronic spreadsheet proposed by Dias Junior and Pierce (1995).

The obtained σ_P values were represented in the y-axis and the soil water contents (WC) in the x-axis. Thus, the soil load-bearing capacity model (LBCM) of the NT control treatment was obtained, in each soil layer, by adjusting Equation 1 and defining the bootstrap confidence interval (IC).

$$\sigma_P = 10^{(a + b\ WC)} \quad (1)$$

In which: σp is the soil precompression pressure (kPa); WC is the gravimetric soil water content (kg kg^{-1}); a and b are adjustment parameters.

The σ_P versus WC data points of the OT treatments were represented in the LBCM plot. Then, three regions were defined, according to an adaptation of Dias Junior et al. (2005), using the bootstrap confidence interval (IC) (Peixoto et al., 2019a). In the LBCM plot, “a” is the region above the IC upper limit and indicates that, after 18 months, OT rearranged the soil structure to a condition of higher soil compaction than NT. Within the IC, the “b” region indicates that there is no longer OT effect. Lastly, “c” is the region below the IC lower limit and indicates that OT alleviates soil structure and that effect lasts for more than 18 months after tillage.

2.4.Least limiting water range (LLWR)

The least limiting water range was determined according to Silva et al. (1994). The water retention curves (WRC) and penetration resistance curves (PRC) were adjusted by the equations as described below:

$$\theta = \exp(a + b\ Bd)\ \psi^c \quad (2)$$

$$PR = d\ \theta^e\ Bd^f \quad (3)$$

In which: θ = volumetric soil water content (m^3 m^{-3}); Bd = soil bulk density (mg m^{-3}); ψ = matric potential (MPa); PR = penetration resistance (MPa); *a, b, c, d, e, f* = adjustment parameters.

We considered the LLWR upper critical limit as the θ in field capacity (θFC), estimated at the -0.010 MPa potential, or as the θ in which air-filled porosity is 0.10 m^3 m^{-3} (θAP). The lower critical limit was considered as the θ in permanent wilting point (θPWP), estimated at the

-1.5 MPa potential, or as the θ in which PR is 2 MPa (θPR) – value regarded as critical to root growth. For each Bd value, θFC and θPWP were estimated through the WRC (Eq. (2)); θAP was calculated by Eq. (4), and θPR was obtained by the PRC, using PR = 2 MPa (Eq. (3)):

$$\theta AP = (1 - Bd/Pd) - 0.10 \tag{4}$$

In which: θAP = volumetric soil water content at the 0.10 m^3 m^{-3} air-filled porosity; Bd = soil bulk density (mg m^{-3}); Pd = particle density (2.65 g cm^{-3}).

2.5.Integrating the concepts of applied vertical stresses, σ_p, and LLWR

We related the σ_p to the LLWR using the modified LBCM added with the initial Bd (Bdo), that is, the Bd before the uniaxial compression test. Further, we replaced the WC by the θ, following Equation 5. The vertical stress applied by agricultural machinery was inserted in the MSLBC using Equation 6, thus defining the θ upper critical limit in which the pressure applied does not cause additional compaction (θVS). Therefore, θVS is the moisture content below which there is no additional compaction by the traffic of a given agricultural machine, according to the soil load-bearing capacity (σ_p).

$$\sigma_p = 10^{(g + h\,\theta)}\,Bdo^{i} \tag{5}$$

$$\theta VS = (-\log10\,(VS/Bdo^{i}) + g) / h \tag{6}$$

In which: θVS = volumetric soil water content at which the vertical stress applied by a given machine does not cause additional compaction; VS = vertical stress applied by the agricultural machinery Bdo = initial soil bulk density; g, h, and i are adjusting parameters of the modified LBCM.

Based on the limit indicated by the θVS, we proposed the calculation of the modified LLWR with the inclusion of the θVS, named least limiting water range to plant growth and compaction resistance (LLWRσ_p). Thus, the LLWRσ_p indicates the θ range in which the physical restrictions to plant growth are minimal, and the traffic of a given agricultural machine does not promote additional compaction to the soil. The LLWRσ_p calculation was modified from that initially presented by Silva et al. (1994). In each Bd, the LLWRσ_p is the difference between the lower and upper limits. However, the upper limit is the lower θ among θFC, θAP, and θVS. The lower limit is the higher θ between θPWP and θPR. The region/area defined by the variation between θFC and θVS as a function of Bd, which occurs when θVS < θFC (the red-colored region in the figures), was represented in the graph containing the variations of the LLWR limits. This region represents part of the region of the classic LLWR proposed by Silva et al. (1994), in which additional soil compaction may occur within the θ range delimited by the LLWR.

To exemplify the linkage between applied vertical stress, σ_p, and LLWR in the two soil layers evaluated in this study, we used the results of the tire-soil contact area and propagation of soil vertical stresses applied by a John Deere Hydro 1175 maize harvester. These data were obtained from an experiment conducted by Lima et al. (2019) on an Oxisol with a sandy loam texture (206 g kg^{-1} clay) in Ponta Grossa, Paraná State, southern Brazil. We chose this dataset since their experimental area was also cultivated with grains. Further, the maize harvester used in their experiment was similar to the one used in the farm where our experiment is set up. The simulation of the vertical stresses applied by the front and rear tires is described in Lima et al. (2019). However, in the current study, we used the simulated pressures at the mean depth of the 0-0.05 m (0.025 m) and 0.25-0.30 m (0.275 m) soil layers.

2.6.Data analysis and statistics

The soil physical and mechanical properties obtained from the uniaxial compression curve were submitted to analysis of variance. After, they were submitted to the Dunnett test ($p < 0.05$) to compare the means of the OT treatments relative to the NT control in each soil layer evaluated.

The LBCM were evaluated by the significance of the adjustment parameters and determination coefficient (R^2). The LBCM confidence interval was estimated using the resampling technique with bootstrap reposition with 1,000 replications ($p < 0.05$). The WRC, PRC, and the modified LBCM were evaluated by the adjustment parameters' significance.

The tire-soil contact area and the vertical stresses applied by the John Deere Hydro 1175 maize harvester at the 0.025 m and 0.275 m soil depths were estimated based on the following information: tire inflation pressure, recommended tire inflation pressure, tire diameter and width, and wheel load (Lima et al., 2019). For this, we used the stressTraffic() function of the *soilphysics* package version 3.1 (Lima et al., 2021). The R software version 3.6.3 (R Development Core Team, 2019) was used to perform all data analyses and statistics and create figures.

3. Results and Discussion

3.1.Responses of soil mechanical properties to OT

At the 0-0.05 m depth, the NTSDL had lower DC and $Bd\sigma_p$, and higher $TP\sigma_p$, Red $TP\sigma_p$, and Red $Bd\sigma_p$ than NT (Table 1). Even though NTSDL was sampled 18 months after the soil tillage, its σ_p did not differ from NT. In a recent meta-analysis, Peixoto et al. (2020) observed that the OT effects at the 0-0.20 m persisted up to 12 months for Bd and more than 24 months for TP. The other OT treatments did not affect the other analyzed soil properties, which did not differ from NT. In grain production areas, the soil surface layer is greatly affected by soil management, which leads to increased variability in the soil properties. Mechanized planting operations, including seeders equipped with furrow openers stand out in soybean, maize, and bean cropping systems reaching up to the 0.15 m depth (Drescher et al., 2017), particularly in the cropping system adopted in the experimental area, which includes two or three crop seasons per year, in which wheat was cultivated as a fall/winter crop (2016), then maize was grown on summer (2016/2017) with a 0.17 m spacing between sowing lines. Among the subsoiling treatments, the persistence of the NTSDL effects after 18 months is likely due to the wedge-shaped tip. This tip promotes 2 to 3 times less disturbance to soil than the winged subsoiler used in the NTSSL (Kumar and Thakur, 2005), thus better preserving the soil structure and giving more time to its rearranging.

In the 0.25-0.30 m soil layer, OT did not affect the soil mechanical properties, except for the increased TPσ_p under NTC (Table 1). The persistence of OT effects on soil physical properties is influenced by some factors, such as the type of attribute analyzed, the soil preparation method, the soil management system after preparation, soil texture, soil organic matter content, among others (Blanco-Canqui and Wortmann, 2020; Drescher et al., 2016, 2011; Peixoto et al., 2020). In the 0-0.20 m, the persistence of OT effects on penetration resistance, macroporosity, and total soil porosity has been higher than 24 months but lower than 12 months for soil bulk density (Peixoto et al., 2020). The short-term effect of chiseling on soil mechanical properties was also observed by Reichert et al. (2017).

Soil physical properties that are highly influenced by the WC, such as σ_p and PR, should be evaluated within a WC range and not only at one matric potential. This evaluation can be done through models that describe their relationship, as verified by Peixoto et al. (2019a) for PR and as discussed in the following section for the σ_p.

Table 1. Soil mechanical properties, pre-compression stress (σ_p), compressibility coefficient (Cc), total porosity at σ_p (TPσ_p), reduction of TP at σ_p (Red TPσ_p), bulk density (Bd) at σ_p (Bdσ_p), reduction in Bd at σ_p (Red Bdσ_p) in two sampling depths and four management systems 18 months after the soil preparation, with soil equilibrated at -100 kPa.

Management system	σ_p (kPa)	DC (%)	Cc -	TPσ_p ($m^3\ m^{-3}$)	Red TPσ_p (%)	Bdσ_p ($Mg\ m^{-3}$)	Red Bdσ_p (%)
				Soil layer, 0-0.05 m			
NT	308	85	0.324	0.527	6.71	1.22	5.27
NTC	301^{ns}	78^{ns}	0.332^{ns}	0.546^{ns}	7.31^{ns}	1.16^{ns}	6.42^{ns}
NTSDL	238^{ns}	68*	0.426*	0.579*	9.06*	1.06*	10.8*
NTSSL	345^{ns}	82^{ns}	0.309^{ns}	0.502^{ns}	6.91^{ns}	1.28^{ns}	4.93^{ns}
				Soil layer, 0.25-0.30 m			
NT	339	84	0.302	0.476	6.04	1.35	3.06
NTC	342^{ns}	82^{ns}	0.306^{ns}	0.519*	6.65^{ns}	1.28^{ns}	4.10^{ns}
NTSDL	288^{ns}	78^{ns}	0.377^{ns}	0.493^{ns}	8.22^{ns}	1.30^{ns}	5.27^{ns}
NTSSL	346^{ns}	82^{ns}	0.316^{ns}	0.486^{ns}	7.17^{ns}	1.32^{ns}	5.19^{ns}

NT: Continuous no-tillage (control); NTC: no-tillage with chiseling; NTSDL: no-tillage with subsoiling + liming application at the 0.40-0.60 m depth; NTSSL: no-tillage with subsoiling + liming application on the soil surface. Means compared to the NT control by the Dunnett test ($p < 0.05$). "*": means differ significantly from the NT control; ns: not significantly different from the NT control.

3.2.Load-bearing capacity model (LBCM)

The control treatment (NT) LBCM and the OT treatments data points (σp x WC) in the 0-0.05 m and 0.25-0.30 m soil layers are shown in figures 1 and 2, respectively. The models were highly significant and had a determination coefficient (R^2) of 0.90 at the 0-0.05 m depth and 0.82 at the 0.25-0.30 m soil depth.

In the 0-0.05 m soil depth, the OT treatments with subsoiling effectively alleviated the accumulated pressures in soils under NT cultivated with grains. NTSDL had 82% and NTSSL had 76% of the points in region "c" (Fig. 1). These results show the persistence of the effects of OT with subsoiling on soil compressibility after 18 months of preparation. NTC had only 14% of the points in region "c". Thus, chiseling was less efficient to alleviate the soil structure, as most data points were in regions "a" and "b" (Fig. 1). We attribute this effect to the reduced soil mobilization by the chisel plow compared to the subsoilers, and to the rearrangement of the soil structure by the intensive machinery traffic in grain production areas. The rearrangement of the soil structure also occurs due to natural processes, such as the movement of soil particles and pore obstruction between aggregates, which favor soil hardening (Dexter et al., 1988; Moraes et al., 2017). In Oxisols, the relatively quick rearrangement of soil has been favored by the clay mineralogy, which is rich in kaolinite and Al- and Fe-(hydr)oxides, and the virtual absence of permanent negative charges, combined with the clayey texture (Bavoso et al., 2012; Bonetti et al., 2017; Reichert et al., 2009a).

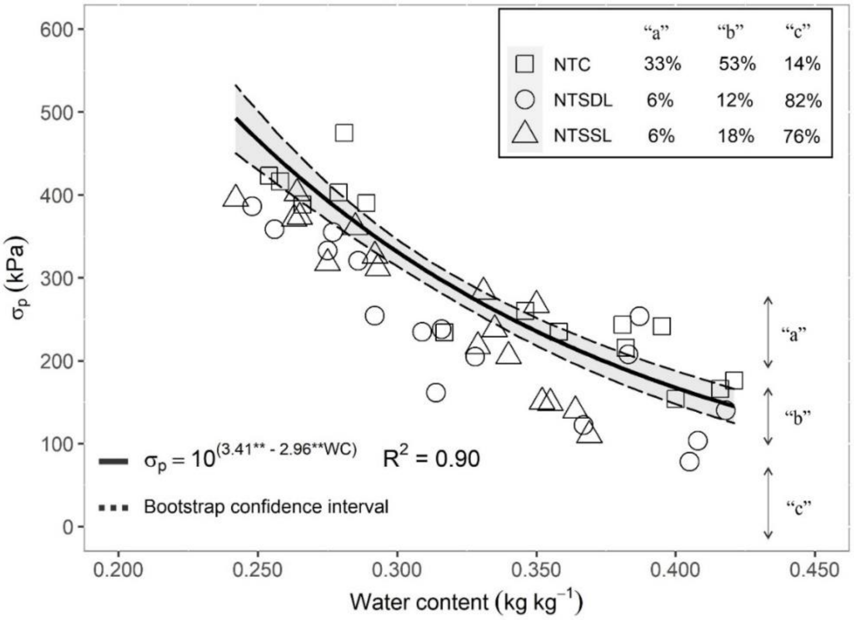

Fig. 1. Load-bearing capacity model in the 0-0.05 m depth in soil under continuous NT. The different data points represent the OT managements with their respective percentages in each region of the model. Briefly, region "a" indicates structural rearrangement, region "b" indicates that there is no OT effect, and region "c" indicates structural alleviation due to OT. NT: Continuous no-tillage (control); NTC: no-tillage with chiseling; NTSDL: no-tillage with subsoiling + liming application at the 0.40-0.60 m depth; NTSSL: no-tillage with subsoiling + liming application on the soil surface.

Unlike the evaluation only at the 100 kPa matric potential, in the last section, the study of σ_p within a WC range with the LBCM adjustment showed the sensitivity of the soil mechanical properties to the OT effects after 18 months of soil preparation. Studies evaluating the impacts of machinery traffic on agricultural areas have shown the efficiency of the LBCM (Dias Junior et al., 2005; Martins et al., 2018; Tassinari et al., 2019), corroborating the data of the present study in detecting the OT effect.

In the 0.25-0.30 m, the OT methods had similar effects on the soil compressive behavior. Region "c" had 54%, 56%, and 44% of the data points for the NTC, NTSDL, and NTSSL treatments, respectively (Fig. 2). The persistence of the structural alleviation in the subsurface shows the beneficial effects of OT with depth, improving the physical conditions for in-depth root growth, optimizing the use of water and nutrients, and gas exchanges (Schneider et al., 2017). Previous studies in this experimental area showed that the 0.25-0.30 m soil layer posed increased physical limitations to crop development (Peixoto et al., 2019a, 2019b). The persistence of OT effects in the 0.25-0.30 m soil depth after 18 months of soil preparation confirms that the area presented subsurface compaction and that OT was efficient to mitigate the problem. Further, the propagation of vertical stresses promoted by the machinery traffic in the 0.25-0.30 m layer is lower than under the 0-0.05 m soil depth (Fig. 3*c* and *d*), resulting in higher persistence of OT effects due to the reduced rearrangement of soil structure.

