UNIVERSIDADE FEDERAL DO PARANÁ

DANIEL MALHEIRO DO NASCIMENTO

SISTEMAS DE PREPARO DO SOLO A LONGO PRAZO E SEUS EFEITOS NOS INDICADORES FÍSICOS-MECÂNICOS E PRODUTIVIDADE DAS CULTURAS

CURITIBA

2022

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Tese apresentada ao programa de Pós-Graduação em Ciência do Solo, Setor de Ciências Agrárias, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Doutor em Ciência do Solo.

Orientadora: Prof[a]. Dr[a]. Karina Maria Vieira Cavalieri Polizeli

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RESUMO

A degradação do solo é avaliada usando atributos e indicadores de qualidade física do solo (IQFS), que causam perdas de rendimento em grandes culturas, tais como soja, trigo e milho. O objetivo geral desse estudo foi determinar, analisar e integrar parâmetros de indicadores físicos-mecânicos relacionando-os com a produtividade das culturas, em diferentes sistemas de preparo do solo de longo prazo. Para atingir esse objetivo, o estudo foi dividido em dois capítulos. Capítulo 1: destaca o estudo de IQFS sob diferentes sistemas de preparo de longo prazo, verificando-se qual(is) sistema(s) afeta(am) as funções físicas do solo, causando impactos na produtividade das culturas de soja e trigo. Foram realizadas também correlações entre os IQFS e a produtividade dessas culturas. O Capítulo 2 apresenta a integração de parâmetros físicos-mecânicos, relacionados com a densidade do solo, para propor intervalos de pressões aplicadas ao mesmo, que podem afetar a produtividade das culturas e, a capacidade de suporte de carga do solo. O estudo foi realizado em uma área experimental pertencente à Fundação ABC, no município de Ponta Grossa–PR. O delineamento experimental adotado foi em blocos ao acaso, sendo os tratamentos os sistemas de preparo do solo: plantio direto (PD), plantio direto escarificado (PD_E) e preparo convencional do solo (PC). Foram realizadas amostragens em 2014, 2015, e 2016, em um Latossolo Vermelho distrófico típico, de textura argilosa, no centro das camadas de 0,00–0,15 e 0,15–0,30 m. No primeiro capítulo observou-se que apenas alguns IQFS, das funções atreladas à capacidade de suportar o crescimento de raízes e resistência do solo à degradação correlacionaram-se significativamente com a produtividade de trigo. O volume médio de mesoporos, (∅ entre 100 e 30 μm), não apresentou diferenças significativas entre os sistemas de preparo. Assim como, as funções físicas que tratam do equilíbrio entre fluxo e armazenamento de água no solo. Entretanto, o PD foi indicado como o mais adequado para sustentabilidade do solo e produtividade das culturas entre os três sistemas. No segundo capítulo foi possível estabelecer relações entre a produtividade e, a frequência maior de um volume desfavorável de mesoporos ($\Phi_{MesAdverso}$), e a densidade do solo crítica ($\rho_{scrítica}$). O PD apresentou maior rendimento acumulado entre os três sistemas, tendo relação significativamente negativa com a maior frequência de volume de mesoporos de 0,07 m^3 m^{-3} ($\Phi_{MesAdverso}$), e positiva com a $\rho_{scrítica}$. Ademais, o uso de indicadores como a densidade de alerta (ρ_{sa}), $\rho_{scrítica}$, $\Phi_{MesAdverso}$, e a pressão de preconsolidação (σ_P), propiciaram parâmetros físicos que subsidiaram a determinação de pressões consideradas desfavoráveis ao desenvolvimento de plantas, e à capacidade de suporte de carga do solo. Nesse estudo, o $\Phi_{MesAdverso}$ indicou efeitos deletérios na disponibilidade de água, mesmo sem promover deformações plásticas (σ_P) ou condições de alta degradação física, como a $\rho_{scrítica}$. O intervalo de pressões físico-mecânicas adversas do solo mostrou-se aplicável, com a integração da CRA, da CCS e do intervalo hídrico ótimo, considerando não apenas as pressões que causam compactação adicional ao solo, mas também àquelas que afetam a disponibilidade hídrica às plantas, e consequentemente, sua produtividade.

Palavras-chave: conservação do solo, distribuição do tamanho dos poros, mesoporos, pressão de preconsolidação, intervalo hídrico ótimo.

ABSTRACT

Soil degradation is assessed using attributes and soil physical quality indicators (SFQI), that cause yield losses in large crops, such as soybeans, wheat and corn. The general objective of this study was to determine, analyze and integrate physical-mechanical parameters of indicators, relating them to crop yield, in different long-term soil tillage systems. To achieve this objective, the study was divided into two chapters. Chapter 1: highlights the SPQI in different long-term tillage systems, verifying which system(s) affect the soil physical function(s), causing an impact on the yield of soybean and wheat crops. Correlations were also made between the SFQI and the yield of these crops. The Chapter 2 presents the integration of physical-mechanical parameters related to soil bulk density (ρ_B) to propose ranges of applied stresses, which can affect crop yield and soil load-bearing capacity. The study was carried out in an experimental area that belongs to the Fundação ABC, in the municipality of Ponta Grossa-PR. The experimental design adopted was randomized block experimental design, with the treatments being the following systems: no-tillage (NT), strategic tillage (ST) and conventional tillage (CT). The soil sampling was performed in 2014, 2015 and 2016, in a Rhodic Ferralsol, with a clayey texture, at the center of the two layers (0.00–0.15 and 0.15–0.30 m). In the first chapter, it was observed that only some SFQI, of the functions linked to the capacity to support root growth and soil resistance to degradation, were significantly correlated with wheat yield. The mean volume of mesopores, (∅ between 100 and 30 μm), had no significant differences between tillage systems. As well, the physical functions that deal with the balance between flows and water storage in the soil. Nonetheless, the NT system was indicated as the most suitable for yielding and soil sustainability among the three systems. In the second chapter, it was possible to establish relationships between yield and, the increased frequency of an adverse volume of mesopores ($\Phi_{MesAdverse}$), and the critical soil bulk density ($\rho_{BCritical}$). The NT showed the highest accumulated yield among the three systems, having a significantly negative relationship with the highest frequency of mesopores volume of 0.07 m^3 m^{-3} ($\Phi_{MesAdverse}$), and a positive relationship with $\rho_{BCritical}$. Furthermore, the use of indicators as bulk density alert value (ρ_{BA}), $\rho_{BCritical}$, $\Phi_{MesAdverse}$, and precompression stress (σ_P), provided physical parameters that supported the determination of stresses considered adverse for plant growth, and the soil load-bearing capacity. In this study, $\Phi_{MesAdverse}$ indicated deleterious effects on water availability, even without promoting plastic deformations, through (σ_P) or conditions of high physical degradation, like the $\rho_{BCritical}$. Soil adverse physical-mechanical stress range proved to be applicable, with the integration of SWRC, SCC and least limiting water range, considering not only the stresses that causes additional compaction to the soil but also those that affect water availability to plants and consequently, their yield.

Keywords: soil conservation, pore size distribution, mesopores, precompression stress, least limiting water range.

SUMÁRIO

INTRODUÇÃO GERAL

A mecanização na agricultura resultou em um aumento constante na massa dos veículos agrícolas, as cargas das rodas dos tratores aumentaram de cerca de 1,5 Mg, em 1960, para 4,0 Mg, em 2000, e as colheitadeiras de cerca de 1,5 Mg, em 1960, para 9,0 Mg no presente, resultando em um aumento dos níveis de densidade do solo (ρs) e diminuição da condutividade hidráulica (KELLER et al., 2019). NUNES et al. (2019) citam que um dos principais fatores de compactação de solos agrícolas sob plantio direto é o uso de máquinas e implementos agrícolas, que geralmente aplicam pressões maiores que a capacidade de suporte de carga do solo, causando compactação adicional ao solo.

Estudos que relacionam os diferentes indicadores de qualidade física do solo, como a curva de retenção de água (CRA), a curva de compressão (CCS) e o intervalo hídrico ótimo (IHO) ainda são escassos, podendo-se citar IMHOFF et al. (2001), que relacionou a CCS e IHO, utilizando o valor da densidade do solo crítica do IHO como limitante. Tanto a CCS quanto o IHO dependem do teor de água e da ρs, uma propriedade física que pode traduzir alguns efeitos do manejo no solo, podendo ser inserida na CRA via *n*, um parâmetro de ajuste da curva empírico adimensional, conforme descrito por TORMENA et al. (1999).

A determinação da CRA é uma das práticas mais comuns em física do solo. Com este parâmetro é possível detectar o efeito do manejo no equilíbrio da água no solo e a condição estrutural do solo. Um dos modelos mais utilizados para ajustar a CRA é o de VAN GENUCHTEN (1980), que relaciona o conteúdo volumétrico de água com o potencial matricial.

A partir da CRA pode-se obter a classificação do tamanho dos poros do solo em diferentes funções (BREWER, 1964; KOOREVAAR et al. 1983; LAL and SHUKLA, 2004), que incluem mesoporos e macroporos muito finos e finos que podem ser responsáveis pela absorção de água pelas raízes e sua redistribuição no perfil do solo. Já a curva de compressão (CASAGRANDE, 1936), pode produzir informações sobre a compressibilidade do solo e a capacidade de suporte de carga, através da pressão de preconsolidação (σ_P), limite entre as deformações elásticas (recuperável) e plásticas (não recuperáveis) (HOLTZ and KOVACS, 1981).