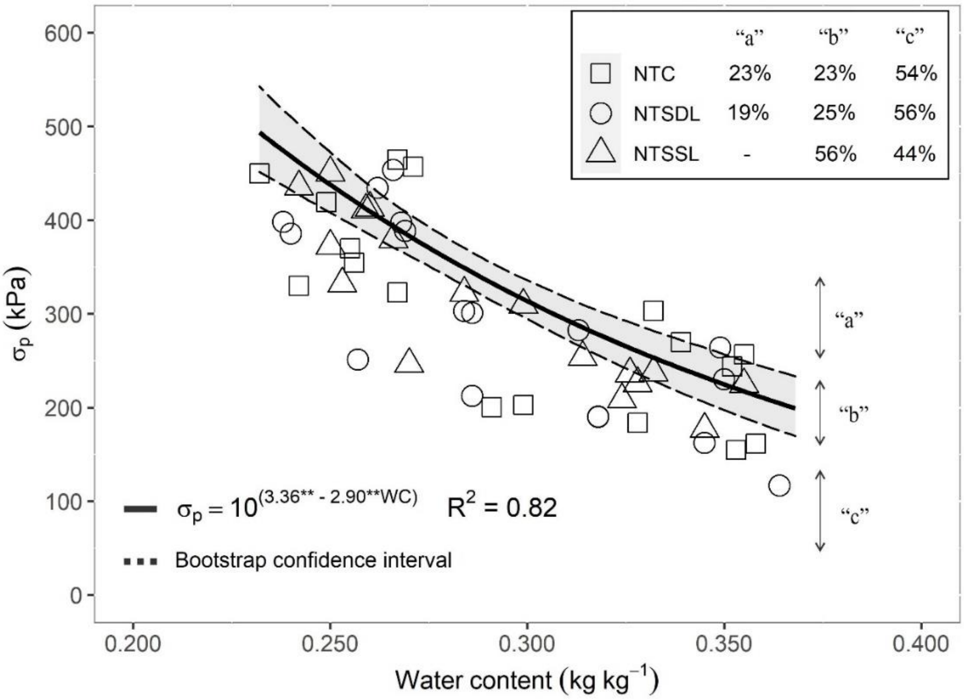

Fig. 2. Load-bearing capacity model in the 0.25-0.30 m depth in soil under continuous NT. The different data points represent the OT managements with their respective percentages in each region of the model. Briefly, region “a” indicates structural rearrangement, region “b” indicates that there is no OT effect, and region “c” indicates structural alleviation due to OT. NT: Continuous no-tillage (control); NTC: no-tillage with chiseling; NTSDL: no-tillage with subsoiling + liming application at the 0.40-0.60 m depth; NTSSL: no-tillage with subsoiling + liming application on the soil surface.

3.3.Integrating vertical stresses applied, σ_p, and LLWR

The maximum contact pressure of the John Deere Hydro 1175 maize harvester was 278 kPa and 209 kPa for the front and rear tires, respectively (Figs. 3a and b). The vertical stress applied in the center of the 0-0.05 m layer was 253 kPa and 202 kPa for the front and rear tires, respectively. In the center of the 0.25-0.30 m layer, the vertical stress applied was 175 kPa and

84 kPa for the front and rear tires, respectively (Figs. 3*c* and *d*). As discussed by Lima et al. (2019), the applied stresses are similar to those reported in the literature; however, information on the vertical stresses applied by the machinery used in grain cultivation systems is still scarce. In a study conducted in a grain production area in São Paulo, Brazil, the maximum vertical stresses applied were 194 kPa to 271 kPa for tractors (Cardoso, 2007). The authors observed stresses of 282 kPa to 362 kPa for the same harvester described in this study (John Deere 1175) and 318 kPa to 452 kPa for a self-propelled sprayer (Cardoso, 2007). In an NT area, Bertollo et al. (2021) estimated that the maximum vertical pressures applied by a tractor ranged from 181 kPa to 192 kPa, and between 217 kPa and 393 kPa for a grain harvester.

The information on vertical stresses and the load-bearing capacity of the soil surface layer evidenced the risk of additional compaction resulting from agricultural machinery traffic, especially when soil moisture is higher than -100 kPa. Under these conditions, the lowest σ_p was 238 kPa (NTSDL), and the highest σ_p was 345 kPa (NTSSL), situations of high and low risk of compaction, respectively. Thus, integrating the information on vertical stresses applied by agricultural machinery, soil load-bearing capacity, and soil water content is critical for adequate and sustainable soil management. This integrated knowledge may help to decide the proper time to perform mechanized operations in the field, thus mitigating additional compaction problems and maintaining structural soil quality.

The vertical stresses applied by a harvester in the center of the 0-0.05 and 0.25-0.30 m layers (Figs. 3c and d) were used to define the θ upper limit, as a function of Bdo, in which the traffic of this agricultural machinery does not exceed σp, and thus not causing additional compaction. The θ limits as a function of Bdo in the stresses applied by the front and rear tires were plotted on the LLWR graph for the two soil layers evaluated (Figs. 4 and 6).

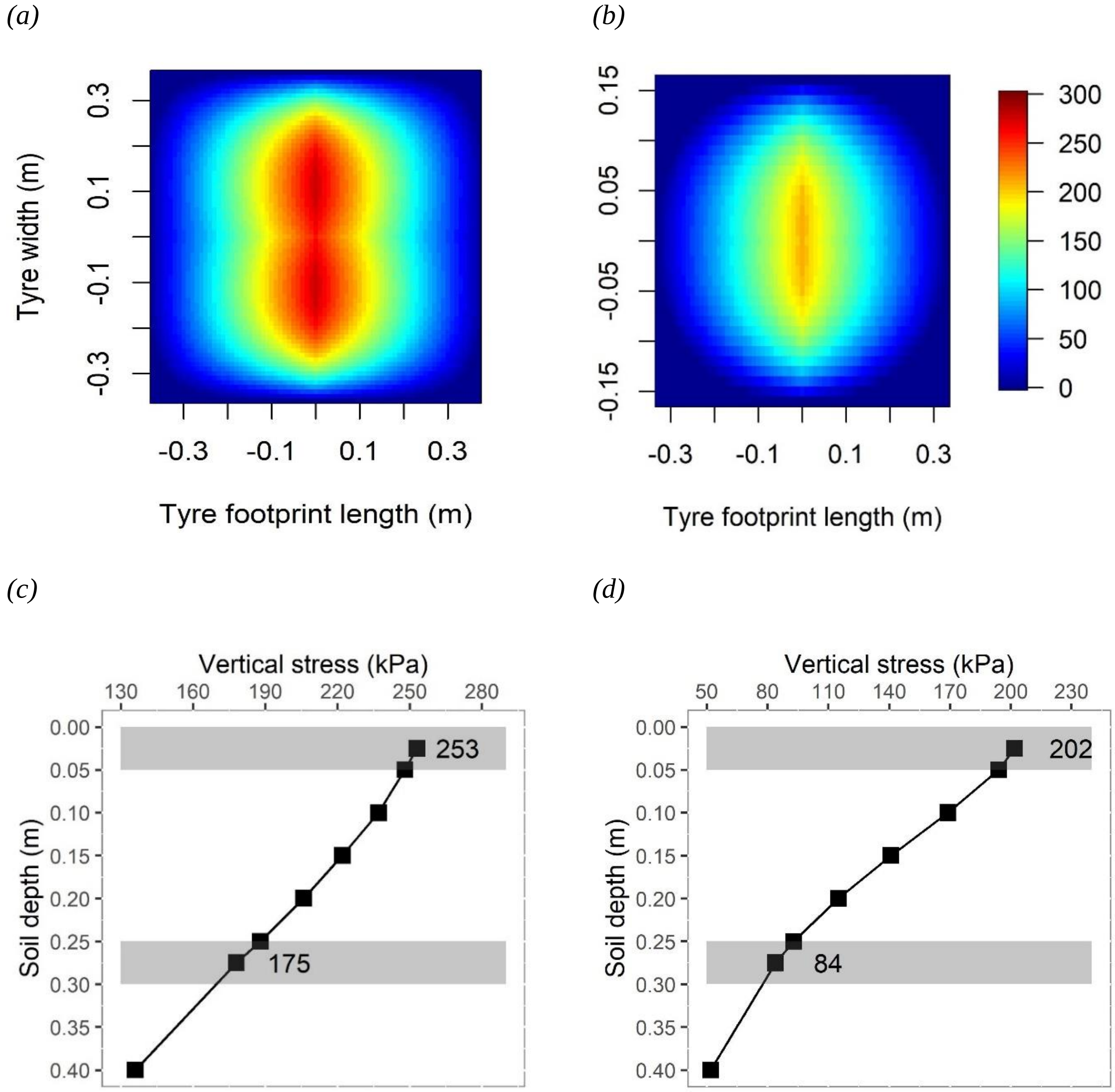

Fig. 3. Contact area and vertical stress (kPa) of the front (a) and rear tires (b). Vertical stress values of 253, 175, 202, and 84, as a function of soil layer, indicate vertical stress at the 0.025 m and 0.275 m depth beneath the center of the front (c) and rear (d) tires, respectively. The grey area in (c) and (d) represents the sampled soil layer.

Figure 4 shows the LLWR in the 0-0.05 m layer added with the θ limit and considering the 253 kPa pressure on the front tires and 202 kPa on the rear tires of the harvester. The θPR was the lower LLWR limit for Bd > 1.10 Mg m^{-3} in the evaluated management systems, except for NTSDL, which was not limited by the excessive mechanical resistance to plant roots. The upper LLWR limit was delimited by the θFC up to Bd values ~ 1.30 Mg m^{-3} for the NT, NTC, and NTSSL treatments. In higher values, θAP became restrictive. The NTSDL did not reach Bd values in which θAP was limiting.

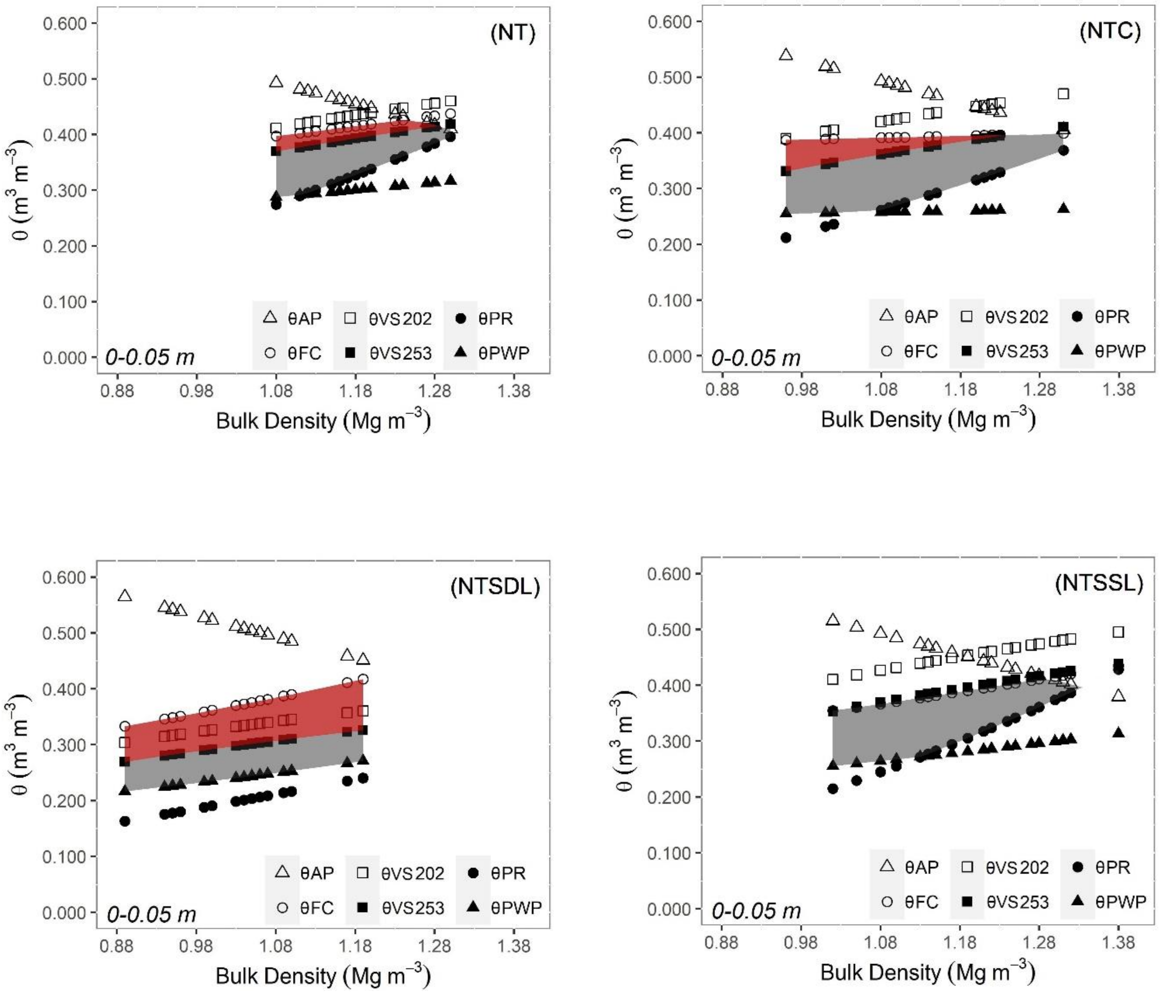

Fig. 4. Soil water content variation as a function of bulk density at critical levels of estimated field capacity (θFC), permanent wilting point (θPWP), air-filled porosity of 0.10 m3m-3 (θAP), penetration resistance of 2 MPa, and vertical stress applied by the maize harvester without promoting additional compaction, 253 kPa for the front tires (θVS253) and 202 kPa for the rear tires (θVS202), at the 0-0.05 m depth. NT: Continuous no-tillage (control); NTC: no-tillage with chiseling; NTSDL: no-tillage with subsoiling + liming application at the 0.40-0.60 m depth; NTSSL: no-tillage with subsoiling + liming application on the soil surface. The gray area represents the least limiting water range to plant growth and resistance to additional soil compaction (LLWRσ_p). The red area is the part of the classical LLWR in which harvesting traffic can cause additional compaction.

Considering the vertical stress of 253 kPa applied by the harvester front tires and the σp in each management system, we observed that the limit of θ for traffic without causing additional compaction to the soil is below the upper LLWR limit in the NT, NTC, and NTSDL treatments (Figs. 4). As for the rear tires, vertical stress of 202 kPa was only below the upper LLWR limit in the NTSDL treatment. This result indicates that even when physical limitations to plant growth are minimal, there is a mechanical limitation for machinery traffic, particularly in the management system that reduced σ_p, as observed for NTSDL. Thus, σ_p becomes a limiting factor for the conservation management of soil and crops. If there is harvester traffic in a soil moisture content higher than the θVS, additional soil compaction will occur, thus leading to degradation of soil structure. Studies have shown that soil tillage reduces σ_p (Nunes et al., 2019; Silva et al., 2003; Veiga et al., 2007) and makes the soil more susceptible to compaction (Chan et al., 2006; Hamza and Anderson, 2005; Nunes et al., 2019; Veiga et al., 2007), corroborating the LLWRσ_p results obtained in this work.

Due to the low σ_p, the appropriate θ limit for machine traffic fell into the middle of the LLWR for the NTSDL treatment. As for the other treatments, the θ limit was a little below (NT and NTC) or even above (NTSSL) the upper LLWR limit (red area in figure 4). Thus, the lower the θVS, the less resistant the soil is to compaction, or the vertical stresses applied by the agricultural machinery increase. This trend expands the range of soil moisture content within the LLWR in which additional compaction can occur (red area in figure 4). The integration of σ_p and vertical pressures in the LLWR graph does not mean that σ_p will pose physical limitations to plant growth. This because the mechanical impediment is already characterized by PR in the LLWR. The inclusion of θVS meant to indicate the range of soil moisture content in which agricultural machinery traffic does not cause additional soil compaction. Moreover, it indicates whether the LLWR is included within this range or not. Thus, we propose a new indicator, the LLWRσ_p. This indicator consists of a range of soil moisture content of minimal physical limitations to the development of crops, in which the traffic of previously known machines does not lead to additional soil compaction.