O IHO é um indicador da qualidade física do solo que incorpora fontes mensuráveis relevantes de estresse crítico que o solo impõe ao crescimento das plantas, como resistência do solo à penetração, aeração e teor de água na capacidade de campo e ponto de murcha (DA SILVA et al., 1994; LIMA et al., 2021; TORMENA et al., 1999). Geralmente, o aumento da ρs resulta em uma redução no IHO, na direção dos valores de ρs onde o IHO pode chegar à zero, esta ρs é denominada densidade do solo crítica ($\rho_{scrítica}$) (DA SILVA et al.,1994; TORMENA et al., 1999).

NUNES et al. (2019) mencionam que a relação entre as propriedades compressivas do solo e o crescimento das plantas é insuficientemente estudada em diferentes sistemas de preparo, e que as propriedades mecânicas do solo podem estar correlacionadas, tanto com o desenvolvimento da planta, quanto com os atributos do solo que afetam o crescimento da planta, tais como teores de água e matéria orgânica, textura e ρs. IMHOFF et al. (2016) relataram que a determinação das relações entre o IHO, σ_P e o índice de compressão e sua dependência das propriedades intrínsecas do solo seriam muito úteis para avaliar os sistemas de preparo do solo. Os autores ainda indicam que a pressão máxima aceitável a ser aplicada durante as operações de preparo do solo pode ser calculada introduzindo os valores estimados de $\rho_{scrítica}$ para o crescimento das plantas no modelo da CCS.

Portanto, a ligação entre parâmetros da CRA, CCS e do IHO, pode fornecer informações sobre pressões aplicadas ao solo que podem afetar o crescimento e desenvolvimento das raízes, e não promover deformações plásticas, ou seja, compactação adicional. Além disso, é possível analisar se a pressão de preconsolidação está refletindo, não apenas condições desfavoráveis ao solo, mas também ao crescimento das plantas.

Além disso, tais indicadores auxiliam na avaliação de impactos negativos na produtividade e sustentabilidade das culturas. Sendo que atributos físicos do solo agrupados de acordo com a(s) função(ões) física(s) que exercem no solo, podem indicar qual(is) função(ões) está(ão) afetando mais a produtividade (ANDREWS et al., 2002; CAVALCANTI et al., 2020; CHERUBIN et al., 2016; SANTOS et al., 2021). Há uma variação na literatura quanto às funções, de acordo com os indicadores físicos, químicos ou biológicos utilizados, sendo esses indicadores, geralmente divididos em quatro funções (CAVALCANTI et al., 2020; CHERUBIN et al., 2016; SANTOS et al., 2021).

A hipótese geral é que sob condições edafoclimáticas similares, com adequada distribuição de chuvas, diferentes sistemas de preparo do solo proporcionam que, algumas funções físicas do solo, como f(i) capacidade de suportar o crescimento das raízes; f(ii) retenção de água; f(iii) fluxos de água e ar; ou f(iv) resistência do solo à degradação, afetem mais a produtividade das culturas que outras. Assim como o conhecimento específico de indicadores físicos sensíveis às alterações de produtividade, atrelados à ρs, podem ser relacionados, não somente à produtividade das culturas, mas também à capacidade de suporte de carga do solo. Desta forma, propicia intervalos de pressões aplicadas ao solo, que evitem ou reduzam os efeitos negativos na produção das culturas, sob diferentes sistemas de preparo.

O presente trabalho encontra-se subdividido em dois capítulos:

Capítulo 1 – Qualidade física do solo e produtividade de culturas em diferentes sistemas de preparo de longo prazo – *Soil physical quality and crop yield in different long-term tillage systems.*

Capítulo 2 – Estimativa de pressões físicas-mecânicas adversas no solo ligadas à produtividade das culturas - *Estimate of adverse physical-mechanical stresses in the soil linked to crop yield.*

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CHAPTER 1- SOIL PHYSICAL QUALITY AND CROP YIELD IN DIFFERENT LONG-TERM TILLAGE SYSTEMS

Abstract

Soil degradation has been assessed by several indicators and their indexes, sometimes demonstrating negative effects on crop yield. The soil physical quality indicators (SPQI) can be measured according to the functions that they perform into the soil for plant root growth and development. This study aimed: i) to evaluate and compare SPQI in different long-term tillage systems, such as: no-tillage (NT), strategic tillage (ST), and conventional tillage (CT); ii) to verify relationships between SPQI and crop yield, to define those indicators that affect mostly the crops; and iii) to indicate the tillage system most suitable for yielding, and crop sustainability. The study was carried out in the municipality of Ponta Grossa-PR, which climate is Cfb – humid subtropical highland climate. The soil sampling was performed in a Rhodic Ferralsol, with a clayey texture, at the center of the two layers (0.00–0.15 and 0.15–0.30 m). The SPQI studied were visual evaluation of soil structure (VESS), soil total organic carbon content, structural stability index, soil bulk density, degree of compactness (Dc), macro and micropores, soil water storage capacity, soil aeration capacity, precompression stress, and compression index. Soil water retention curve (SWRC) was previously determined in the area and was fitted by updating it with soil bulk density data, and then, the pore size distribution curve (PSD), and plant-available water capacity were obtained. From PSD, fine roots pore volume and mesopores volume were obtained. Crop yield was determined for the winter/summer seasons in 2016/17, and correlated with the SPQI. There were no significant differences ($p<0.05$) between the tillage systems for most of the SPQI evaluated, as well as between the two layers within each system. However, it was observed that the SPQI linked to the capacity to support root growth -*f(i)*, such as Dc ($r = -0.81$), and soil resistance to degradation -f(*iv*), as Sq_{VESS} ($r = -0.76$), were significantly correlated with wheat yield, but none correlated with soybean yield. These indicators were efficient to show the effects of tillage systems on crop yield. The mean mesopores volume (∅ between 100 - 30 μm) had no significant differences between tillage systems in both layers, as well as the physical functions related to the balance between flows and water storage in the soil. The NT system was considered the best tillage system, after 23 years of experiment, in the studied conditions, which kept all soil physical functions adequate, besides mostly contributing to soil conservation.

Keywords: soil conservation; soil water retention curve; pore size distribution; fine roots pore; mesopores.

1.1. Introduction

The soil structure can be significantly modified by management practices and changes in the environment. Practices that increase yield and decrease soil disturbance, increase aggregation and structural developments (BRONICK and LAL, 2005). According to these authors, depending on the management system adopted, there may be improvements, maintenance, or damages in the soil structure, which in the latter case may result in compaction, negatively affecting infiltration and the availability of air and water for the plants. Thus soil physical quality indicators are useful to indicate good management practices for cropping.

No-tillage is an important management system for the conservation of soil and water in different crops and climates around the world (BUSARI et al., 2015). However, due to the non-disturbing soil, there is an increase in the degree of compactness (Dc) and the soil's mechanical resistance to penetration (NUNES et al., 2019). There are recurrent studies that highlight that the NT system has the potential to damage soil quality through compaction, which has always been a problem for agricultural yield, especially in clayey soils (NUNES et al., 2015).

Besides the negative aspects of NT, the adoption of conservationist tillage systems brings several benefits by prioritizing the maintenance of plant residues on the soil surface and reducing runoff, being considered one of the primary differences between NT and conventional tillage (CT). Consequently, there is a decrease in soil loss due to erosion, an increase in soil water retention and infiltration, organic carbon and biological activity (DE MORAES SÁ et al., 2015) as well as reductions in soil temperature and soil water content variation, and soil structure improvement compared to CT (BUSARI et al., 2015; RHOTON, 2000). Then, the use of NT is consider, at most of studies, better than CT.

However, to ameliorate the negative effects in NT, such as soil compaction, one of the recommended procedures is the adoption of soil chiseling over time (FREITAS et al., 2017). According to the authors, the use of chiseling leads to the breaking of compacted layers, improving the soil's physical attributes, with greater aeration and water movement across the soil profile (CONYERS et al., 2019). Meanwhile, the period in which a mechanical chisel should or should not be carried out has been tested by several authors, with periods ranging from six months to three years usually (CONYERS et al., 2019; MORAES et al., 2014; NUNES et al., 2019).

To assess the soil physical quality indicators (SPQI), and their indexes, attributes that influence the soil's capacity to perform agricultural functions can be used (CHERUBIN et al., 2016; SANTOS et al., 2021). The most desirable attributes are those more sensitive to management and easily obtained in laboratories (ARSHAD and MARTIN, 2002; REYNOLDS et al., 2009). When discriminating soils with signs of degradation, the SPQI highlights the need for the adoption of systems that favor soil structure, such as those that increase the levels of organic matter (BRONICK and LAL, 2005; BUSARI et al., 2015). Then NT has an important role in this sense.

Between SPQI, soil bulk density is an attribute often used as an indirect indicator of aeration, compaction, and the soil capacity to store and transmit water (DADDOW and WARRINGTON, 1983; NASCIMENTO et al., 2019; PACHEPSKY and PARK, 2015; USDA-NRCS, 1996). The soil water storage capacity and soil aeration capacity indicate the capacity of the soil to supply water and air as a function of its total porosity (REYNOLDS et al., 2002; SANTOS et al., 2021). The plant-available water capacity – soil moisture between field capacity and permanent wilting point –, is also widely used in studies of physical soil quality (NASCIMENTO et al., 2019; REYNOLDS et al., 2007; TORMENA et al., 1999). In addition, the soil compactness degree, obtained through the reference soil bulk density, can quantify the compaction of agricultural soils, being an effective indicator of several SPQI, and it correlates well with crop yield (REICHERT et al., 2009; VIZIOLI et al., 2021).

However, to better understand the behavior of the soil structure, it is necessary to use specific indicators (CHERUBIN et al., 2016; SANTOS et al., 2021). PIERI (1992) proposed the structural stability index, based on organic carbon content and texture. The visual evaluation of soil structure is a semi-quantitative approach method to assess the soil structural quality, and it aims to identify different structural layers of soil surface (GUIMARÃES et al., 2011). This approach has been globally used, in soils with different textural classes, and submitted to distinct management and cultivation practices, under contrasting climates (FRANCO et al., 2019).

The soil compression curve, in turn, can produce information about soil compressibility and the soil load-bearing capacity (CASAGRANDE, 1936). Thus, some authors have used the soil compression curve to assess the soil compressive behavior (KELLER et al., 2011; LARSON et al., 1980; REICHERT et al., 2018). Two parameters derived from the compression curve are mainly used, the compression index (Ci), which is the slope of the virgin compression curve, used to determine the susceptibility to soil compaction, and the precompression stress (σ_P), which indicates the memory of the stresses to which the soil was subjected (LARSON et al., 1980), consequently, the soil load-bearing capacity. Additional compaction that exceeds σ_P causes physical soil deterioration and has been described in several studies (IMHOFF et al., 2004; SAFFIH-HDADI et al., 2009). This additional compaction influences the size and distribution of soil pores, which have different functions and can be quantified through the soil water retention curve (SWRC) (VAN GENUCHTEN, 1980), including mesopores, very fine and fine macropores that may be responsible for water absorption by roots and its redistribution in the soil profile (BREWER, 1964; KOOREVAAR et al. 1983; LAL and SHUKLA, 2004).

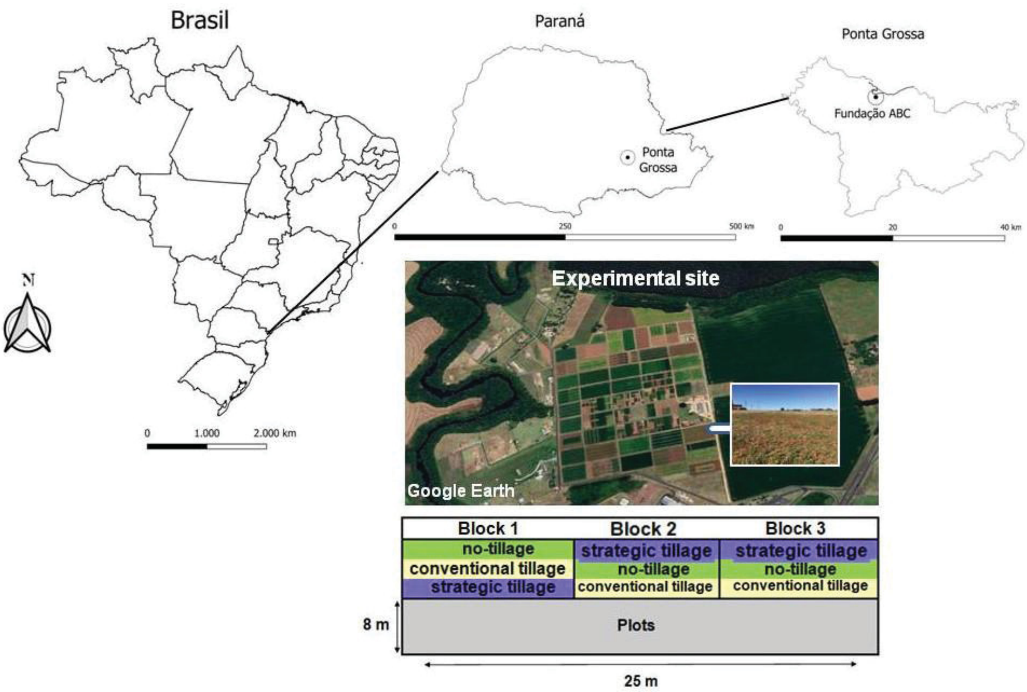
This study hypothesized that the adopted tillage system can favor some physical functions over others, maximizing crop yield. Thus, under subtropical conditions, functions linked to water storage and capacity to support root growth are the main causes to reduce plant yield.

The study aimed i) to evaluate and compare SPQI in different long-term tillage systems, such as: no-tillage (NT), strategic tillage (ST), and conventional tillage (CT); ii) to verify relationships between SPQI and crop yield, to define those indicators that affect mostly the crops; and iii) to indicate the tillage system most suitable for yielding, and crop sustainability.

1.2. Material and Methods

1.2.1. Experimental area

The study was carried out in Ponta Grossa, PR, Brazil, at an experimental site in the Fundação ABC (Fig.1). According to ALVARES et al. (2013), the climate is Cfb humid subtropical climate, with temperate summer, and an annual mean temperature of 17 °C (21 °C in the warmest month and 13 °C in the coldest month). The mean annual rainfall is 1,550 mm, slightly concentrated in the summer months, and the driest months usually are July and August. The rainfall of the experimental area is presented in Fig. 2.



Site	Coordinates		Altitude	Climate		
	Latitude	Longitude	m.a.s.l.	Koppen classification	MAT	MAP
Fundação ABC	25° 00' 51.07"	50º 09' 06.87"	975	Cfb- humid subtropical	17.0	1,550

Figure 1: Geographic location and climate classification of the study site in southern Brazil. m.a.s.l.: meter above sea level; MAT: mean annual temperature; MAP: mean annual precipitation.

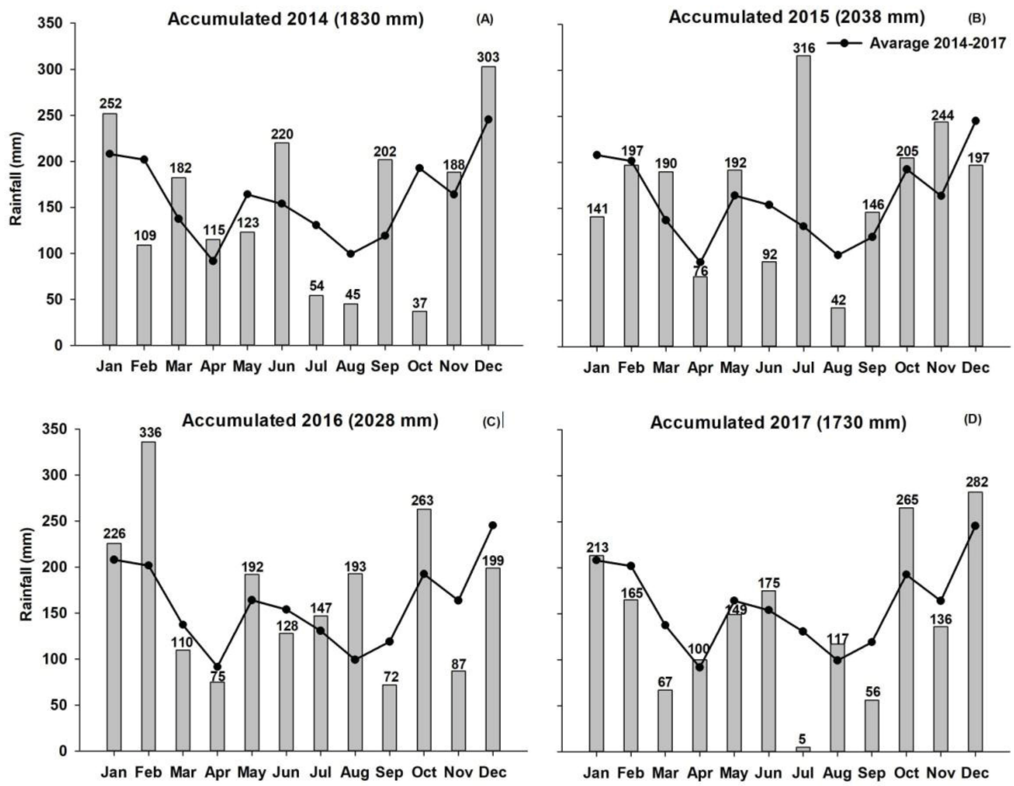


Figure 2: Monthly rainfall of 4 years at the experiment evaluation site.

The relief is plain to slightly undulating (slope 2-4%) and the soil is classified as a Rhodic Ferralsol (FAO, 1998) or “Latossolo Vermelho Distrófico típico” in the Brazilian soil classification system (EMBRAPA, 2018), clayey textured. Soil's physical attributes are shown in Table 1.

The experimental area was under native vegetation until 1967 when conversion to cropland occurred. In 1989 the experiment started to be prepared and the last application of limestone was in 1994, details about fertilizing can be found in DE PIERRI et al. (2019). Three soil tillage systems were implemented: no-tillage (NT), strategic tillage (ST), and conventional tillage (CT).