The range of soil moisture content in which the soil physical limitations to the growth of plants' roots are minimal (LLWR) is already well known and discussed in the literature (Chen et al., 2014; Lapen et al., 2004; Moura et al., 2021a; Neyshabouri et al., 2014; Safadoust et al., 2014; Silva et al., 1994, 2015). Studies have shown that machinery traffic can affect the LLWR (Betz et al., 1998; Beutler et al., 2008; Lapen et al., 2004; Lima et al., 2019). Thus, adding σp and the vertical stresses applied by agricultural machinery to this indicator is critical. Various mechanized operations can be performed with soil in the LLWR, especially in the summer crop season (October to March in the grain production areas of Brazil), when most rainfall occurs. This condition is considered ideal for the development of crops. However, machinery traffic when soil is in the LLWR may lead to additional compaction, thus increasing Bd and possibly reducing the LLWR.

Figure 5 shows the difference between the LLWR (Fig. 5a) and LLWRσ_p (Fig. 5b) for the different soil management systems. The LLWR was higher for the NTSDL treatment, followed by NTC up to the Bd value of 1.10 Mg m^{-3}. From that value, the LLWR for the NTC treatment was similar to NT and NTSSL (Fig. 5a). The critical soil bulk density (IHO = 0) was 1.35 Mg m^{-3} for NTC and NTSSL. Unlike the LLWR, LLWRσ_P was lower for NTSDL and higher for NTSSL up to Bd ~ 1.28 Mg m^{-3}. From that, the behavior of the two indicators became similar. Therefore, soils submitted to OT may have reduced physical limitations to the root growth of cultivated plants However, the reduction in σ_P will limit machine traffic, as soils also become more susceptible to compaction.

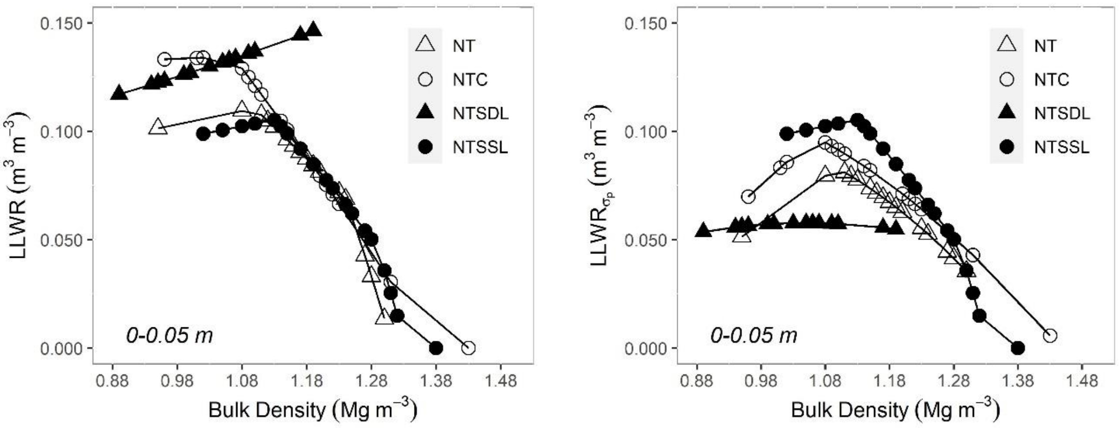

Fig. 5. Least limiting water range (a) and modified least limiting water range integrated with the soil load-bearing capacity (b) as a function of soil bulk density in four soil management systems at the 0-0.05 m soil depth. NT: Continuous no-tillage (control); NTC: no-tillage with chiseling; NTSDL: no-tillage with subsoiling + liming application at the 0.40-0.60 m depth; NTSSL: no-tillage with subsoiling + liming application on the soil surface.

Figure 6 shows the LLWR in the 0.25-0.30 m layer added with the θVS limit associated with the σ_P, considering the vertical stresses of 175 kPa in the front tires and 84 kPa in the rear tires. Unlike the soil surface layer, θVS is higher than the upper LLWR limit. Thus, the harvester can traffic in any θ condition within the range delimited by the LLWR without causing additional compaction in the subsurface.

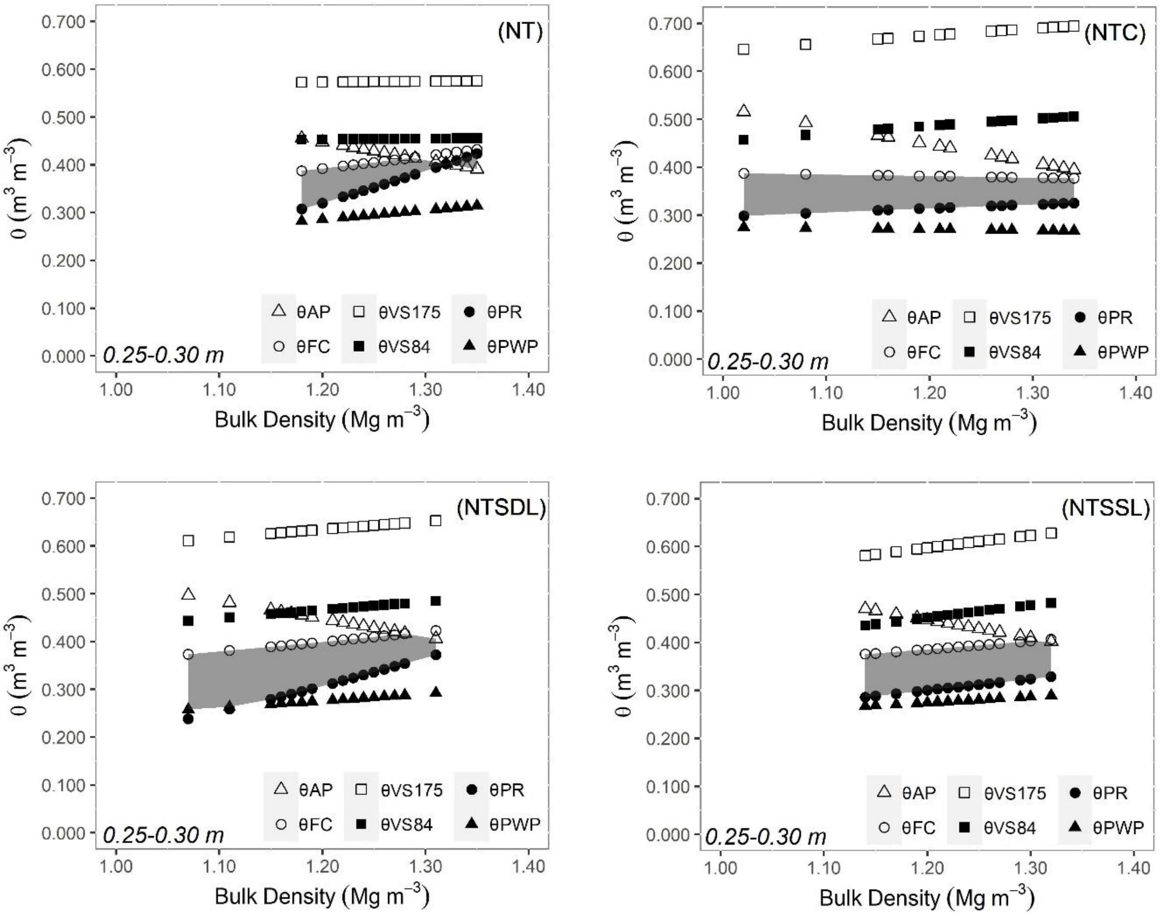

Fig. 6. Soil water content variation as a function of bulk density at critical levels of estimated field capacity (θFC), permanent wilting point (θPWP), air-filled porosity of 0.10 m3m-3 (θAP), penetration resistance of 2 MPa, and vertical stress applied by the corn harvester that does not promote additional compaction, 175 kPa for the front tires (θVS175) and 84 kPa for the rear tires (θVS84), at the 0.25-0.30 m depth. NT: Continuous no-tillage (control); NTC: no-tillage with chiseling; NTSDL: no-tillage with subsoiling + liming application at the 0.40-0.60 m depth; NTSSL: no-tillage with subsoiling + liming application on the soil surface. The gray area represents the least limiting water range to plant growth and resistance to soil additional compaction (LLWRσ_p).

The upper LLWR limit was the θFC for the entire range of Bd values for the NTC and NTSSL treatments. The lower LLWR limit for all management systems was the θPR. The NT management system reached the critical density around 1.32 Mg m^{-3}, limited by the θAP in the upper region and the θPR in the lower region. These limits were not observed for the OT management systems. OT was efficient in reducing soil compaction in the subsurface, thus alleviating the stress caused by excessive mechanical resistance and deficient aeration to the roots of cultivated plants.

At a depth of 0.25-0.30 m, θVS was always higher than the upper LLWR limit. Thus, the LLWRσ_p was equal to the classical LLWR. This result was due to the lower vertical stress applied by the harvester traffic on this soil layer. Comparing the effects of treatments, areas that received OT had increased LLWR values than NT in almost the entire range of Bd values (Fig.7). Among the OT management systems, subsoiling was more effective in increasing the LLWR than chiseling. Up to the Bd value of 1.23 mg m^{-3}, the NTSDL presented a higher LLWR than the NTSSL. However, from this Bd value, the LLWR in NTSDL became lower than in NTSSL. This reverse trend is explained by the higher intensity of the mechanical resistance to penetration, thus reducing the LLWR in the NTSDL treatment. The different behaviors among the subsoiling management systems can be explained by the tip shape. In the NTSDL treatment, the subsoiler has a wedge-type tip, whereas, in the NTSSL treatment, it has a winged tip. Subsoilers with wedge-type tips promote 2 to 3 times less disturbance to the soil than winged-tip subsoilers (Kumar and Thakur, 2005). Thus, wedged-type subsoilers preserve the soil structure better and may extend the time necessary to rearrange the soil particles.

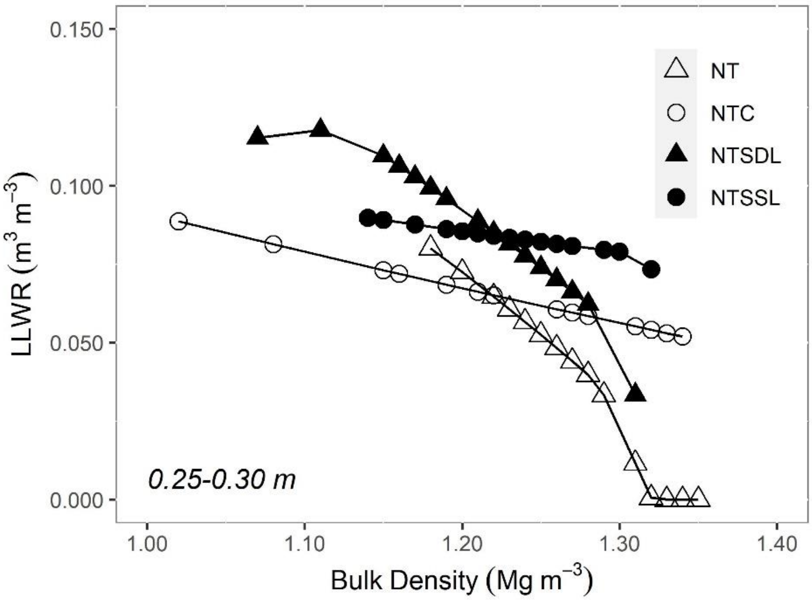

Fig. 7. Least limiting water range (LLWR) in the 0.25-0.30 m soil depth as a function of soil bulk density in four soil management systems. NT: Continuous no-tillage (control); NTC: no-tillage with chiseling; NTSDL: no-tillage with subsoiling + liming application at the 0.40-0.60 m depth; NTSSL: no-tillage with subsoiling + liming application on the soil surface.

4. Conclusion

Physical (matric potential) and mechanical (pre-compression pressure) soil properties, based on the uniaxial compression test in only one specific matric potential (e.g., -100 kPa), were not adequate to evaluate the OT effects. However, the soil load-bearing capacity model, which represents the pre-compression pressure (σ_p) as a function of the soil moisture content, proved to be a sensitive indicator to the effect of OT in NT, even 18 months after the soil preparation.

OT alleviated the physical limitations to the growth of crops' roots, particularly in the subsurface. OT increased the least limiting water range (LLWR), especially by reducing the mechanical penetration resistance. Subsoiling was more effective and persistent than chiseling to reduce σ_p and enhance the LLWR in both soil layers evaluated (0-0.05 m and 0.25-0.30 m).

We propose a new upper limit for the LLWR by integrating the model of soil load-bearing capacity and the vertical stress applied by agricultural machinery. Based on this new limit, we defined a range of soil moisture content in which the traffic of agricultural machinery does not lead to additional soil compaction. This limit defines the least limiting water range for the growth of cultivated plants and resistance to additional compaction (LLWRσ_p). The LLWRσ_p is a range of soil moisture content in which the physical limitations to the development of the roots of cultivated plants are minimal, and the traffic of a previously known machine does not cause additional soil compaction. The proposed indicator was tested on the soil surface layer and subsoil, considering the vertical pressure applied by a corn harvester and the soil load-bearing capacity. The new indicator can help to choose the best moment to perform mechanized operations in grain production areas.

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6. References

Ajayi, A.E., Dias Júnior, M.S., Curi, N., Okunola, A., Souza, T.T.T., Pires, B.S., 2010. Assessment of Vulnerability of Oxisols to Compaction in the Cerrado Region of Brazil. Pedosphere 20, 252–260. https://doi.org/10.1016/S1002-0160(10)60013-6

Bavoso, M.A., da Silva, A.P., Figueiredo, G.C., Tormena, C.A., Giarola, N.F.B., 2012. Resiliência física de dois latossolos vermelhos sob plantio direto. Rev. Bras. Cienc. do Solo 36, 1892–1904. https://doi.org/10.1590/S0100-06832012000600023

Benevenute, P.A.N., de Morais, E.G., Souza, A.A., Vasques, I.C.F., Cardoso, D.P., Sales, F.R., Severiano, E.C., Homem, B.G.C., Casagrande, D.R., Silva, B.M., 2020. Penetration resistance: An effective indicator for monitoring soil compaction in pastures. Ecol. Indic. 117. https://doi.org/10.1016/j.ecolind.2020.106647

Bengough, A.G., Bransby, M.F., Hans, J., McKenna, S.J., Roberts, T.J., Valentine, T.A., 2006. Root responses to soil physical conditions; growth dynamics from field to cell. J. Exp. Bot. 57, 437–447. https://doi.org/10.1093/jxb/erj003

Bertollo, A.M., Moraes, M.T. de, Franchini, J.C., Soltangheisi, A., Balbinot Junior, A.A., Levien, R., Debiasi, H., 2021. Precrops alleviate soil physical limitations for soybean root growth in an Oxisol from southern Brazil. Soil Tillage Res. 206, 104820. https://doi.org/10.1016/j.still.2020.104820

Betz, C.L., Allmaras, R.R., Copeland, S.M., Randall, G.W., 1998. Least Limiting Water Range: Traffic and Long-term Tillage Influences in a Webster Soil. Soil Sci. Soc. Am. J. 62, 1384–1393. https://doi.org/10.2136/sssaj1998.03615995006200050034x

Beutler, A.N., Centurion, J.F., Silva, A.P. Da, Centurion, M.A.P.D.C., Leonel, C.L., Freddi, O.D.S., 2008. Soil compaction by machine traffic and least limiting water range related to soybean yield. Pesqui. Agropecuária Bras. 43, 1591–1600. https://doi.org/10.1590/S0100-204X2008001100019

Blanco-Canqui, H., Ruis, S.J., 2018. No-tillage and soil physical environment. Geoderma 326, 164–200. https://doi.org/10.1016/j.geoderma.2018.03.011

Blanco-Canqui, H., Wortmann, C.S., 2020. Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil Tillage Res. 198, 104534. https://doi.org/10.1016/j.still.2019.104534

Bonetti, J.A., Anghinoni, I., Moraes, M.T., Fink, J.R., 2017. Resilience of soils with different texture, mineralogy and organic matter under long-term conservation systems. Soil Tillage Res. 174, 104–112. https://doi.org/10.1016/j.still.2017.06.008

Cardoso, V.M.F., 2007. Sustentabilidade estrutural de um solo na região do Alto Paranapanema, submetido a dois sistemas de cultivo. Universidade Estadual Paulista.