In the NT, crops have been sown using a no-tillage seeder that disturbs only the soil under the crop row, while in the ST the soil is cultivated as no-tillage, but it is chiseled every three years, at the 0.30 m of depth, before the winter crop sowing, what the last occurred in 2014 (Appendix 1 – Chapter 1 – Table 1), and the CT has been tilled through conventional moldboard plow to 0.25 m depth and harrowed twice to 0.20 m depth before planting each crop. The experimental design is the randomized block with three replicates, under a split plots scheme, the plots were the treatments, and the subplots were the layers (0.00–0.15 and 0.15–0.30 m). Each plot had an area of 8 × 25 m, with a border of 1 m on all sides (Fig.1).

Table 1: Soil physical attributes of the study areas.

Soil Particle Distribution						
			Sand			ρ_p
	Clay	Silt	Coarse	Fine	Total	
	g kg^{-1}					Mg m^{-3}
	0.00–0.15 m					
NT	529	90	196	185	381	2.62
ST	479	131	200	190	390	2.57
CT	519	106	183	192	375	2.59
	0.15–0.30 m					
NT	571	70	175	175	350	2.61
ST	523	100	187	190	377	2.59
CT	531	121	167	181	348	2.58

NT: no-tillage; ST: strategic tillage (one chiseling every three years); CT: conventional tillage; ρ_p: particle density; adapted from VIZIOLI et al. (2021).

Black oats (*Avena strigosa*) were sown as a cover crop in May 1993, since then, a crop rotation with maize *(Zea mays),* and soybean *(Glycine Max)* in the summer and black oats, white oats *(Avena sativa)*, wheat *(Triticum sativum),* and vetch *(Vicia sativa L.)* in the winter have been done, sowing at the 0.17 m row spacing, with a small disc seeder (crop rotation for the period can be seen in (Appendix 1 – Chapter 1–Table 1).

Wheat was seeding as a winter crop in 2016, and the harvest took place on 11/10/2016. Seeding of soybean 2016/17 took place on 11/22/2016 and the harvest in the first half of April 2017. The planting density of 325,000 plants ha^{-1} was used.

The wheat crop received as basic fertilization 300 kg ha^{-1} of 10-20-20 (N P K) at the time of sowing and broadcast fertilization of 200 kg ha^{-1} urea. The 2016/17 soybean crop received as basic fertilization 300 kg ha^{-1} of 12-32-00 + Zn (N P K) + 1 kg ha^{-1} of Zn at the time of seeding.

1.2.2. Soil sampling and analysis

In 2014 was performed the first sampling, which was obtained, among others SPQI, the soil water retention curve (SWRC), and critical soil bulk density ($\rho_{BCritical}$), which the tillage operations for CT and ST being performed earlier than sampling (VIZIOLI et al., 2021). These data were used to estimate some soil physical indicators dependent on soil bulk density such as degree of compactness, plant available water content, fine root pores volume, and mesopores volume.

The visual evaluation of soil structure (VESS) was performed in September 2015 in agreement with GUIMARÃES et al. (2011), evaluating 27 monoliths (3 treatments x 3 blocks x 3 trenches). Also, it was measured soil gravimetric water content (Ug) and total soil organic carbon content (OC) of each layer identified by VESS scores (Sq_{VESS}).

In November 2016, undisturbed soil samples were collected with volumetric cylinders (length–3.0 cm, diameter–6.85 cm ≅ 110 cm^3) at the center of the two layers (0.00–0.15 and 0.15–0.30 m), totaling 72 samples (3 treatments x 3 blocks x 4 samples × 2 layers).

The following soil physical attributes were determined for this study:

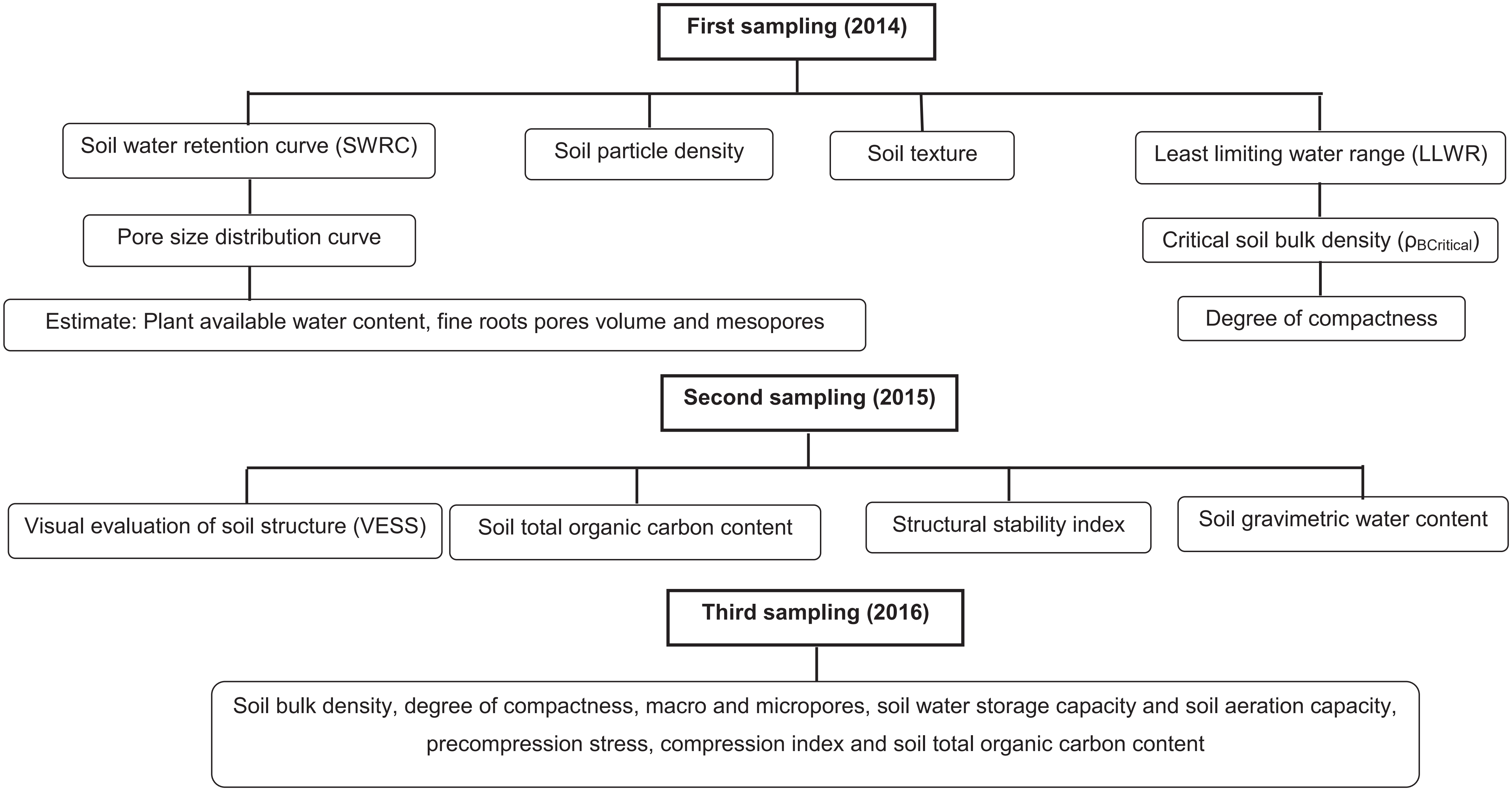
a) Soil texture by the Bouyoucos densimeter method (GEE and BAUDER, 1986) (2014 samples);

b) Soil particle density (ρ_p) by the volumetric flask method (BLAKE and HARTGE, 1986) (2014 samples);

c) Total organic carbon content (OC) was determined by the wet oxidation method in potassium dichromate solution in sulfuric medium (WALKLEY and ARMSTRONG BLACK, 1934) (2015 and 2016 samples);

d) Soil total porosity, obtained through the volumetric water content at saturation θ_s= soil matric potential (h)= 0; Microporosity, obtained by Richards chambers under h= -100 hPa, equivalent to pores with diameters <30 μm; Macroporosity, obtained as the difference between total porosity and microporosity (2016 samples).

Flowchart 1: Chronology of soil samples performed in the study and the indicators obtained.



1.2.3. Soil compression curve (SCC) and precompression stress (σ_P)

The SCC was determined for each treatment and soil layer from the 2016 samples. (Appendix 1 – Chapter 1 – Figure 1). The soil samples were saturated for 72 hours and weighed to determine the θ_s and subsequently equilibrated at the soil matric potential of -100 hPa, using Richards chambers (KLUTE, 1986). The samples were submitted to an uniaxial compression test in a compression apparatus described by FIGUEIREDO et al. (2011). The sequential stresses in the test were 25, 50, 75, 100, 150, 200, 300, 400, 800, and 1200 kPa, in which each load was applied for 5 minutes (ABNT, 2020). For this device, the soil deformation during the compression test had annotation manually by soil height in the cylinder, after each loading step.