Chan, K.Y., Oates, A., Swan, A.D., Hayes, R.C., Dear, B.S., Peoples, M.B., 2006. Agronomic consequences of tractor wheel compaction on a clay soil. Soil Tillage Res. 89, 13–21. https://doi.org/10.1016/j.still.2005.06.007

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 Tillage Res. 136, 61–69. https://doi.org/10.1016/j.still.2013.09.004

Companhia Nacional de Abastecimento, 2019. Boletim da Safra de Grãos: Acompanhamento da safra 2018/19 brasileira de grãos - 12º levantamento. CONAB, Brasília, DF.

Correa, J., Postma, J.A., Watt, M., Wojciechowski, T., 2019. Soil compaction and the architectural plasticity of root systems. J. Exp. Bot. 70, 6019–6034. https://doi.org/10.1093/jxb/erz383

Denardin, J.E., Faganello, A., Santi, A., 2008. Falhas na implementação do sistema plantio direto levam à degradação do solo. Rev. Plantio Direto 18, 3–4.

Deuschle, D., Minella, J.P.G., Hörbe, T. de A.N., Londero, A.L., Schneider, F.J.A., 2019. Erosion and hydrological response in no-tillage subjected to crop rotation intensification in southern Brazil. Geoderma 340, 157–163. https://doi.org/10.1016/j.geoderma.2019.01.010

Dexter, A.R., Horn, R., Kemper, W.D., 1988. Two mechanisms for age-hardening of soil. J. Soil Sci. 39, 163–175. https://doi.org/10.1111/j.1365-2389.1988.tb01203.x

Dias Júnior, M. de S., 1994. Compression of three soils under long-term tillage and wheel traffic. Michigan State University.

Dias Junior, M. de S., Leite, F.P., Lasmar Júnior, E., Araújo Junior, C.F., 2005. Traffic effects on the soil preconsolidation pressure due to eucalyptus harvest operations. Sci. Agric. 62, 248–255. https://doi.org/10.1590/S0103-90162005000300008

Dias Júnior, M. de S., Martins, P.C.C., 2017. Ensaio de compressão uniaxial e modelos de capacidade de suporte de carga do solo, in: Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G. (Eds.), Manual de Métodos de Análise de Solo. Embrapa, Brasília, DF, p. 574.

Dias Junior, M.S., Pierce, F.J., 1995. A simple procedure for estimating preconsolidation pressure from soil compression curves. Soil Technol. 8, 139–151. https://doi.org/10.1016/0933-3630(95)00015-8

Dias Júnior, M.S., Pierce, F.J., 1996. Revisão de literatura: o processo de compactação do solo e sua modelagem. Rev. Bras. Cienc. do Solo 20, 175–182.

Drescher, M.S., Eltz, F.L.F., Denardin, J.E., Faganello, A., 2011. Persistência do efeito de intervenções mecânicas para a descompactação de solos sob plantio direto. Rev. Bras. Ciência do Solo 35, 1713–1722. https://doi.org/10.1590/S0100-06832011000500026

Drescher, M.S., Reinert, D.J., Denardin, J.E., Gubiani, P.I., Faganello, A., Drescher, G.L., 2016. Duração das alterações em propriedades físico-hídricas de Latossolo argiloso decorrentes da escarificação mecânica. Pesqui. Agropecuária Bras. 51, 159–168. https://doi.org/10.1590/S0100-204X2016000200008

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

FEBRAPD, 2019. Área do Sistema Plantio Direto [WWW Document]. Fed. Bras. Plantio Direto e Irrig. URL https://febrapdp.org.br/area-de-pd (accessed 10.31.20).

Ferreira, C.J.B., Tormena, C.A., Severiano, E.D.C., Zotarelli, L., Betioli Júnior, E., 2020. Soil compaction influences soil physical quality and soybean yield under long-term no-tillage. Arch. Agron. Soil Sci. 0, 1. https://doi.org/10.1080/03650340.2020.1733535

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems. Soil Tillage Res. 82, 121–145. https://doi.org/10.1016/j.still.2004.08.009

Imhoff, S., Sliva, Á.P., Dias Junior, Moacir de Souza Tormena, C.A., 2001. Quantificação De Pressões Críticas para o crescimento das plantas. Rev. Bras. Cienc. do Solo 25, 11–18.

Kassam, A., Friedrich, T., Derpsch, R., 2018. Global spread of Conservation Agriculture. Int. J. Environ. Stud. 76, 29–51. https://doi.org/10.1080/00207233.2018.1494927

Keller, T., da Silva, A.P., Tormena, C.A., Giarola, N.F.B., Cavalieri, K.M. V, Stettler, M., Arvidsson, J., 2015. SoilFlex-LLWR: Linking a soil compaction model with the least limiting water range concept. Soil Use Manag. 31, 321–329. https://doi.org/10.1111/sum.12175

Keller, T., Défossez, P., Weisskopf, P., Arvidsson, J., Richard, G., 2007. SoilFlex: A model for prediction of soil stresses and soil compaction due to agricultural field traffic including a synthesis of analytical approaches. Soil Tillage Res. 93, 391–411. https://doi.org/10.1016/j.still.2006.05.012

Keller, T., Sandin, M., Colombi, T., Horn, R., Or, D., 2019. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. Soil Tillage Res. 194, 104293. https://doi.org/10.1016/j.still.2019.104293

Kumar, A., Thakur, T.C., 2005. An investigation into comparative test of conventional and winged subsoilers, in: 2005 ASAE Annual International Meeting. American Society of Agricultural and Biological Engineers, St. Joseph, MI. https://doi.org/10.13031/2013.19770

Lamandé, M., Schjønning, P., 2011a. Transmission of vertical stress in a real soil profile. Part II: Effect of tyre size, inflation pressure and wheel load. Soil Tillage Res. 114, 71–77. https://doi.org/10.1016/j.still.2010.08.011

Lamandé, M., Schjønning, P., 2011b. Transmission of vertical stress in a real soil profile. Part I: Site description, evaluation of the Söhne model, and the effect of topsoil tillage. Soil Tillage Res. 114, 57–70. https://doi.org/10.1016/j.still.2011.05.004

Lapen, D.R., Topp, G.C., Gregorich, E.G., Curnoe, W.E., 2004. Least limiting water range indicators of soil quality and corn production, eastern Ontario, Canada. Soil Tillage Res. 78, 151–170. https://doi.org/10.1016/j.still.2004.02.004

Letey, J., 1985. Relationship between Soil Physical Properties and Crop Production, in: Stewart, B.A. (Ed.), Advances in Soil Science, Advances in Soil Science. Springer New York, New York, NY, pp. 277–294. https://doi.org/10.1007/978-1-4612-5046-3_8

Li, S., Wu, X., Liang, G., Gao, L., Wang, B., Lu, J., Abdelrhman, A.A., Song, X., Zhang, M., Zheng, F., Degré, A., 2020. Is least limiting water range a useful indicator of the impact of tillage management on maize yield? Soil Tillage Res. 199, 104602. https://doi.org/10.1016/j.still.2020.104602

Lima, R.P., Silva, A.R., Silva, Á.P., 2021. soilphysics: An R package for simulation of soil compaction induced by agricultural field traffic. Soil Tillage Res. 206, 104824. https://doi.org/10.1016/j.still.2020.104824

Lima, R.P.D., Keller, T., Giarola, N.B.F., Tormena, C.A., Silva, A.R.D., Rolim, M.M., 2019. Measurements and simulations of compaction effects on the least limiting water range of a no-till Oxisol. Soil Res. 58, 62–72. https://doi.org/10.1071/SR19074

Lipiec, J., Horn, R., Pietrusiewicz, J., Siczek, A., 2012. Effects of soil compaction on root elongation and anatomy of different cereal plant species. Soil Tillage Res. 121, 74–81. https://doi.org/10.1016/j.still.2012.01.013

Lipiec, J., Stępniewski, W., 1995. Effects of soil compaction and tillage systems on uptake and losses of nutrients. Soil Tillage Res. 35, 37–52. https://doi.org/10.1016/0167-1987(95)00474-7

Martins, P.C.C., Dias Junior, M.D.S., Ajayi, A.E., Takahashi, E.N., Tassinari, D., 2018. Soil compaction during harvest operations in five tropical soils with different textures under eucalyptus forests. Cienc. e Agrotecnologia 42, 58–68. https://doi.org/10.1590/1413-70542018421005217

Melero, S., Panettieri, M., Madejón, E., Macpherson, H.G., Moreno, F., Murillo, J.M., 2011. Implementation of chiselling and mouldboard ploughing in soil after 8 years of no-till management in SW, Spain: Effect on soil quality. Soil Tillage Res. 112, 107–113. https://doi.org/10.1016/j.still.2010.12.001

Melland, A.R., Antille, D.L., Dang, Y.P., 2017. Effects of strategic tillage on short-term erosion, nutrient loss in runoff and greenhouse gas emissions. Soil Res. 55, 201. https://doi.org/10.1071/SR16136

Mohammadi, M.H., Asadzadeh, F., Vanclooster, M., 2010. Refining and unifying the upper limits of the least limiting water range using soil and plant properties. Plant Soil 334, 221–234. https://doi.org/10.1007/s11104-010-0377-3

Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.R., Luz, F.B., 2017. Age-hardening phenomena in an oxisol from the subtropical region of Brazil. Soil Tillage Res. 170, 27–37. https://doi.org/10.1016/j.still.2017.03.002

Moreira, S.G., 2019. Desafios para a sustentabilidade dos sistemas de produção com culturas anuais. Informações Agronômicas 4, 1–12.

Moura, M.S. de, Silva, B.M., Mota, P.K., Borghi, E., Resende, A.V. de, Acuña-Guzman, S.F., Araújo, G.S.S., da Silva, L. de C.M., de Oliveira, G.C., Curi, N., 2021a. Soil management and diverse crop rotation can mitigate early-stage no-till compaction and improve least limiting water range in a Ferralsol. Agric. Water Manag. 243, 106523. https://doi.org/10.1016/j.agwat.2020.106523

Moura, M.S. de, Silva, B.M., Mota, P.K., Borghi, E., Resende, A.V. De, Acuña-Guzman, S.F., Araújo, G.S.S., da Silva, L. de C.M., de Oliveira, G.C., Curi, N., 2021b. Soil management and diverse crop rotation can mitigate early-stage no-till compaction and improve least limiting water range in a Ferralsol. Agric. Water Manag. 243, 106523. https://doi.org/10.1016/j.agwat.2020.106523

Nawaz, M.F., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron. Sustain. Dev. 33, 291–309. https://doi.org/10.1007/s13593-011-0071-8

Neyshabouri, M.R., Kazemi, Z., Oustan, S., Moghaddam, M., 2014. PTFs for predicting LLWR from various soil attributes including cementing agents. Geoderma 226–227, 179–187. https://doi.org/10.1016/j.geoderma.2014.02.008

Nunes, M.R., Denardin, J.E., Pauletto, E.A., Faganello, A., Pinto, L.F.S., 2015. Mitigation of clayey soil compaction managed under no-tillage. Soil Tillage Res. 148, 119–126. https://doi.org/10.1016/j.still.2014.12.007

Nunes, M.R., Pauletto, E.A., Denardin, J.E., Faganello, A., Spinelli Pinto, L.F., Scheunemann, T., 2014. Persistência dos efeitos da escarificação sobre a compactação de Nitossolo sob plantio direto em região subtropical úmida. Pesqui. Agropecuária Bras. 49, 531–539. https://doi.org/10.1590/S0100-204X2014000700005

Nunes, M.R., Pauletto, E.A., Denardin, J.E., Luis, L.E.A., van Es, H.M., 2019. Dynamic changes in compressive properties and crop response after chisel tillage in a highly weathered soil. Soil Tillage Res. https://doi.org/10.1016/j.still.2018.10.017

O'Sullivan, M.F., Henshall, J.K., Dickson, J.W., 1999. A simplified method for estimating soil compaction. Soil Tillage Res. 49, 325–335. https://doi.org/10.1016/S0167-1987(98)00187-1

Peixoto, D.S., Silva, B.M., de Oliveira, G.C., Moreira, S.G., da Silva, F., Curi, N., 2019a. A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. Soil Tillage Res. 194, 104307. https://doi.org/10.1016/j.still.2019.104307

Peixoto, D.S., Silva, B.M., Silva, S.H.G., Karlen, D.L., Moreira, S.G., Silva, A.A.P., Resende, Á.V., Norton, L.D., Curi, N., 2019b. Diagnosing, Ameliorating, and Monitoring Soil Compaction in No-Till Brazilian Soils. Agrosystems, Geosci. Environ. 2, 180035. https://doi.org/10.2134/age2018.09.0035

Peixoto, D.S., Silva, L. de C.M. da, Melo, L.B.B. de, Azevedo, R.P., Araújo, B.C.L., Carvalho, T.S. de, Moreira, S.G., Curi, N., Silva, B.M., 2020. Occasional tillage in no-tillage systems: A global meta-analysis. Sci. Total Environ. 745, 140887. https://doi.org/10.1016/j.scitotenv.2020.140887

Prats, S.A., Malvar, M.C., Coelho, C.O.A., Wagenbrenner, J.W., 2019. Hydrologic and erosion responses to compaction and added surface cover in post-fire logged areas: Isolating splash, interrill and rill erosion. J. Hydrol. 575, 408–419. https://doi.org/10.1016/j.jhydrol.2019.05.038

R Development Core Team, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Viena, Austria.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.J., 2018. Soil structure as an indicator of soil functions: A review. Geoderma. https://doi.org/10.1016/j.geoderma.2017.11.009

Reichert, J.M., Brandt, A.A., Rodrigues, M.F., da Veiga, M., Reinert, D.J., 2017. Is chiseling or inverting tillage required to improve mechanical and hydraulic properties of sandy clay loam soil under long-term no-tillage? Geoderma 301, 72–79. https://doi.org/10.1016/j.geoderma.2017.04.012

Reichert, J.M., Kaiser, D.R., Reinert, D.J., Riquelme, U.F.B., 2009a. Variação temporal de propriedades físicas do solo e crescimento radicular de feijoeiro em quatro sistemas de manejo. Pesqui. Agropecu. Bras. 44, 310–319. https://doi.org/10.1590/S0100-204X2009000300013

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

Römkens, M.J.M., Miller, R.D., 1971. Predicting root size and frequency from one-dimensional consolidation data — A mathematical model. Plant Soil 35, 237–248. https://doi.org/10.1007/BF01372654

Safadoust, A., Feizee, P., Mahboubi, A.A., Gharabaghi, B., Mosaddeghi, M.R., Ahrens, B., 2014. Least limiting water range as affected by soil texture and cropping system. Agric. Water Manag. 136, 34–41. https://doi.org/10.1016/j.agwat.2014.01.007

Schneider, F., Don, A., Hennings, I., Schmittmann, O., Seidel, S.J., 2017. The effect of deep tillage on crop yield – What do we really know? Soil Tillage Res. https://doi.org/10.1016/j.still.2017.07.005

Silva, A.P., Kay, B.D., Perfect, E., 1994. Characterization of the Least Limiting Water Range of Soils. Soil Sci. Soc. Am. J. 58, 1775–1781. https://doi.org/10.2136/sssaj1994.03615995005800060028x

Silva, B.M., Oliveira, G.C., Serafim, M.E., Silva, É.A., Ferreira, M.M., Norton, L.D., Curi, N., 2015. Critical soil moisture range for a coffee crop in an oxidic latosol as affected by soil management. Soil Tillage Res. 154, 103–113. https://doi.org/10.1016/j.still.2015.06.013

Silva, J.F.G., Linhares, A.J. de S., Gonçalves, W.G., Costa, K.A. de P., Tormena, C.A., Silva, B.M., Oliveira, G.C. de, Eduardo da Costa Severiano, 2021. Are the yield of sunflower and Paiaguas palisadegrass biomass influenced by soil physical quality ? Soil Tillage Res. 208, 104873. https://doi.org/10.1016/j.still.2020.104873

Silva, R.B., Dias Junior, M.S., Silva, F.A.M., Fole, S.M., 2003. O tráfego de máquinas agrícolas e as propriedades físicas, hídricas e mecânicas de um Latossolo dos Cerrados. Rev. Bras. Ciência do Solo 27, 973–983. https://doi.org/10.1590/S0100-06832003000600002

Soil Science Glossary Terms Committee, 2008. Glossary of soil science terms. Soil Science Society of America, Madison, WI.

Szatanik-Kloc, A., Horn, R., Lipiec, J., Siczek, A., Szerement, J., 2018. Soil compaction-induced changes of physicochemical properties of cereal roots. Soil Tillage Res. 175, 226–233. https://doi.org/10.1016/j.still.2017.08.016

Tassinari, D., Andrade, M. luiza de C., Dias Junior, M. de S., Martins, R.P., Rocha, W.W., Pais, P.S.A.M., de Souza, Z.R., 2019. Soil compaction caused by harvesting, skidding and wood processing in eucalyptus forests on coarse-textured tropical soils. Soil Use Manag. 35, 400–411. https://doi.org/10.1111/sum.12509

Tian, S., Ning, T., Wang, Y., Liu, Z., Li, G., Li, Z., Lal, R., 2016. Crop yield and soil carbon responses to tillage method changes in North China. Soil Tillage Res. 163, 207–213. https://doi.org/10.1016/j.still.2016.06.005

Veiga, M., Horn, R., Reinert, D.J., Reichert, J.M., 2007. Soil compressibility and penetrability of an Oxisol from southern Brazil, as affected by long-term tillage systems. Soil Tillage Res. 92, 104–113. https://doi.org/10.1016/j.still.2006.01.008

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PAPER 5 - MACHINE LEARNING FOR DIAGNOSIS OF SOIL COMPACTION IN A CONTINUOUS NO-TILLAGE SYSTEM

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Abstract

Correct diagnosis of the state of soil compaction is a challenge in continuous no-tillage (NT). Many farmers have used occasional tillage (OT) for the purpose of mitigating compaction problems. However, without adequate diagnosis, OT can lead to loss of some benefits of NT and, even so, not provide an increase in crop yield. Within this context, the aim of this study was to evaluate the performance of four learning algorithms to diagnose the state of soil compaction under no-tillage. For these purposes, data from a field experiment conducted in a clayey texture Typic Hapludox with mechanical (chiseling and subsoiling) and chemical (gypsum and limestone) methods for mitigation of soil compaction were used. Soil physical variables [soil bulk density (BD), penetration resistance (PR), macro (MAC) - and microporosity (MIC), air capacity (AC), available water content (AWC), relative field capacity (RFC), and total porosity (TP)] and crop yield (Rel_Yield) were used in the classification algorithms, Classification and Regression Trees (CART), Random Forest (RF), Artificial Neural Network (ANN) and Support Vector Machine (SVM), to diagnose the state of soil compaction in the NT. The most important variables for predicting the state of soil compaction were Rel_Yield and soil porosity (MAC, TP, MIC and AC). The machine learning algorithms had satisfactory performance for diagnosis of the state of compaction using soil properties and crop yield, and the decision tree algorithms (CART and RF) performed better, with accuracy = 0.90, Kappa index = 0.76, and sensitivity = 0.83. The machine learning algorithm approach proved to be an efficient tool in diagnosis of soil compaction in continuous no-tillage, improving decision making concerning use of OT.

Keywords: Occasional tillage; crop yield; Random Forest; decision tree; soil porosity.

1. Introduction

Soil compaction is the main factor in physical degradation of agricultural soils, and it may reduce or limit crop yield (Correa et al. 2019; Hamza and Anderson 2005; Keller et al. 2019; Nawaz et al. 2013). This is a process of an increase in soil bulk density and concomitant reduction in soil porosity due to application of mechanical forces (Soil Science Glossary Terms Committee 2008), restricting root growth, gas exchanges, and water and nutrient uptake by plant roots (Bengough et al. 2006; Correa et al. 2019; Lipiec and Stępniewski 1995; Lipiec et al. 2012; Szatanik-Kloc et al. 2018).

Studies have found compaction problems in soils under a continuous no-tillage (NT) (Blanco-Canqui and Ruis 2018; Nunes et al. 2014, 2015a; Peixoto et al. 2019a, 2019b; Reichert et al. 2009). In Brazil, more than 32 million hectares of farmland are under NT, with soybean and maize as the main crops (Companhia Nacional de Abastecimento 2021). The main causes of compaction in this management system are associated with intensification of the production system (2-3 crops each year) and consequent increase in machine traffic, inefficiency in crop rotation and in use of cover crops, low input of organic matter, and machine traffic under high soil moisture conditions (Denardin et al. 2008; Drescher et al. 2011; Moreira 2019).

To mitigate the adverse effects of soil compaction in NT, farmers and researchers have used and suggested the use of strategic or occasional tillage (OT), especially with chisel plows and subsoilers (Nunes et al. 2014, 2015b; Peixoto et al. 2019a, 2019b). However, OT can lead to soil and nutrient losses through erosion (Deuschle et al. 2019; Melland et al. 2017) and to reduction in organic matter content (Melero et al. 2011; Peixoto et al. 2020), and, in general, it has not increased the crop yield subsequent to the tillage (Peixoto et al. 2020). Therefore, there is the need for studies for more adequate use of this management technique.

The recommendation for OT should be based on the use of indicators that are able to establish a correlation with crop yield (Peixoto et al. 2019a, 2019b), for if OT is not able to promote an increase in crop yield, its use can be questioned. Some studies have shown an increase in crop yield after OT (Botta et al. 2019; Calonego et al. 2017; Calonego and Rosolem 2010; Nascimento et al. 2016; Peixoto et al. 2019a, 2019b), whereas others have not indicated an effect (Drescher et al. 2012; Girardello et al. 2011; López-Garrido et al. 2011; Quincke et al. 2007). These differing results can mainly be explained by different sensitivity of crops to soil compaction (Arvidsson et al. 2014; Arvidsson and Håkansson 2014), water provision during the crop cycle (Girardello et al. 2011; Hakojärvi et al. 2013), quality of the OT operation, and, perhaps most importantly, the lack of accuracy in diagnosis of compaction for recommendation of OT (Denardin et al. 2008; Peixoto et al. 2020). Thus, correct diagnosis across the farm through use of the best physical indicators and best tools available is fundamental.

The procedures of collection, analysis, and interpretation of soil physical properties aiming at diagnosis and decision-making regarding soil compaction demand a great deal of time, financial resources, and specialized personnel. For that reason, the use of more robust and efficient computational tools in integrated analysis of soil physical properties and crop response has become fundamental in interpreting results and making the most accurate decisions possible. According to recent reviews, advances in computational methods have increased the use of machine learning techniques for prediction of crop yield (Chlingaryan et al. 2018; Maya Gopal and Bhargavi 2019; Mishra et al. 2016). Various studies have used predictor covariates obtained by remote sensing (Filippi et al. 2019; Khanal et al. 2018; Pantazi et al. 2016; Richetti et al. 2018), climate data (Everingham et al. 2016; Fukuda et al. 2013; Mathieu and Aires 2018; Tulbure et al. 2012), and soil properties (Pantazi et al. 2016; Peixoto et al. 2019b; Smidt et al. 2016). Machine learning methods are able to provide high accuracy, capacity for identifying the most important covariates for estimating yield, capacity for modeling complex non-linear interactions, and flexibility for diverse statistical analyses (Cutler et al. 2007). The algorithms of Decision Trees (CART), Random Forest (RF), Artificial Neural Network (ANN), and Support Vector Machine (SVM) are frequently used in prediction of crop yield (Chlingaryan et al. 2018; Gonzalez-Sanchez et al. 2014; Jeong et al. 2016; Kim and Lee 2016; Maya Gopal and Bhargavi 2019).

In this context, the learning algorithms approach for predicting crop yield through use of soil physical properties alone is recent. The study of Peixoto et al. (2019b) allowed the most important soil physical variables for predicting soybean yield to be identified with high accuracy. Thus, our hypothesis is that if it is possible to predict crop yield through the use of soil physical properties and these properties characterize the state of soil compaction, it would then be possible to diagnose compacted areas, with crop yields and soil physical properties as variables predictors, using machine learning algorithms (classification approach). In the literature, there is no use of the machine learning approach using soil physical and crop yield covariates for diagnosis of compacted areas. Thus, the aim of this study was to evaluate the performance of four learning algorithms (CART, RF, ANN and SVM) to diagnose the state of soil compaction under continuous no-tillage.

2. Materials and Methods

2.1. Study area

The experiment was set up in October 2015 on the Santa Helena Farm at 21º15’39’’ S and 44º31’04” W, 1020 m altitude, in the municipality of Nazareno in the Campos das Vertentes physiographic region, State of Minas Gerais, Brazil (Fig. 1). Climate is the Cwa type (Köppen classification), with cold and dry winters and hot and humid summers. Mean annual rainfall is 1300 mm and mean annual temperature is 19.7ºC. The soil was classified as Latossolo Vermelho-Amarelo distrófico típico according to Brazilian System of Soil Classification

(Santos et al. 2018), corresponding the Typic Hapludox according to US Soil Taxonomy (Soil Survey Staff 2014). The mean distribution of clay, silt, and sand in the soil profile of the experimental area was 530, 250, and 220 g kg^{-1}, respectively.

To evaluate the efficiency of four machine learning algorithms to diagnose the state of soil compaction under no-tillage, data from an experiment schematized in large strips, with 7 treatments and 4 replications were used. The strips were set up with 18 m width and 80 m length (1,440 m^{2}) and subdivided into 4 experimental plots of 360 m^{2} (Fig. 1). The treatments consisted of soil management practices for mitigation of compaction, combining physical (mainly) and chemical soil conditioning. The treatments were as follows: continuous NT set up in 2005 (control) (NT); NT with surface application of 3,600 kg ha^{-1} of agricultural Gypsum according to van Raij et al. (1997) (NTG); NT with use of a fertilizing Subsoiler with wedge type tip (KAMAQ®) and Deep Lime placement (depth of 0.40-0.60 m) at a dose of 1,440 kg ha^{-1} [total neutralizing power (TNP) = 180%], taking into account the maximum dose as indicated by Sá (1999) for areas under NT, and spacing of 0.75 m between shanks (NTSDL); NT with use of a Chisel plow with 0.26 m length shanks (NTC); NT with use of a Subsoiler with winged type tip (Ikeda®) with 0.60 m length shanks and Surface Lime application ate a dose of 1,440 kg ha^{-1} (TNP = 180%) (NTSSL); NT with use of Subsoiler in October 2015 (NTS); NT with use of Subsoiler with winged type tip (Ikeda®) with 0.60 m length shank every two years (October 2015 and 2017) (NTS2). The NTS2 treatment was designated as NTS up to the date of the second subsoiling.

Soil fertility and crop management practices were carried out as recommended by the technical team of the farm. After the experiment was set up, no limestone soil amendment was made and fertilization was carried out according to projected export of nutrients by each crop based on expected yield. The production system consisted of rotation: soybean (*Glycine max* (L.) Merrill) and maize (*Zea mays* L.) in the spring-summer crop season, and succession: common bean (*Phaseolus vulgaris* L.) and wheat (*Triticum aestivun* L.) in the fall-winter crop season. When the soil moisture conditions allow, oat (*Avena sativa* L.) is grown after the fall-winter crop season as a cover crop and for production of vegetative matter. More details regarding the field experiment, management practices, machinery, and implements used in the experimental area are described in Peixoto et al. (2019a).

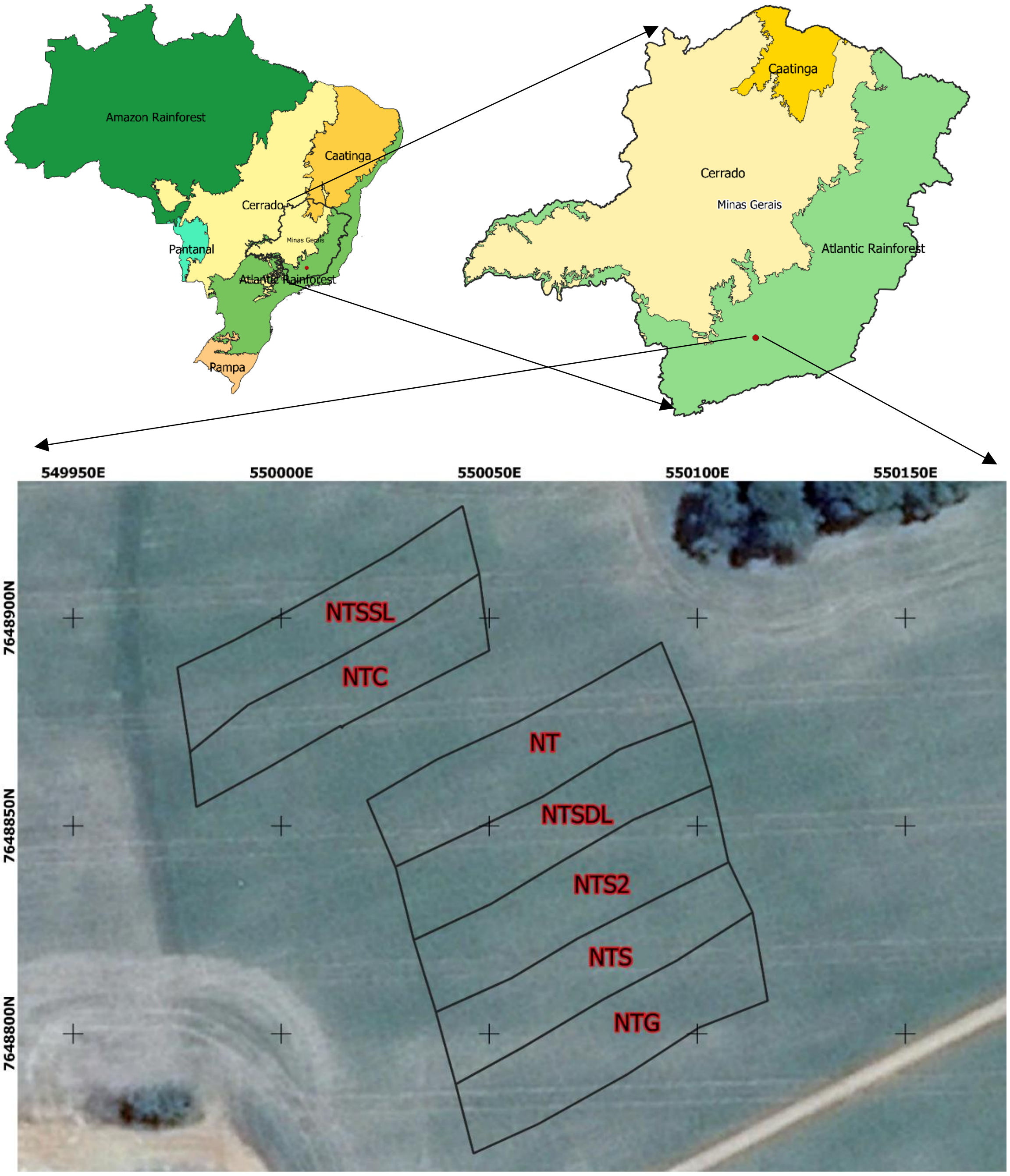

Fig. 1. Design and location of the experimental area for evaluation of strategies for mitigation of soil compaction under continuous no-tillage. NT – continuous NT set up in 2005 (control); NTG - NT with surface application of agricultural gypsum; NTSDL - NT with use of a fertilizing subsoiler and deep lime placement at the depth of 0.40 – 0.60 m; NTC - NT with use of a chisel plow with 0.26 m length shanks; NTSSL - NT with subsoiling and surface lime application; NTS2 - NT with subsoiling every two years (October 2015 and 2017); NTS - NT with subsoiling in October 2015.

2.2.Input data

Soil sampling and analyses: Undisturbed soil samples were taken from each experimental plot at two depths (0.0-0.05 and 0.25-0.30 m) in March 2016 and 2017 and May 2018, corresponding to 6, 18, and 32 months after setting up the experiment, respectively.

Definition of these depths was made based on an initial evaluation with a dynamic penetrometer in the field, where the depth of 0.30 m proved to be physically more restrictive to the crops. The surface layer (0.0-0.05 m) was selected because it is more impacted by soil management. Volumetric rings with dimensions of 0.06 m x 0.025 m (diameter and height) were used for collection of soil samples. Four samples were collected per depth in each experimental plot, for a total of 192 samples in March 2016, 160 samples in March 2017, and 192 samples in May 2018. In 2016, the NTS and NTS2 corresponded to the same treatment (one subsoiling), and thus only the NTS treatment was sampled. In 2017, due to limited financial resources, the NTS and NTS2 treatments were not sampled. In 2018, the NTG treatment was not sampled, in order to reduce sampling and analysis costs, since soil analyses and the results of crop yield from the previous years did not indicate the effect of agricultural gypsum (Peixoto et al. 2019a; Peixoto et al. 2019b).