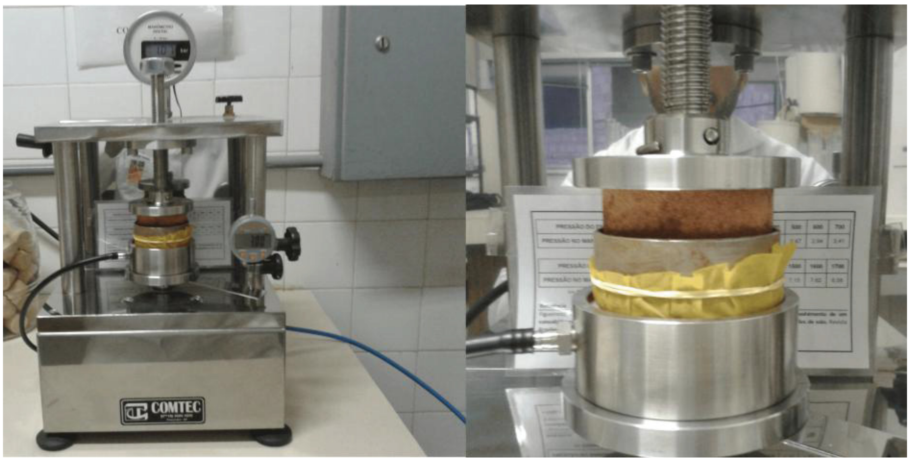


Figure 3: Compression apparatus used in the uniaxial compression test

At the final of the compression test, the samples were oven-dried at 105 °C for 36 h, to obtain the soil dry mass, and the changes in the soil volume (i.e., soil heigh into the cylinder) were used to calculate the soil bulk density (ρ_B) based on the dry mass and the total volume for each pressure applied (BLAKE and HARTGE, 1986).

The initial ρ_B, before application of the selected pressure, was used as an indicator for other SPQI analyses. The void ratio (ε) was calculated for each core, based on ρ_B and soil particle density (ρ_p) as below:

$$\varepsilon = [\left(\frac{\rho_p}{\rho_B}\right) - 1] \quad (1)$$

Where: ε= void ratio (dimensionless);

ρ_p= soil particle density (Mg m^{-3}); and

ρ_B= soil bulk density (Mg m^{-3});

The SCC was constructed for each undisturbed sample, using a fourth-order polynomial curve, fitted using the Excel® software. The precompression stress (σ_P) was determined using the standard CASAGRANDE (1936) fitting method, calculated by a spreadsheet developed by ARVIDSSON and KELLER (2004). Then, the determination of σ_P was performed mathematically, avoiding the subjectivity of the manual method. The compression index (Ci) was determined by the slope of the virgin compression line (HOLTZ and KOVACS, 1981).

All samples collected in the field were processed in the Soil Physics Laboratory of the Department of Soils and Agricultural Engineering, UFPR's Agricultural Sciences Sector.

1.2.4. Reference soil bulk density ($\rho_{BCritical}$) and degree of compactness (Dc)

The reference bulk density was considered the critical soil bulk density ($\rho_{Bcritical}$), found by the least limiting water range, which is equal to zero (LLWR = 0), by VIZIOLI et al. (2021) in the same experiment in 2014.

The degree of compactness (D_C) was obtained according to Equation 2:

$$Dc = \frac{\rho_B}{\rho_{Bcritical}};\ 0 \leq Dc \leq 1 \quad (2)$$

Where: Dc= degree of compactness (dimensionless);

ρ_B= soil bulk density (Mg m^{-3}); and

$\rho_{Bcritical}$ = reference soil density (Mg m^{-3}).

1.2.5. Soil water retention curve and pore size distribution curve

Soil water retention curve (SWRC) data presented in VIZIOLI et al. (2021) were fitted using the procedures described in DA SILVA and KAY (1997). Then, ρ_B obtained in 2016 was incorporated into the model by the parameter *n* of the SWRC, as done by TORMENA et al. (1999), seeking for representing tillage effects updated (Table 2). This approach uses van Genuchten equation, with Mualem restriction (m = 1- (1 / n)) (MUALEM, 1986; VAN GENUCHTEN, 1980) (Eq. 3), and includes ρ_B into the model via *n*, as presented in Eq. 4:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[(1+\alpha h)^n]^{1-1/n}} \quad (3)$$

Where: θ = volumetric water content (m^3 m^{-3}) corresponding to soil matric potential (h);

θ_r = residual water content (m^3 m^{-3});

θ_s = saturated water content (m^3 m^{-3});

h = soil matric potential (hPa);

n = dimensionless empirical curve-fitting parameter; and

α = empirical curve-fitting parameter expressed in hPa^{-1}.

$$n = n_0 + n_1 \rho_B + n_2 \rho_B{}^2 \quad (4)$$

Where: n = dimensionless empirical curve-fitting parameter;

n_0, n_1 and n_2 = dimensionless empirical curve-fitting parameter; and

ρ_B= soil bulk density (Mg m^{-3});

The procedure to include ρ_B into the model via *n* allows the characterization of the influence of ρ_B (class variable) on n_0, n_1, and n_2, multiple regression analyses.

Table 2: Parameters of the model of the pore size distribution curve (dθ/dh) = $S_{v(h)}$.

Parameters	Estimate	Confidence Limits (95%)	
		No-tillage	
α	0.0407	0.0321	0.0493
θ_r	0.2415	0.1472	0.3359
n_0	7.9805	2.4865	13.4744
n_1	-10.2253	-19.1863	-1.2644
n_2	3.9321	0.2791	7.5851
n (0.00–0.15 m)	1.410	–	–
n (0.15–0.30 m)	1.541	–	–
	F= 5232.52	Pr > F <0.0001	
		Strategic tillage	
α	0.0272	0.0200	0.0344
θ_r	0.2645	0.1438	0.3853

n_0	27.4029	7.4366	47.3692
n_1	-40.8117	-72.0752	-9.5481
n_2	15.9845	3.7486	28.2204
n (0.00–0.15 m)	1.609	–	–
n (0.15–0.30 m)	2.174	–	–
	F= 3078.37	Pr > F <0.0001	
		Conventional tillage	
α	0.0296	0.0227	0.0365
θ_r	0.1966	0.0939	0.2994
n_0	11.6087	2.3348	20.8826
n_1	-16.8671	-31.8609	-1.8733
n_2	6.9309	0.8803	12.9816
n (0.00–0.15 m)	1.356	–	–
n (0.15–0.30 m)	1.458	–	–
	F= 4016.42	Pr > F <0.0001	

α = empirical curve-fitting parameter expressed in hPa^{-1}; θ_r = residual water content ($m^3\ m^{-3}$); n_0, n_1 and n_2 = dimensionless empirical curve-fitting parameters.

The first derivative (dθ/dh) of SWRC provided the pore size distribution curve (Eq. 5). Thus, we can estimate the different classes of pores in the tillage systems updating the ρ_B in the SWRC in the current year, considering the mean ρ_B of each soil layer and tillage system.

$$\left(\frac{d\theta}{dh}\right) = \frac{\left\{\left[1-\left(\frac{1}{n}\right)\right]n(\theta_s-\theta_r)(\alpha^n)[h^{(n-1)}]\right\}}{\left\{(\alpha h)^n+1^{\left[1-\left(\frac{1}{n}\right)\right]+1}\right\}} \quad (5)$$

Where: (dθ/dh) = $S_{v(h)}$ pore volume distribution (dimensionless);

θ_r = residual water content ($m^3\ m^{-3}$);

θ_s = saturated water content ($m^3\ m^{-3}$);

h = soil matric potential (hPa);

n = dimensionless empirical curve-fitting parameter; and

α = empirical curve-fitting parameter expressed in hPa^{-1}.

The equivalent pore diameter d_e (µm) was determined using the capillary equation, according to (WARRICK, 2002):

$$d_e = \frac{2\sigma cos\alpha}{\rho_w g h} \quad (6)$$

Where: d_e = equivalent pore diameter (µm);

σ = surface tension of pure water (0,07275 N m^{-1});

cosα = ascending component of capillary force (α=0º);

ρ_w = water density (1000 kg m^{-3});

g = gravity acceleration (9.81 m s^{-2}); and

h = soil matric potential (hPa).

Pores size classification used in this study is in agreement to KOOREVAAR et al. (1983) that defined as equivalent pores diameter in according to its function: macropores > 100 µm $_{(h\ -30\ hPa)}$; mesopores (100 µm $_{(h\ -30\ hPa)}$ - 30 µm $_{(h\ -100\ hPa)}$); and micropores < 30 µm $_{(h\ -100\ hPa)}$.

The mesopores volume (ME) was calculated considering the volumetric water content obtained by SWRC, at matric potential of -100 and -30 hPa (Eq. 7). The fine roots pore size volume (FRp) was calculated considering the pore diameter between 1000 and 50 µm (HAMBLIN, 1986; LAL and SHUKLA, 2004), by volumetric water content obtained, at matric potential of -3 and -60 hPa, (Eq. 8). The FRp refers to commonly seminal and lateral roots from cereals. Both porosity classes are a ratio between pores volume by soil volume.

$$ME = (\theta_{(h-30\ hPa)} - \theta_{(h-100\ hPa)}) \quad (7)$$

Where: ME = mesopores volume ($m^3\ m^{-3}$);

$\theta_{(h\ -30\ hPa)}$ = soil volumetric water content ($m^3\ m^{-3}$) at soil matric potential of -30 hPa;

$\theta_{(h\ -100\ hPa)}$ = soil volumetric water content ($m^3\ m^{-3}$) at soil matric potential of -100 hPa.

$$FRp = (\theta_{(h-3\ hPa)} - \theta_{(h-60\ hPa)}) \quad (8)$$

Where: FR_p = fine roots pores size volume ($m^3\ m^{-3}$);

$\theta_{(h\ -3\ hPa)}$ = soil volumetric water content ($m^3\ m^{-3}$) at soil matric potential of -3 hPa;

$\theta_{(h\ -60\ hPa)}$ = soil volumetric water content ($m^3\ m^{-3}$) at soil matric potential of -60 hPa.

1.2.6 Plant-available water capacity (PAWC)

Plant-available water capacity was calculated by the difference between water content at field capacity (FC), equivalent to matric potential of the -100 hPa (HAISE et al., 1955), and water content at permanent wilting point (PWP), equivalent to matric potential of the -15,000 hPa (RICHARDS and WEAVER, 1944), both estimated from data obtained in 2016 (Flowchart 1) by fitted soil water retention curve (Eq. 3 and 4).

The limits of the PAWC were those established by REYNOLDS et al. (2007, 2009), is considered “ideal” for maximum root growth and development PAWC ≥ 0.20 $m^3\ m^{-3}$, “good” 0.15 ≤ PAWC ≤ 0.20 $m^3\ m^{-3}$, “limiting” 0.10 ≤ PAWC ≤ 0.15 $m^3\ m^{-3}$ and considered “dry” condition PAWC ≤ 0.10 $m^3\ m^{-3}$ (WHITE, 2006; REYNOLDS et al., 2007, 2009).

$$PAWC = \theta_{FC(h=-100\ hPa)} - \theta_{PWP(h=-15,000\ hPa)};\ 0 \le PAWC \le \theta_{FC} \quad (9)$$

Where: PAWC= plant-available water capacity ($m^3\ m^{-3}$);

θ_{FC} = field capacity water content ($m^3\ m^{-3}$);

θ_{PWP} = permanent wilting point water content ($m^3\ m^{-3}$); and

h= soil matric potential (hPa);

1.2.7. Soil water storage capacity (SWSC) and soil aeration capacity (SAC)

They were determined according to REYNOLDS et al. (2002).

$$SWSC = \left(\frac{Mic}{POR_t}\right) \quad (10)$$

Where: SWSC= soil water storage capacity (dimensionless);

Mic = microporosity at a soil matric potential of -100 hPa (m^3 m^{-3});

POR_t = total soil porosity (m^3 m^{-3}), determined as: [1-(ρ_B/ρ_p)], ρ_B= soil bulk density (Mg m^{-3}); ρ_p= particle density (Mg m^{-3}) and

$$SAC = \left(\frac{Mac}{POR_t}\right) \tag{11}$$

Where: SAC= soil aeration capacity (dimensionless);

Mac= macroporosity (m^3 m^{-3});

POR_t = total soil porosity (m^3 m^{-3}).

1.2.8. Visual evaluation of soil structure (VESS)

For the soil structural quality, Sq_{VESS} starts with 1 for friable structures up to 5 for soil structures highly compacted (GUIMARÃES et al., 2011). The final Sq_{VESS} was weighted according to equation (12), in which the monolith was evaluated by similar characteristics of the soil structure layer (CHERUBIN et al., 2017; GUIMARÃES et al., 2011).

$$Sq_{VESS} = \sum_{i=1}^{n} \frac{Sqi\ Ti}{TT} \tag{12}$$

Where: Sq_{VESS} is the overall VESS score;

Sq*i* and T*i* are respectively the score and thickness of each identified soil layer, and TT= is the total thickness of the monolith.

The VESS was carried out with the fragmentation of the monolith with the evaluator's own hands. In addition, the soil gravimetric water content (Ug) was also obtained for each observed layer of the monolith.

1.2.9. Soil total organic carbon content (OC) and structural stability index (SI)

The OC and SI analysis followed the stratifications of the Sq_{VESS} layers, i.e., for each distinct layer identified, the OC and SI analysis were performed, subsequently generating an OC and SI average for each monolith.

The SI was determined in agreement with PIERI (1992), which uses soil organic carbon content (%), and the silt plus clay contents (%). An SI > 9 % indicates stable structure, 7 % < SI ≤ 9 % indicates low risk of structural degradation, 5 % < SI ≤ 7 % indicates high risk of degradation, and SI ≤ 5 % indicates structurally degraded soil.

$$SI = \frac{1{,}724\ OC}{(silt+clay)}\ x\ 100; 0 \leq SI \leq \infty \quad (13)$$

Where: SI = structural stability index (%);

OC = soil organic carbon content (%); and

(Silt + Clay) = soil's combined silt and clay content (%)

1.2.10. Soil physical quality index calculation

The soil physical quality index (SFQ_{Index}) was determined according to CHERUBIN et al. (2016), adapting soil function by the set of soil physical indicators determined in this study.

Three steps were carried out: selection of soil physical indicators as a minimum dataset (MDS), the transformation of indicator values into unitless 0 to 1 scores using scoring curves, and integration into an overall index.

The soil data from 0.00–0.15 and 0.15–0.30 cm were averaged to 0.00–0.30 cm layer to calculate an overall index that better represents the whole soil profile assessed. The Indicator transformation was performed using a non-linear technique (ANDREWS et al., 2002; CHERUBIN et al., 2016).

Step 1- Indicator selection. Based on published literature and the authors' experience, two soil physical quality indicators have been used, as an MDS, for each function: f(i) capacity to support root growth: soil bulk density (ρ_B) and degree of compactness (Dc); f(ii) water retention: micropores (Mic) and soil water storage capacity (SWSC); f(iii) water and air fluxes: macropores (Mac) and soil aeration capacity (SAC); and f(iv) soil resistance to degradation: visual evaluation of soil structure (VESS) and soil total organic carbon content (OC). The additive SPQIndex was a summation of the scores from all minimum data set indicators of the four functions.

Step 2- Indicator interpretation. Each indicator was scored using one of the following curves: "more is better" (upper asymptote sigmoid curve), "less is better" (lower asymptote sigmoid curve), and "mid-point optimum" (Gaussian curve). The non-linear Eq.s 14 and 15 were used for "more is better" and "less is better" scoring curve shapes, respectively. For “mid-point optimum” curve the Eq.s 14 and 15 were jointly used in the increasing and decreasing parts of the curve, respectively.

$$Score = \frac{a}{\left[1+\left(\frac{B-UB}{X-UB}\right)^{S}\right]} \quad (14)$$

$$Score = \frac{a}{\left[1+\left(\frac{B-LB}{X-LB}\right)^{S}\right]} \quad (15)$$

Where: Score= soil indicator which ranging from 0 to 1(dimensionless);

a= the maximum score which was equal to 1 in this study;

B= the baseline value of the soil indicator where the score equals 0.5;

LB= the lower threshold;

UB= the upper threshold;

X= the measured soil indicator value; and

S= the slope of equation set to -2.5.

Threshold and baseline values for each soil indicator were based on literature references, as presented in Table 3. Indicator scoring calculations were performed using a Microsoft Excel® spreadsheet.

Step 3- Indicator integration into an index. The indicator scores were integrated into indexes through weighted additive (Eq. 16).

$$SFQ_{index} \sum_{i=1}^{n} WiSi \quad (16)$$

Where: SFQ_{index}= soil physical quality index (dimensionless);

n= the number of indicators integrated in the índex;

Wi= the weighted value of the indicators; and

Si= the indicator score.

The step-by-step procedure used for calculating the SFQ_{Index} is shown in Table 4.

Table 3: Soil functions, indicator thresholds and scoring curves.

Functions	Indicator	Unit	Lower Threshold	Lower Baseline	Upper Threshold	Upper Baseline	Optimum point	Scoring curve	Reference
ƒ(i)*	ρ_B**	Mg dm^{-3}	1.10	1.25	1.40			Less is better	DADDOW and WARRINGTON (1983)
	Dc	–	0.70	0.78	1.00	0.91	0.85	Optimum	ASGARZADEH et al. (2011)
ƒ(ii)	Mic	m^3 m^{-3}	0.15	0.20	0.35			More is better	CHERUBIN et al. (2016)
	SWSC	–	0.30	0.45	0.90	0.80	0.66	Optimum	REYNOLDS et al. (2002)
ƒ(iii)	Mac	m^3 m^{-3}	0.05	0.075	0.15			More is better	REYNOLDS et al. 2007, 2009)
	SAC	–	0.15	0.25	0.55	0.45	0.34	Optimum	REYNOLDS et al. (2002)
ƒ(iv)	VESS	Sq_{VESS}	1.50	3.50	5.00			Less is better	BALL et al. (2007); GUIMARÃES et al. (2011)
	OC	g Kg^{-1}	10.00	17.50	25.00			More is better	CASTRO LOPES et al. (2013)

**ƒ*(i) capacity to support root growth; *ƒ*(ii) water retention; *ƒ*(iii) water and air fluxes and *ƒ*(iv) soil resistance to degradation. **soil bulk density (ρ_B); degree of compactness (Dc); micropores (Mic); soil water storage capacity (SWSC); macropores (Mac); soil aeration capacity (SAC); visual evaluation of soil structure (VESS) and soil total organic carbon content (OC).

Table 4: Model of soil functions framework and indicators used to develop the SFQ_{Index}.