After that, the samples were prepared in the laboratory, removing excess soil, and then they were gradually saturated by capillarity. Upon reaching saturation, the samples were divided into 4 groups, each group containing a sample from each depth and experimental plot. The first group was placed under the matric potential of -0.006 MPa, and the second group under the matric potential of -0.010 MPa in an automated tension table (Ecotek®). The third group was equilibrated at -0.10 MPa and the fourth group at -1.50 MPa in a Richards chamber (Klute and Klute 1986).

After equilibrium at each matric potential, the samples were weighed, and those of the third group (matric potential of -0.10 MPa) were tested for penetration resistance (PR) with a digital bench top penetrometer, Marconi MA 933, with a circular straight cone tip of 45º, 3.84 mm diameter, and constant speed of 10 mm min^{-1} (Peixoto, Silva, Oliveira, et al. 2019). Finally, the sample was dried in a laboratory oven at 105-110 ºC for 48 h for quantification of moisture content.

The following determinations were made through analysis: soil bulk density (BD), microporosity (MIC), macroporosity (MAC), total porosity (TP), air capacity (AC), available water content (AWC), and relative field capacity (RFC):

$$BD = M_S / V_B \tag{1}$$

$$MIC = \theta_M \ (\Psi = -0.006 \ MPa) \tag{2}$$

$$MAC = \theta_S \ (\Psi = 0) - Mic \tag{3}$$

$$TP = 1 – (Bd/Pd) \quad (4)$$

$$AC = \theta_S (\Psi = 0) – \theta_{FC} (\Psi = -0.01 \text{ MPa}) \quad (5)$$

$$AWC = \theta_{FC} (\Psi = -0.01 \text{ MPa}) – \theta_{PWP} (\Psi = -1.5 \text{ MPa}) \quad (6)$$

$$RFC = \theta_{FC} / \theta_S \quad (7)$$

where M_S (Mg) is the mass of dry soil; V_B (m^3) is the corresponding volume of soil; θ_M (m^3 m^{-3}) is the volumetric water content at equilibrium at $\Psi = -0.006$ MPa; θ_S (m^3 m^{-3}) is the volumetric water content when saturated; θ_{FC} (m^3 m^{-3}) is the volumetric water content at field capacity ($\Psi = -0.01$ MPa); and θ_{PWP} (m^3 m^{-3}) is the volumetric water content at the permanent wilting point ($\Psi = -1.5$ MPa).

Crop yield: In the 2015/2016 spring-summer crop season, conventional soybean cv. VTOP was grown, and in the fall-winter, wheat cv. BRS 264. In the 2016/2017 spring-summer crop season, the maize hybrid DKB 230 PRO3 was grown, followed by common bean cv. IPR Tuiuiú in the fall-winter, and oats between crop seasons. In the 2017/2018 crop season, soybean cv. MONSOY 5719 IPRO was grown in the spring-summer, and wheat cv. BRS 264 in the fall-winter.

For this study, soybean yields were evaluated in the 2015/2016 and 2017/2018 crop seasons and maize yields in the 2016/2017 crop season. In each experimental plot, the grain from three plant rows of five-meter length (7.5 m^2) was sampled at random. For soybean in the 2017/2018 crop season, two rows of five-meter length (5.0 m^2) were collected. Yield was adjusted considering grain moisture content of 13% and extrapolated to one hectare. For the predictive analysis, crop yield was relativized. Relative yield (Rel_Yield) was calculated as a ratio between the crop yield at each plot and the average yield of the experimental area for each crop season.

2.3.Models

Four algorithms with distinct characteristics were used predict soil compaction in continuous no-tillage: CART, RF, ANN, and SVM. A brief description concerning our purposes are present below.

CART: These are the learning algorithms most frequently used in the literature for constructing prediction models from a dataset. The structure consists of nodes and leaves, where each node is a partition of the training dataset. The aim is to maximize homogeneity within the node and heterogeneity between nodes based on the rules of node division generated from the set of predictor variables (Breiman et al. 1984). Leaves are the terminal nodes in which a decision is made in relation to the response variable. Decision trees are able to represent non-linear and non-soft relationships between predictor and response variables, as well as interaction effects. In addition, the models are flexible, and can handle numerical, ordinal, or discrete predictors and do not require suppositions regarding normality (Breiman et al. 1984).

Regression trees are for dependent variables that assume continuous or ordered discrete values, with prediction error generally measured by the squared difference between observed and predicted values. Classification trees, for their part, are projected for dependent variables that receive a finite number of non-ordered values or qualitative factors, with prediction error measured in terms of the cost of incorrect classification (Loh 2011).

RF: The Random Forest algorithm is conceptually similar to CART and shares the same advantages. Nevertheless, various decision trees are trained, creating a forest, and the results are based on the predictions of a set of individual trees (Breiman 2001). In RF, each tree is trained from a random bootstrap sample of the whole training set, and a subset of predictors of the node division is selected at random.

ANN: The idea of the neural network is to develop data processes similar to the biological nervous system. The structure consists of a set of interconnected units (similar to neurons) that estimate the non-linear correlations between each variable. The input neurons (predictor variables) are connected to one or various layers of hidden neurons, which are then linked to the output neurons (response variable). During the neural network training process, the connections between neurons are established, attributing weights based on an intrinsic learning process, where weights are adjusted interactively to correspond to the outputs of the training dataset (Behrens et al. 2005).

SVM: This is a supervised learning algorithm with the purpose of classifying a certain set of data points that are mapped for a space of multidimensional characteristics using a kernel function, an approach used for classifying problems. In this approach, the limit of decision in the input space is represented by a hyperplane in the upper dimension in the space (Saradhi et al. 2005).

2.4.Prediction of the state of soil compaction

The algorithms CART, RF, ANN, and SVM were used in prediction of the state of soil compaction. For this, the treatments of continuous no-tillage (NT and NTG) were included in the category "compacted" and the treatments of occasional tillage (NTC, NTS, NTS2, NTSSL, and NTSDL) in the category "non-compacted". The state of soil compaction in continuous no-tillage and occasional tillage in the experimental area has been presented in previous studies (Peixoto et al. 2019a, 2019b). These studies showed differences on soil physical properties and crop yield, and no effects on soil fertility. The predictor variables were the following: BD, PR, MAC, MIC, AC, AWC, RFC, TP, and Rel_Yield.

All the models were implemented using the statistical software *R* 3.6.1 (R Development Core Team 2019) and the “caret” package (Kuhn 2008). The CART, ANN, RF, and SVM algorithms were implemented using the “treebag”, “nnet”, “rf”, and “svmRadial” functions, respectively. A training set (n = 48) with 70% of the data was partitioned for analysis, and an external validation set (n = 20) was partitioned with the remaining 30%. To make a just comparison among the various algorithms, each one was parametrized using the resampling procedure with leave-one-out cross validation in training the models.

Three separately analyzed datasets were used for each model: depth of 0.0-0.05 m for the three crop seasons; depth of 0.25-0.30 m for the three crop seasons; and one last dataset of the mean values of the two previous depths, corresponding to depth of 0.0-0.30 m, also for the three crop seasons.

Performance of the models using the external validation data was evaluated by the confusion matrix, which establishes the percentage of hits and errors in classification of the algorithms in relation to the data observed, and by the overall accuracy statistics, Kappa index, and sensitivity of the model in ascertaining the category considered positive, in this case, the “compacted” category. In addition, the results of the importance of the soil properties for the prediction models of soybean yield were extracted. The importance of the predictor variables indicates which soil property was most important in prediction of the models.

3. Results and Discussion

3.1.Diagnosis of the state of soil compaction

The descriptive statistics of the variables used in the calibration (n = 48) and validation (n = 20) to predict the state of soil compaction in continuous no-tillage under occasional tillage are shown in Table 1. The calibration and validation dataset were similar, as can be seen by the values of central tendency and dispersion. The most dispersed variables were: PR, MAC and AC; and with less dispersion were: Rel_Yield, TP and BD.

Table 1. Descriptive statistics of the variables in the calibration and validation dataset for prediction of the state of soil compaction (2015/2016, 2016/2017 and 2017/2018 crop season) in continuous no-tillage under occasional tillage.

Soil properties	**Calibration set (n = 48)**					**Validation set (n = 20)**				
	Min	**Max**	**Mean**	**SD**	**CV**	**Min**	**Max**	**Mean**	**SD**	**CV**
Depth of 0.0 – 0.05 m										
Rel_Yield (%)	83	117	101	7	7	87	111	98	7	7
PR (MPa)	0.29	1.66	0.87	0.33	38	0.25	2.53	0.91	0.60	66
BD (Mg m^{-3})	0.86	1.32	1.05	0.12	11	0.92	1.22	1.07	0.09	8
TP (m^3 m^{-3})	0.46	0.67	0.58	0.04	7	0.54	0.65	0.59	0.04	7
MAC (m^3 m^{-3})	0.08	0.34	0.18	0.06	33	0.08	0.26	0.16	0.05	31
MIC (m^3 m^{-3})	0.31	0.51	0.41	0.04	10	0.32	0.46	0.40	0.04	10
AC (m^3 m^{-3})	0.08	0.35	0.21	0.06	28	0.10	0.34	0.23	0.07	30
RFC	0.46	0.85	0.64	0.09	14	0.47	0.81	0.61	0.10	16
AWC (m^3 m^{-3})	0.09	0.25	0.14	0.03	21	0.06	0.18	0.12	0.04	33
Depth of 0.25 – 0.30 m										
Rel_Yield (%)	83	117	101	7	7	87	111	98	7	7
PR (MPa)	0.28	3.42	1.36	0.82	60	0.24	2.95	1.13	0.81	72
BD (Mg m^{-3})	0.90	1.33	1.14	0.10	9	0.97	1.25	1.10	0.08	7
TP (m^3 m^{-3})	0.46	0.66	0.56	0.04	7	0.45	0.63	0.57	0.04	7
MAC (m^3 m^{-3})	0.05	0.24	0.16	0.05	31	0.01	0.22	0.14	0.05	36
MIC (m^3 m^{-3})	0.35	0.48	0.40	0.03	7	0.36	0.48	0.40	0.03	7
AC (m^3 m^{-3})	0.08	0.32	0.19	0.06	31	0.01	0.31	0.21	0.08	38
RFC	0.49	0.84	0.67	0.09	13	0.51	0.97	0.64	0.12	19
AWC (m^3 m^{-3})	0.05	0.16	0.11	0.02	18	0.05	0.17	0.10	0.03	30
Depth of 0.0 – 0.30 m										
Rel_Yield (%)	83	117	101	7	7	87	111	98	7	7
PR (MPa)	0.35	2.30	1.12	0.52	46	0.30	2.33	1.02	0.63	62
BD (Mg m^{-3})	0.97	1.29	1.09	0.08	7	0.99	1.23	1.08	0.07	6
TP (m^3 m^{-3})	0.51	0.64	0.57	0.03	5	0.51	0.64	0.58	0.04	7
MAC (m^3 m^{-3})	0.10	0.28	0.17	0.04	23	0.09	0.23	0.15	0.04	27
MIC (m^3 m^{-3})	0.34	0.46	0.40	0.02	5	0.36	0.45	0.40	0.02	5

AC (m^{3} m^{-3})	0.09	0.32	0.20	0.05	25	0.11	0.31	0.22	0.07	32
RFC	0.51	0.83	0.66	0.08	12	0.51	0.80	0.62	0.09	14
AWC (m^{3} m^{-3})	0.08	0.18	0.13	0.02	15	0.07	0.16	0.11	0.03	27

Rel_Yield: Relative yield; PR: penetration resistance; Bd: bulk density; TP: total porosity; Mac: macroporosity; Mic: microporosity; AC: air capacity; RFC: relative field capacity; AWC: available water content.

The descriptive statistics of the soil physical properties from three crop season show that lower maximum values for MAC, MIC, and AC, and higher of PR at the depth of 0.25-0.30 m, compared to the depth of 0.0-0.05 m (Table 1). The greatest soil physical restriction of this soil depth had already been observed in an evaluation with a field penetrometer before the implementation of the experiment (Peixoto et al. 2019b), and confirmed in subsequent studies as the most physically restrictive to crop yield (Peixoto et al. 2019a, 2019b). Previous studies with this same database showed higher yield of soybean and maize for OT treatments compared to NT (Peixoto et al. 2019a, 2019b).

At the depth of 0.0-0.05 m, the algorithm ANN had better performance (accuracy = 0.85; Kappa index = 0.62) in diagnosis of the state of soil compaction, CART and RF had similar performance (accuracy = 0.80; Kappa index = 0.56), and SVM had lower performance (accuracy = 0.80; Kappa index = 0.47) (Table 2). Of a total of six samples regarded as compacted, CART and RF ascertained five, ANN four and SVM three, and of the 14 regarded as non-compacted, ANN and SVM ascertained 13, CART and RF 11. The greatest sensitivity in identifying the compacted class was CART and RF (sensitivity = 0.83), followed by ANN (sensitivity = 0.67) and finally by SVM (sensitivity = 0.50).

The algorithms performed well even when the soil physical covariates were of the surface layer (0.0-0.05 m), which is highly affected by crop management practices, and although machine traffic primarily affects this layer, sowing of crops promotes soil mobilization, especially in the management system that has wheat as the fall-winter crop (with between-row spacing of 0.17 m), reducing the effects of surface compaction. Although the ANN presents greater accuracy than the others, the decision tree algorithms were more sensitive in the classification of the compacted condition (83% of correctness), showing to be an excellent tool in the diagnosis of compacted areas.

Table 2. Performance of validation of the learning algorithms regarding prediction of the state of soil compaction in continuous no-tillage under occasional tillage in three crop season, depth of 0.0-0.05 m.

------------- Confusion Matrix ------------			----------------- Statistics -------------		
Observed / Predicted	Compacted	Non Compacted	Overall accuracy	Kappa index	Sensitivity
		CART			
Compacted	5	3	0.80	0.56	0.83
Non Compacted	1	11			
		RF			
Compacted	5	3	0.80	0.56	0.83
Non Compacted	1	11			
		ANN			
Compacted	4	1	0.85	0.62	0.67
Non Compacted	2	13			
		SVM			
Compacted	3	1	0.80	0.47	0.50
Non Compacted	3	13			

CART = Classification and Regression Trees; RF = Random Forest; ANN = Artificial Neural Network; SVM = Support Vector Machine.

At the depth of 0.25-0.30 m, the algorithms CART and RF had better performance (accuracy = 0.90; Kappa index = 0.76) in diagnosis of the state of soil compaction, followed by SVM (accuracy = 0.85; Kappa index = 0.62), and ANN had lower performance (accuracy = 0.80; Kappa index = 0.56) (Table 3). Of a total of six samples regarded as compacted, CART, RF and ANN ascertained five, and SVM four, and of the 14 regarded as non-compacted, CART, RF and SVM ascertained 13, and ANN 11. The greatest sensitivity in identifying the compacted class was CART, RF and ANN (sensitivity = 0.83), followed by SVM (sensitivity = 0.67). The performance of the models was superior with use of the covariables at the depth of 0.25-0.30 m.

Considering the most restrictive physically soil depth to crop yield (0.25-30 m), the CART and RF algorithms were most efficient in diagnosis of the state of soil compaction, and ANN had the worst performance. The advantages of decision tree algorithms, especially RF, over the other learning algorithms include greater accuracy in classification, establishment of an innovative method in determination of the importance of variables, ability in modeling complex interactions, flexibility for conducting varied types of statistical analysis of data, and efficiency with absent data (Cutler et al. 2007). Studies have shown the efficiency of RF for predictive classification analysis (Cutler et al. 2007; Fernandes et al. 2019; Gislason et al. 2006; Maxwell et al. 2018; Pal 2005); however, for classification of the state of soil compaction, there is no record in the literature. The advantage of RF in relation to CART is that the former maintains good accuracy in the presence of extreme and absent values and is efficient in the handling and processing of large datasets (Elavarasan et al. 2018). Similarity in the performance of CART and RF may be due to the dataset being smaller, without absent values and with few extreme values. In addition, many of the variables are correlated, improving the performance of CART (Elavarasan et al. 2018).