Functions	Weight	Indicator	Weight	Transformed indicator value	Soil indicator score	Soil physical function score	Weighted soil physical function score	SFQ_{Index}
						∑(II x III)		
	(I)		(II)	(III)	(II x III)	IV	(IV x I)	∑(IV x I)
ƒ(i)*	0.25	ρ_B**	0.50	0.93	0.47	0.87	0.22	0.88
		Dc	0.50	0.81	0.41			
ƒ(ii)	0.25	Mic	0.50	1.00	0.50	0.98	0.24	
		SWSC	0.50	0.96	0.48			
ƒ(iii)	0.25	Mac	0.50	1.00	0.50	0.94	0.23	
		SAC	0.50	0.88	0.44			
ƒ(iv)	0.25	VESS	0.50	0.85	0.42	0.74	0.19	
		OC	0.50	0.64	0.32			

**ƒ*(i) capacity to support root growth; *ƒ*(ii) water retention; *ƒ*(iii) water and air fluxes and *ƒ*(iv) soil resistance to degradation. **soil bulk density (ρ_B); degree of compactness (Dc); micropores (Mic); soil water storage capacity (SWSC); macropores (Mac); soil aeration capacity (SAC); visual evaluation of soil structure (VESS) and soil total organic carbon content (OC).

1.2.11. Crop yield

The crop yields of wheat (winter season 2016), and soybean (summer season 2016/17) were measured in a useful area from each plot (138 m^2), and expressed in kg ha^{-1}, after correction to 13% of grain water content. The harvest was semi-mechanized without plant desiccation. The crop yields were correlated with SFQI.

1.2.12. Statistical analysis

The data were submitted to the Shapiro-Wilk test, to verify the data normality, then ANOVA was performed. When the F test was significant ($p<0.05$), the differences between tillage systems or layers were compared by the Tukey test ($p < 0.05$). In addition, for fitting curves was used linear and non-linear regression techniques using Sigma Plot program and the statistical program SAS.

1.3. Results and Discussion

1.3.1. Soil pore size distribution curve

The tillage systems provided differences in the pore size distribution curves (Fig. 4). It is possible to notice a larger pore volume frequency in the NT system between 30 μm $_{(h\ -100\ hPa)}$ and 1000 μm $_{(h\ -3\ hPa)}$ diameter, as well as, there was a more accentuated drop in the volume of these pores in the ST system. BREWER (1964); LAL and SHUKLA (2004) classified this range of pores as mesopores and/or very fine macropores/transmission pores. Although there are different classifications for mesopores, such as LUXMOORE (1981) that suggested mesopores the range of pores with equivalent pore diameter between 10 μm $_{(h\ -300\ hPa)}$ and 1000 μm $_{(h\ -3\ hPa)}$ and mention that they are responsible for drainage, hysteresis, the gravitational driving force for water dynamics, which means their importance to redistribution of water into the soil.

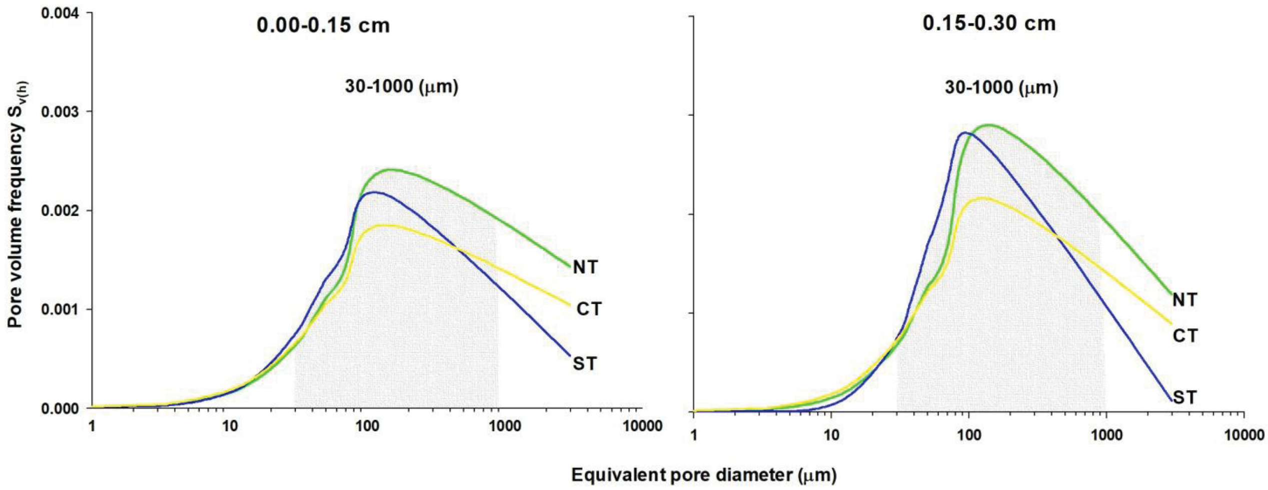


Figure 4: Soil pore volume frequency plotted against equivalent pore diameter (μm), on a log10 scale in two soil layers under no-tillage (NT), strategic tillage (ST) and conventional tillage (CT). The values in the hatched area correspond to the pore volume frequency $S_{v(h)}$ corresponding to the pore diameter between 30 and 1000 μm.

The pore classification concerning pore function is wide, but in general, transmission pores have equivalent pore diameter >50 μm $_{(h\ -60\ hPa)}$ and its function is air movement and drainage of excess water (GREENLAND, 1977; LAL and SHUKLA, 2004). This classification encompasses the pore sizes present in Fig. 4, showing that these pores are important for the redistribution of water in the soil, and can directly influence the water availability for plants during the growing season.

TUREK et al. (2020) estimated and mapping field capacity (h_{fc}) in Brazilian soils and found h_{fc} around a soil matric potential of -30 hPa, equivalent pore diameter of 100 μm, suggesting that the volume of mesopores (100 μm $_{(h\ -30\ hPa)}$ - 30 μm $_{(h\ -100\ hPa)}$) can be very important in the water availability in the soil as well.

The mesopores volume decreases with increasing of ρ_B linearly in the three tillage systems, as can be seen in Fig. 5 ABC. It is noted as well that the volume within the same ρ_B at the three systems is similar, within the range of bulk densities observed. The mesopores volume in the ST system presents a more accentuated reduction with the increase of the ρ_B at the 0.00-0.15 cm layer (Fig. 5A), indicating that the chisel is not contributing to the stability of these pores size at soil surface. Overall, analyzing 0.00-0.30 m CT presented the higher impact of ρ_B on mesopores volume.

Fig. 5 DEF shows the fine roots pores volume frequency, (1000 µm $_{(h\ -3\ hPa)}$ - 50 µm $_{(h\ -60\ hPa)}$), in which the ST system presents a greater volume at lower densities in both studied layers. However, as well as in the mesopores volume, it showed a greater decrease in these pores size compared to NT and CT systems by increasing bulk density. This behavior is clear considering the 0.00-30 cm layer (Fig. 5F), in which the pores' diameter size between 50 µm and 1000 µm is what stands out most in NT system in terms of frequency, as can also be seen in Fig. 4.

Although the classification of pores according to their diameter and function is not a settled issue, it can be noted that pores involving water retention against gravity and release, and air movement and drainage of excess water are presented in this study, we can mention that they have directly influenced the differences in crop yield found between treatments, once was not verified dryer periods that could affect the yield.