Table 3. Performance of validation of the learning algorithms regarding prediction of the state of soil compaction in continuous no-tillage under occasional tillage in three crop season, depth of 0.25-0.30 m.

------------- **Confusion Matrix** ------------			----------------- **Statistics** -------------		
Observed / Predicted	Compacted	Non Compacted	Overall accuracy	Kappa index	Sensitivity
		CART			
Compacted	5	1	0.90	0.76	0.83
Non Compacted	1	13			
		RF			
Compacted	5	1	0.90	0.76	0.83
Non Compacted	1	13			
		ANN			
Compacted	5	3	0.80	0.56	0.83
Non Compacted	1	11			
		SVM			
Compacted	4	1	0.85	0.62	0.67
Non Compacted	2	13			

CART = Classification and Regression Trees; RF = Random Forest; ANN = Artificial Neural Network; SVM = Support Vector Machine.

At the depth of 0.0-0.30 m, the performance of the algorithms was equal (accuracy = 0.85; Kappa index = 0.62; sensitivity = 0.67) (Table 4). Of a total of six samples regarded as compacted, the algorithms ascertained four, and of the 14 regarded as non-compacted, the algorithms ascertained 13. These results show that using mean values of the soil layer produces similar responses from the machine learning algorithms for the diagnosis of soil compaction. In this study, the performance of the models for the three depths was shown to understand the application of the tool, however, the diagnosis of soil compaction must be made by evaluating the most restrictive layer.

Table 4. Performance of validation of the learning algorithms regarding prediction of the state of soil compaction in continuous no-tillage under occasional tillage in three crop season, depth of 0.0-0.30 m.

------------- **Confusion Matrix** ------------			----------------- **Statistics** -------------		
Observed / Predicted	Compacted	Non Compacted	Overall accuracy	Kappa index	Sensitivity
		CART			
Compacted	4	1	0.85	0.62	0.67
Non Compacted	2	13			
		RF			
Compacted	4	1	0.85	0.62	0.67
Non Compacted	2	13			

		ANN			
Compacted	4	1	0.85	0.62	0.67
Non Compacted	2	13			
		SVM			
Compacted	4	1	0.85	0.62	0.67
Non Compacted	2	13			

CART = Classification and Regression Trees; RF = Random Forest; ANN = Artificial Neural Network; SVM = Support Vector Machine.

The most important variables, with percentage of relative importance > 50%, for the diagnosis of the state of soil compaction were: Depth of 0.05-0.05 m – (CART = Rel_Yield, TP, PR, AC and RFC; RF = Rel_Yield; ANN = Rel_Yield and MAC; SVM = Rel_Yield, AC and TP); Depth of 0.25-0.30 m – (CART and RF = Rel_Yield; ANN = Rel_Yield and MAC; SVM = Rel_Yield and MIC); and Depth of 0.0-0.30 m – (CART = Rel_Yield, MAC, PR, and RFC; RF = Rel_Yield; ANN = Rel_Yield, MAC, AWC and MIC; SVM = Rel_Yield, MAC, and MIC) (Fig. 2). The importance of variables in predictive analysis for purposes of this classification indicates the variables that are most able to differentiate compacted and non-compacted soils. The importance of variables is different according to the algorithm, because each algorithm has its own predictive analysis method.

The great importance of the crop yield (Rel_Yield) in the diagnosis of the state of soil compaction shows that it is essential to evaluate the crop's response to the soil physical conditions, avoiding making decisions based only on soil physical properties. In a recent meta-analysis, it was shown that occasional tillage improves the soil physical properties, however, in general, there is no response in crop yield (Peixoto et al. 2020). These results demonstrate that the diagnosis of soil compaction has been flawed and has not considered the crop response. Regarding the soil physical properties, the least important were BD and AWC, regardless of depth, showing low sensitivity for the diagnosis of soil compaction in NT. Oppositely, BD is the second most used indicator for soil physical quality assessment approaches according a recent review (Bünemann et al. 2018).

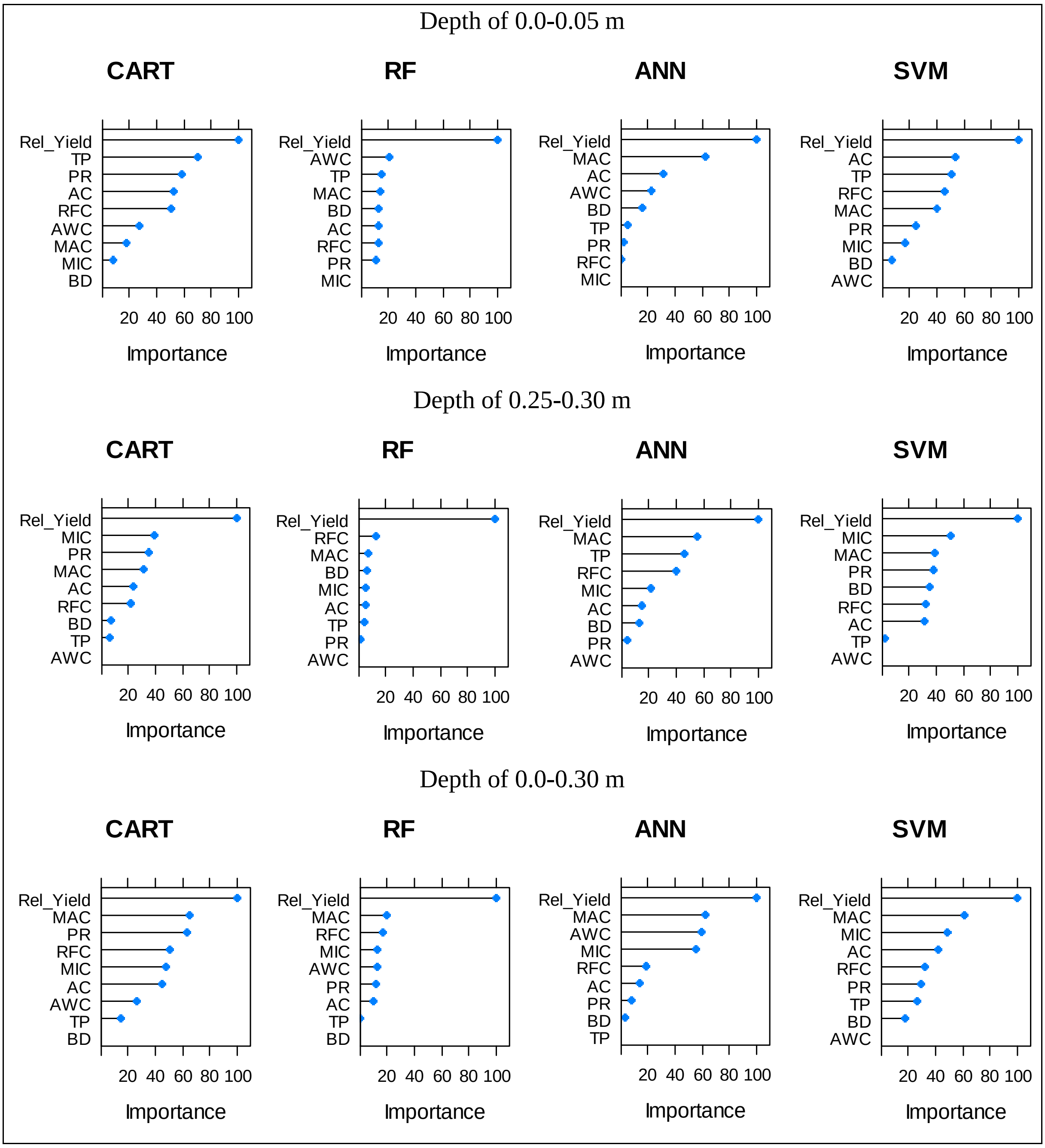

Fig. 2. Relative importance (%) of variables for the diagnosis of the state of soil compaction in three crop seasons, using four learning algorithms. CART = Classification and Regression Trees; RF = Random Forest; ANN = Artificial Neural Network; SVM = Support Vector Machine.

The low sensitivity of AWC to compaction can be explained due both FC and PWP tend to increase in a similar magnitude with increasing BD, thus AWC remain near the same value among the state of compaction (Moura et al. 2021; Reynolds et al. 2009; Silva et al. 2015). The most important were those that characterize the soil porosity (MAC, TP, MIC and AC), with PR being intermediate, differently from the prediction of crop yield, where PR was the most important soil property (Peixoto et al. 2019b). The soil physical properties MAC, TP, AC and PR are commonly used and recommended as soil physical quality indicator for biomass production (Lehmann et al. 2020; Peixoto et al. 2019b; Rabot et al. 2018; Reynolds et al. 2002, 2008, 2009). We highlight that our results show that the physical properties that best contributed to the classification of the state of compaction may vary in importance between the seasons. Thus, the need to use more than one indicator for the diagnosis of compaction is reinforced.

The application of the results of this study at the farm level can be implemented, since machine learning algorithms proved to be accurate in diagnosing soil compaction. For this purpose, we recommend a sequential methodology carried out on the farm. The first step (1) is to train the algorithm (for example RF) with data on soil physical properties and crops yield from areas on the farm that are certainly compacted and non-compacted. For this, experiments with different degrees of soil compaction obtained artificially (machine passes) may be implemented. The second step (2) is to identify areas with soil characteristics and history of use and management similar to those used for training, and to determine the same soil physical properties and crops yield of the previous step (1). The third step (3) consists of predicting the state of soil compaction in the areas of the second step (2) based on the training done in the first step (1).

4. Conclusions

The machine learning algorithms had satisfactory performance for diagnosis of the state of soil compaction using soil properties and crop yield, and the decision tree algorithms (CART and RF) were most accurate and sensitive. Considering the most restrictive soil layer (0.25-0.30 m), the algorithms CART and RF had accuracy = 0.90, Kappa index = 0.76, and sensitivity = 0.83. The most important variables for predicting the state of soil compaction were crop yield and soil porosity (MAC, TP, MIC and AC).

Therefore, the learning algorithms approach proved to be an efficient tool in diagnosis and prediction of soil compaction in continuous no-tillage, providing greater certainty in decision making regarding the use of occasional tillage.

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6. References

Arvidsson, J., Etana, A., & Rydberg, T. (2014). Crop yield in Swedish experiments with shallow tillage and no-tillage 1983-2012. *European Journal of Agronomy*, *52*, 307–315. https://doi.org/10.1016/j.eja.2013.08.002

Arvidsson, J., & Håkansson, I. (2014). Response of different crops to soil compaction—Short-term effects in Swedish field experiments. *Soil and Tillage Research*, *138*, 56–63. https://doi.org/10.1016/j.still.2013.12.006

Behrens, T., Förster, H., Scholten, T., Steinrücken, U., Spies, E.-D., & Goldschmitt, M. (2005). Digital soil mapping using artificial neural networks. *Journal of Plant Nutrition and Soil Science*, *168*(1), 21–33. https://doi.org/10.1002/jpln.200421414

Bengough, A. G., Bransby, M. F., Hans, J., McKenna, S. J., Roberts, T. J., & Valentine, T. A. (2006). Root responses to soil physical conditions; growth dynamics from field to cell. *Journal of Experimental Botany*, *57*(2), 437–447. https://doi.org/10.1093/jxb/erj003

Blanco-Canqui, H., & Ruis, S. J. (2018). No-tillage and soil physical environment. *Geoderma*, *326*, 164–200. https://doi.org/10.1016/j.geoderma.2018.03.011

Botta, G. F., Antille, D. L., Bienvenido, F., Rivero, D., & Contessotto, E. E. (2019). Energy requirements for alleviation of subsoil compaction and the effect of deep tillage on sunflower (Helianthus annus L.) yield in the western region of Argentina's rolling pampa. *Engineering for Rural Development*, *18*, 174–178. https://doi.org/10.22616/ERDev2019.18.N216

Breiman, L. (2001). Random forests. *Machine Learning*, *45*(1), 5–32. https://doi.org/10.1023/A:1010933404324

Breiman, L., Friedman, J. H., Olshen, R. A., & Stone, C. J. (1984). *Classification And Regression Trees*. *Cytometry* (Vol. 8). Routledge. https://doi.org/10.1201/9781315139470

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., et al. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105–125. https://doi.org/10.1016/J.SOILBIO.2018.01.030

Calonego, J. C., Raphael, J. P. A., Rigon, J. P. G., Oliveira Neto, L. de, & 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. https://doi.org/10.1016/j.eja.2017.02.001

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. https://doi.org/10.1016/j.eja.2010.06.002

Chlingaryan, A., Sukkarieh, S., & Whelan, B. (2018). Machine learning approaches for crop yield prediction and nitrogen status estimation in precision agriculture: A review. *Computers and Electronics in Agriculture*. Elsevier. https://doi.org/10.1016/j.compag.2018.05.012

Companhia Nacional de Abastecimento. (2021). *Boletim da Safra de Grãos: Acompanhamento da safra 2020/21 brasileira de grãos - 8º levantamento*. Brasília, DF: CONAB. https://www.conab.gov.br/

Correa, J., Postma, J. A., Watt, M., & Wojciechowski, T. (2019). Soil compaction and the architectural plasticity of root systems. *Journal of Experimental Botany*, *70*(21), 6019–6034. https://doi.org/10.1093/jxb/erz383

Cutler, D. R., Edwards, T. C., Beard, K. H., Cutler, A., Hess, K. T., Gibson, J., & Lawler, J. J. (2007). Random Forest for classification in ecology. *Ecology*, *88*(11), 2783–2792.

https://doi.org/10.1890/07-0539.1

Denardin, J. E., Faganello, A., & Santi, A. (2008). Falhas na implementação do sistema plantio direto levam à degradação do solo. *Revista Plantio Direto*, *18*, 3–4.

Deuschle, D., Minella, J. P. G., Hörbe, T. de A. N., Londero, A. L., & Schneider, F. J. A. (2019). Erosion and hydrological response in no-tillage subjected to crop rotation intensification in southern Brazil. *Geoderma*, *340*, 157–163. https://doi.org/10.1016/j.geoderma.2019.01.010

Drescher, M. S., Eltz, F. L. F., Denardin, J. E., & Faganello, A. (2011). Persistência do efeito de intervenções mecânicas para a descompactação de solos sob plantio direto. *Revista Brasileira de Ciência do Solo*, *35*(5), 1713–1722. https://doi.org/10.1590/S0100-06832011000500026

Drescher, M. S., Eltz, F. L. F., Denardin, J. E., Faganello, A., & Drescher, G. L. (2012). Resistência à penetração e rendimento da soja após intervenção mecânica em latossolo vermelho sob plantio direto. *Revista Brasileira de Ciencia do Solo*, *36*(6), 1836–1844. https://doi.org/10.1590/S0100-06832012000600018

Elavarasan, D., Vincent, D. R., Sharma, V., Zomaya, A. Y., & Srinivasan, K. (2018). Forecasting yield by integrating agrarian factors and machine learning models: A survey. *Computers and Electronics in Agriculture*. Elsevier. https://doi.org/10.1016/j.compag.2018.10.024

Everingham, Y., Sexton, J., Skocaj, D., & Inman-Bamber, G. (2016). Accurate prediction of sugarcane yield using a random forest algorithm. *Agronomy for Sustainable Development*, *36*(2), 27. https://doi.org/10.1007/s13593-016-0364-z

Fernandes, D., Machado, T., Silva, H. G., Curi, N., & Duarte De Menezes, M. (2019). Soil type spatial prediction from Random Forest: different training datasets, (June), 243–254. http://dx.doi.org/10.1590/1678-992X-2017-0300

Filippi, P., Jones, E. J., Wimalathunge, N. S., Somarathna, P. D. S. N., Pozza, L. E., Ugbaje, S. U., et al. (2019). An approach to forecast grain crop yield using multi-layered, multi-farm data sets and machine learning. *Precision Agriculture*, *20*(5), 1015–1029. https://doi.org/10.1007/s11119-018-09628-4

Fukuda, S., Spreer, W., Yasunaga, E., Yuge, K., Sardsud, V., & Müller, J. (2013). Random Forests modelling for the estimation of mango (Mangifera indica L. cv. Chok Anan) fruit yields under different irrigation regimes. *Agricultural Water Management*, *116*, 142–150. https://doi.org/10.1016/j.agwat.2012.07.003

Girardello, V. C., Amado, T. J. C., Nicoloso, R. da S., Hörbe, T. de A. N., Ferreira, A. de O., Tabaldi, F. M., & Lanzanova, M. E. (2011). Alterações nos atributos físicos de um latossolo vermelho sob plantio direto induzidas por diferentes tipos de escarificadores e o rendimento da soja. *Revista Brasileira de Ciencia do Solo*, *35*(6), 2115–2126. https://doi.org/10.1590/S0100-06832011000600026

Gislason, P. O., Benediktsson, J. A., & Sveinsson, J. R. (2006). Random Forests for land cover classification. *Pattern Recognition Letters*, *27*(4), 294–300. https://doi.org/10.1016/j.patrec.2005.08.011

Gonzalez-Sanchez, A., Frausto-Solis, J., & Ojeda-Bustamante, W. (2014). Predictive ability of machine learning methods for massive crop yield prediction. *Spanish Journal of Agricultural Research*, *12*(2), 313–328. https://doi.org/10.5424/sjar/2014122-4439

Hakojärvi, M., Hautala, M., Ristolainen, A., & Alakukku, L. (2013). Yield variation of spring cereals in relation to selected soil physical properties on three clay soil fields. *European Journal of Agronomy*, *49*, 1–11. https://doi.org/10.1016/j.eja.2013.03.003

Hamza, M. A., & Anderson, W. K. (2005). Soil compaction in cropping systems. *Soil and Tillage Research*, *82*(2), 121–145. https://doi.org/10.1016/j.still.2004.08.009

Jeong, J. H., Resop, J. P., Mueller, N. D., Fleisher, D. H., Yun, K., Butler, E. E., et al. (2016). Random forests for global and regional crop yield predictions. *PLoS ONE*, *11*(6), e0156571.

https://doi.org/10.1371/journal.pone.0156571

Keller, T., Sandin, M., Colombi, T., Horn, R., & Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil and Tillage Research*, *194*, 104293. https://doi.org/10.1016/j.still.2019.104293

Khanal, S., Fulton, J., Klopfenstein, A., Douridas, N., & Shearer, S. (2018). Integration of high resolution remotely sensed data and machine learning techniques for spatial prediction of soil properties and corn yield. *Computers and Electronics in Agriculture*, *153*(July), 213–225. https://doi.org/10.1016/j.compag.2018.07.016

Kim, N., & Lee, Y. W. (2016). Machine learning approaches to corn yield estimation using satellite images and climate data: A case of Iowa State. *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography*, *34*(4), 383–390. https://doi.org/10.7848/ksgpc.2016.34.4.383

Klute, A., & Klute, A. (1986). Water Retention: Laboratory Methods (p. 1207). https://doi.org/10.2136/sssabookser5.1.2ed.c26

Kuhn, M. (2008). Building Predictive Models in R Using the caret Package. *Journal of Statistical Software*, *28*(5), 1–26. https://doi.org/10.18637/jss.v028.i05

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, *1*(10), 544–553. https://doi.org/10.1038/s43017-020-0080-8

Lipiec, J., & Stępniewski, W. (1995). Effects of soil compaction and tillage systems on uptake and losses of nutrients. *Soil and Tillage Research*, *35*(1–2), 37–52. https://doi.org/10.1016/0167-1987(95)00474-7

Lipiec, Jerzy, Horn, R., Pietrusiewicz, J., & Siczek, A. (2012). Effects of soil compaction on root elongation and anatomy of different cereal plant species. *Soil and Tillage Research*, *121*, 74–81. https://doi.org/10.1016/j.still.2012.01.013

Loh, W. Y. (2011). Classification and regression trees. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, *1*(1), 14–23. https://doi.org/10.1002/widm.8

López-Garrido, R., Madejón, E., Murillo, J. M., & Moreno, F. (2011). Soil quality alteration by mouldboard ploughing in a commercial farm devoted to no-tillage under Mediterranean conditions. *Agriculture, Ecosystems and Environment*, *140*(1–2), 182–190. https://doi.org/10.1016/j.agee.2010.12.001

Mathieu, J. A., & Aires, F. (2018). Assessment of the agro-climatic indices to improve crop yield forecasting. *Agricultural and Forest Meteorology*, *253–254*, 15–30. https://doi.org/10.1016/J.AGRFORMET.2018.01.031

Maxwell, A. E., Warner, T. A., & Fang, F. (2018, May 3). Implementation of machine-learning classification in remote sensing: An applied review. *International Journal of Remote Sensing*. Taylor & Francis. https://doi.org/10.1080/01431161.2018.1433343

Maya Gopal, P. S., & Bhargavi, R. (2019). Performance Evaluation of Best Feature Subsets for Crop Yield Prediction Using Machine Learning Algorithms. *Applied Artificial Intelligence*, *33*(7), 621–642. https://doi.org/10.1080/08839514.2019.1592343

Melero, S., Panettieri, M., Madejón, E., Macpherson, H. G., Moreno, F., & Murillo, J. M. (2011). Implementation of chiselling and mouldboard ploughing in soil after 8 years of no-till management in SW, Spain: Effect on soil quality. *Soil and Tillage Research*, *112*(2), 107–113. https://doi.org/10.1016/j.still.2010.12.001

Melland, A. R., Antille, D. L., & Dang, Y. P. (2017). Effects of strategic tillage on short-term erosion, nutrient loss in runoff and greenhouse gas emissions. *Soil Research*, *55*(3), 201. https://doi.org/10.1071/SR16136

Mishra, S., Mishra, D., & Santra, G. H. (2016). Applications of machine learning techniques in agricultural crop production: A review paper. *Indian Journal of Science and Technology, 9*(38). https://doi.org/10.17485/ijst/2016/v9i38/95032

Moreira, S. G. (2019). Desafios para a sustentabilidade dos sistemas de produção com culturas anuais. *Informações Agronômicas*, *4*, 1–12.

Moura, M. S. de, Silva, B. M., Mota, P. K., Borghi, E., Resende, A. V. De, Acuña-Guzman, S. F., et al. (2021). Soil management and diverse crop rotation can mitigate early-stage no-till compaction and improve least limiting water range in a Ferralsol. *Agricultural Water Management*, *243*(September 2020), 106523. https://doi.org/10.1016/j.agwat.2020.106523

Nascimento, V., Arf, O., Tarsitano, M. A. A., Garcia, N. F. S., Penteado, M. S., & Sabundjian, M. T. (2016). Economic analysis of rice and common bean production in succession to green manure crops and mecahnical soil decompression in Brazilian Savannah. *Revista Ceres*, *63*(3), 315–322. https://doi.org/10.1590/0034-737X201663030006

Nawaz, M. F., Bourrié, G., & Trolard, F. (2013). Soil compaction impact and modelling. A review. *Agronomy for Sustainable Development*, *33*(2), 291–309. https://doi.org/10.1007/s13593-011-0071-8

Nunes, M. R., Denardin, J. E., Pauletto, E. A., Faganello, A., & Pinto, L. F. S. (2015a). Mitigation of clayey soil compaction managed under no-tillage. *Soil and Tillage Research*, *148*, 119–126. https://doi.org/10.1016/j.still.2014.12.007

Nunes, M. R., Denardin, J. E., Pauletto, E. A., Faganello, A., & Pinto, L. F. S. (2015b). Effect of soil chiseling on soil structure and root growth for a clayey soil under no-tillage. *Geoderma*, *259–260*, 149–155. https://doi.org/10.1016/j.geoderma.2015.06.003

Nunes, M. R., Pauletto, E. A., Denardin, J. E., Faganello, A., Spinelli Pinto, L. F., & Scheunemann, T. (2014). Persistência dos efeitos da escarificação sobre a compactação de Nitossolo sob plantio direto em região subtropical úmida. *Pesquisa Agropecuária Brasileira*, *49*(7), 531–539. https://doi.org/10.1590/S0100-204X2014000700005

Pal, M. (2005). Random forest classifier for remote sensing classification. *International Journal of Remote Sensing*, *26*(1), 217–222. https://doi.org/10.1080/01431160412331269698

Pantazi, X. E., Moshou, D., Alexandridis, T., Whetton, R. L., & Mouazen, A. M. (2016). Wheat yield prediction using machine learning and advanced sensing techniques. *Computers and Electronics in Agriculture*, *121*, 57–65. https://doi.org/10.1016/j.compag.2015.11.018

Peixoto, D. S., Silva, B. M., Godinho Silva, S. H., Karlen, D. L., Moreira, S. G., Pereira da Silva, A. A., et al. (2019b). Diagnosing, Ameliorating, and Monitoring Soil Compaction in No-Till Brazilian Soils. *Agrosystems, Geosciences & Environment*, *2*(1), 1–14. https://doi.org/10.2134/age2018.09.0035

Peixoto, D. S., Silva, B. M., Oliveira, G. C. de, Moreira, S. G., da Silva, F., & Curi, N. (2019a). A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. *Soil and Tillage Research*, *194*, 104307. https://doi.org/10.1016/j.still.2019.104307

Peixoto, D. S., Silva, L. de C. M. da, Melo, L. B. B. de, Azevedo, R. P., Araújo, B. C. L., Carvalho, T. S. de, et al. (2020). Occasional tillage in no-tillage systems: A global meta-analysis. *Science of The Total Environment*, *745*, 140887. https://doi.org/10.1016/j.scitotenv.2020.140887

Quincke, J. A., Wortmann, C. S., Mamo, M., Franti, T., Drijber, R. A., & García, J. P. (2007). One-time tillage of no-till systems: Soil physical properties, phosphorus runoff, and crop yield. *Agronomy Journal*, *99*(4), 1104–1110. https://doi.org/10.2134/agronj2006.0321

R Development Core Team. (2019). *R: A Language and Environment for Statistical Computing*. Viena, Austria: R Foundation for Statistical Computing. https://www.rproject.org.

Rabot, E., Wiesmeier, M., Schlüter, S., & Vogel, H. J. (2018). Soil structure as an indicator of soil functions: A review. *Geoderma*. Elsevier. https://doi.org/10.1016/j.geoderma.2017.11.009

Reichert, J. M., Suzuki, L. E. A. S., Reinert, D. J., Horn, R., & Håkansson, 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. https://doi.org/10.1016/j.still.2008.07.002

Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S., & Lu, X. (2002). Indicators of good soil physical quality: Density and storage parameters. *Geoderma*, *110*(1–2), 131–146. https://doi.org/10.1016/S0016-7061(02)00228-8

Reynolds, W. D., Drury, C. F., Tan, C. S., Fox, C. A., & Yang, X. M. (2009). Use of indicators and pore volume-function characteristics to quantify soil physical quality. *Geoderma*, *152*(3–4), 252–263. https://doi.org/10.1016/j.geoderma.2009.06.009

Reynolds, W. D., Drury, C. F., Yang, X. M., & Tan, C. S. (2008). Optimal soil physical quality inferred through structural regression and parameter interactions. *Geoderma*, *146*(3–4), 466–474. https://doi.org/10.1016/j.geoderma.2008.06.017

Richetti, J., Judge, J., Boote, K. J., Johann, J. A., Uribe-Opazo, M. A., Becker, W. R., et al. (2018). Using phenology-based enhanced vegetation index and machine learning for soybean yield estimation in Paraná State, Brazil. *Journal of Applied Remote Sensing*, *12*(02), 1. https://doi.org/10.1117/1.jrs.12.026029

Sá, J. C. de M. (1999). Manejo da fertilidade do solo no Sistema Plantio Direto. In J. O. Siqueira, F. M. S. Moreira, A. S. Lopes, L. R. G. Guilherme, V. Faquim, & A. E. Furtini Neto (Eds.), *Inter-relações fertilidade, biologia do solo e nutrição de plantas* (pp. 267–319). Lavras, MG: Sociedade Brasileira de Ciência do Solo.

Santos, H. G. dos, Jacomine, P. K. T., Anjos, L. H. C. dos, Oliveira, V. Á. de, Lumbreras, J. F., Coelho, M. R., et al. (2018). *Sistema brasileiro de classificação de solos*. *Embrapa Solos* (5th ed.). Brasília, DF.

Saradhi, V. V., Karnik, H., & Mitra, P. (2005). A decomposition method for support vector clustering. In *Proceedings of 2005 International Conference on Intelligent Sensing and Information Processing, 2005.* (Vol. 2005, pp. 268–271). IEEE. https://doi.org/10.1109/ICISIP.2005.1529460

Silva, B. M., Oliveira, G. C., Serafim, M. E., Silva, É. A., Ferreira, M. M., Norton, L. D., & Curi, N. (2015). Critical soil moisture range for a coffee crop in an oxidic latosol as affected by soil management. *Soil and Tillage Research*, *154*, 103–113. https://doi.org/10.1016/j.still.2015.06.013

Smidt, E. R., Conley, S. P., Zhu, J., & Arriaga, F. J. (2016). Identifying Field Attributes that Predict Soybean Yield Using Random Forest Analysis. *Agronomy Journal*, *108*(2), 637. https://doi.org/10.2134/agronj2015.0222

Soil Science Glossary Terms Committee. (2008). *Glossary of soil science terms*. Madison, WI: Soil Science Society of America.

Soil Survey Staff. (2014). *Keys to Soil Taxonomy*. *USDA Natural Resources Conservation Services* (12th ed.). Washington, DC.

Szatanik-Kloc, A., Horn, R., Lipiec, J., Siczek, A., & Szerement, J. (2018). Soil compaction-induced changes of physicochemical properties of cereal roots. *Soil and Tillage Research*, *175*(May 2017), 226–233. https://doi.org/10.1016/j.still.2017.08.016

Tulbure, M. G., Wimberly, M. C., Boe, A., & Owens, V. N. (2012). Climatic and genetic controls of yields of switchgrass, a model bioenergy species. *Agriculture, Ecosystems & Environment*, *146*(1), 121–129. https://doi.org/10.1016/J.AGEE.2011.10.017

van Raij, B., Cantarella, H., Quaggio, J. A., & Furlani, A. M. C. (1997). *Recomendações de adubação e calagem para o Estado de São Paulo* (2 ed. rev.). Campinas, SP: IAC.

FINAL CONSIDERATIONS

Soil compaction is a major challenge in grain production areas under no tillage system in Brazil. To mitigate this problem, farmers and researchers have adopted the OT, mainly using a chisel and subsoiler. However, decision making regarding the use of OT does not have well-defined criteria, especially due to the low accuracy in diagnosing soil compaction. Thus, many farmers have frequently (for example annualy) use tillage as a management practice, losing the main benefits of NT system and not achieving crop yield improvements in some cases.

This thesis contributed to the understanding of the main effects of OT on soil physical, chemical and biological properties, annual crop yield, soil erosion and weed control and improving the diagnosis, monitoring and alleviation of soil compaction in no tillage system.

The effect of soil physical properties on crop response depends on many factors, such as climatic conditions, type of crops, management, soil fertility, among many others. In the meta-analysis, in general, there was no effect of OT on crop yield, however, when subsoiler was used or no-tillage was in the transitional phase or the condition was water restriction, the effect was positive. Therefore, more studies need to be done in order to improve the prediction of crop responses to variations in soil physical conditions.

Occasional tillage carried out in the experiment of this thesis using chisel, wedge tip subsoiler and wing tip subsoiler increased soybean yield in sequence. The average cost of subsoiling on the farm in 2015 was R$200 and the treatment with a wedge tip subsoiler produced 15 bags ha^{-1} more than the control (no-tillage). The average price of a soybean bag in 2015 was R$70. Right from the first crop post occasional tillage, there was already a benefit of R$850 ha^{-1}.

The methodologies for diagnosing soil compaction presented here require constant adjustments and their use and adaptations are encouraged in different climatic conditions, types of crops, soils, use and management. In the farm-level use of the diagnosis using penetration resistance has already had adjustments. For example, evaluate the reference area only with soil moisture at the matric potential of -100kPa, equal to the areas suspected of compaction, instead of making the penetration resistance curve. This modification reduces the costs and time of sampling and analysis.

This thesis focused on mechanical methods, however, there is a huge potential for the use of cover crops (biological method) and the association of mechanical methods and cover crops in mitigating soil compaction. More research is needed in this regard. In addition, preventive management of soil compaction is essential, observing the soil load-bearing capacity, the vertical stress applied by each agricultural machine and the soil moisture conditions for traffic. Studies and incentives for the use of controlled traffic is also an excellent option to restrict compacted areas in the crop.