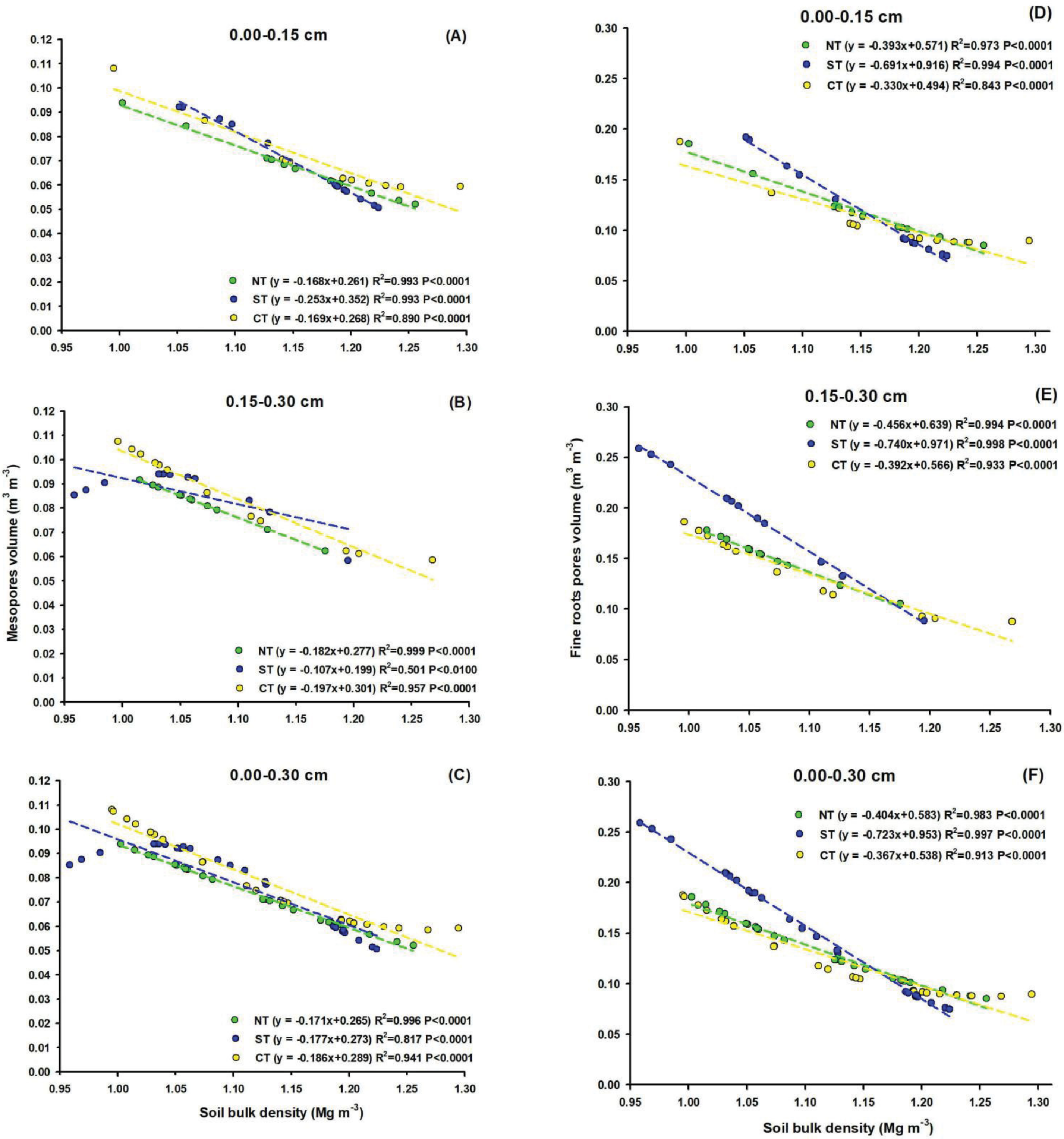


Figure 5: Mesopores volume and fine roots pores volume plotted against soil bulk density (Mg m^{-3}) in 0.00-0.15, 0.15-0.30, and 0.00-0.30 cm soil layers under no-tillage (NT), strategic tillage (ST) and conventional tillage (CT).

1.3.2. Other soil physical quality indicators

Most soil physical indicators had no significant difference between the tillage systems according to the F test ($P < 0.05$) (Table 5), with some exceptions in the 0.15–0.30 m layer between the NT and CT systems for the degree of compactness (Dc), and in the 0.00–0.15 m, 0.15–0.30 and 0.00–0.30 m layers for plant-available water capacity (PAWC), in which CT was higher than others (Table 6). The analysis between layers within each system showed differences in the three systems for soil bulk density (ρ_B), fine roots pores volume (FR_p), soil water storage capacity (SWSC), mesopores volume (ME) (Table 5) and degree of compactness (Dc) (Table 6). The precompression stress (σ_P) and compression index (Ci) showed differences only for NT system.

Table 5: Mean values of soil physical quality indicators that varied only in depths and those in which there were no interactions (treatments) and variation (depths) of the systems no-tillage (NT), strategic tillage (ST) and conventional tillage (CT).

	Soil physical quality indicators						
Depth (m)	ρ_B (Mg m^{-3})	FR_p (m^3 m^{-3})	Mic (m^3 m^{-3})	SWSC (-)	ME (m^3 m^{-3})	Mac (m^3 m^{-3})	SAC (-)
0.00–0.15	1.16 (0.07) A	0.11 (0.03) B	0.38 (0.02) A	0.70 (0.07) A	0.07 (0.01) B	0.14 (0.04) A	0.30 (0.07) A
0.15–0.30	1.07 (0.07) B	0.16 (0.03) A	0.37 (0.02) A	0.66 (0.07) B	0.08 (0.01) A	0.16 (0.03) A	0.34 (0.07) A
0.00–0.30	1.12 (0.08)	0.14 (0.05)	0.38 (0.04)	0.68 (0.07)	0.08 (0.02)	0.15 (0.05)	0.32 (0.07)
CV (%)	7.56	33.54	9.65	10.45	20.63	26.29	22.20
"Optimal"	$\rho_B \leq 1.40$	–	–	SWSC= 0.66	–	Mac ≥ 0.15	SAC= 0.34

Mean values with the same letters in-depth do not differ statistically by Tukey's test ($P < 0.05$).

"Optimal" range: $\rho_B \leq 1.40$ (DADDOW and WARRINGTON, 1983; USDA-NRCS, 1996); SWSC= 0.66 and SAC= 0.34 (REYNOLDS et al., 2002); Mac ≥ 0.15 (REYNOLDS et al., 2009, 2007; WHITE, 2006).

ρ_B= soil bulk density; FR_p= fine roots pores volume; Mic= microporosity; SWSC= soil water storage capacity; ME= mesopores volume; Mac= macroporosity; SAC= soil aeration capacity. Values into parentheses correspond to standard deviation. CV = Coefficient of variation.

Table 6: Mean values of soil physical quality indicators, considering the interactions between treatments and depths of the systems no-tillage (NT), strategic tillage (ST), and conventional tillage (CT).

	Soil physical quality indicators					
	NT	ST	CT	NT	ST	CT
Depth (m)	Degree of compactness (–)			Plant-available water capacity (m^3 m^{-3})		
0.00–0.15	0.81 (0.05) Aa	0.84 (0.05) Aa	0.85 (0.06) Aa	0.15 (0.00) Aab	0.13 (0.02) Ab	0.18 (0.01) Aa
0.15–0.30	0.69 (0.03) Bb	0.71 (0.05) Bab	0.81 (0.06) Ba	0.15 (0.01) Ab	0.12 (0.02) Ab	0.18 (0.01) Aa
0.00–0.30	0.75 (0.08) a	0.77 (0.08) a	0.83 (0.06) a	0.15 (0.01) b	0.13 (0.02) b	0.18 (0.01) a
"Optimal"	Dc < 0.85			0.15 ≤ PAWC ≤ 0.20		

	Soil physical quality indicators					
	NT	ST	CT	NT	ST	CT
Depth (m)	Precompression stress (kPa)			Compression index (–)		
0.00–0.15	177 (87.81) Aa	193 (63.52) Aa	144 (60.77) Aa	0.19 (0.02) Ba	0.20 (0.02) Aa	0.18 (0.02) Aa
0.15–0.30	124 (44.04) Ba	121 (35.70) Aa	121 (46.80) Aa	0.24 (0.07) Aa	0.23 (0.02) Aa	0.21 (0.03) Aa
0.00–0.30	151 (75.48) a	157 (62.69) a	133 (54.93) a	0.22 (0.06) a	0.21 (0.03) a	0.19 (0.03) a
"Optimal"	–			–		

Mean values with the same lowercase letters in the lines, as well as uppercase letters in the columns do not differ statistically by Tukey's test ($P < 0.05$).

"Optimal" range: Dc < 0.85 ASGARZADEH et al. (2011); PAWC: 0.15 ≤ PAWC ≤ 0.20 (WHITE, 2006; REYNOLDS et al., 2007, 2009). Values into parentheses correspond to standard deviation.

In the three systems, ρ_B presented values lower than the critical limit considered for clayey soils, which is approximately 1.40 Mg m^{-3}, for clayey to loamy clay soils, values between 1.40 and 1.50 Mg m^{-3} are often the minimum value at which root restriction may be observed (DADDOW and WARRINGTON, 1983; USDA-NRCS, 1996). REYNOLDS et al. (2007) also mention that in soils with fine and medium texture, the ρ_B considered adequate for maximum crop production would be between 0.90 to 1.20 Mg m^{-3}, values below 0.90 Mg m^{-3}, which could cause production losses due to inadequate plant anchorage and low capacity to provide water and dissolved nutrients to the roots. In this study both layers analyzed were below 1.20 Mg m^{-3}, even in the 0.00–0.15 m layer, where the highest value of ρ_B was obtained, indicating that the ρ_B in the studied systems probably did not compromise the capacity to support root growth.

The NT system obtained in the 0.00–0.15 m layer greater ρ_B and Dc in relation to the 0.15–0.30 m layer, but both layers had low Dc values (BROCH and KLEIN, 2017; CARTER, 1990) and $\rho_B \leq 1.40$ Mg m^{-3} (DADDOW and WARRINGTON, 1983; USDA-NRCS, 1996), indicating that there is no compaction in this system. Although there were differences in these indicators between the layers. The increased ρ_B values in no-till soils, commonly reported for clay soils in Brazil (NUNES et al., 2015), were not verified in this long-term study, previously (VIZIOLI et al., 2021).

ASGARZADEH et al. (2011) observed that the soil physical quality increases when Dc and the ρ_B decrease and that values of Dc < 0.85 indicate good soil physical condition. SUZUKI et al. (2007) concluded that the soybean crop is favored by a Dc < 86 in Ferralsol and that increasing the Dc leads to a linear reduction of Mac and hydraulic conductivity, and increases soil resistance to penetration. In this context, the three systems obtained values within the considered good, demonstrating that there was no soil physical degradation over time in the three systems.

The FR_p can be very important for root development, MORAES and GUSMÃO (2021) reported that the root elongation of soybean crop decay exponentially due to the reduction of the water potential. The authors emphasized that the pore size distribution characteristics in the soil profile are the most important factor to root elongation rate because it directly affects the soil's resistance to root penetration, influence the flow of soil water, degree of soil saturation, and soil permeability to water and air.

The SWSC index values at the 0.00–0.15 m layer were a little above the threshold value (SWSC= 0.66) (REYNOLDS et al., 2002) and the 0.15–0.30 m layer obtained the value considered ideal, with significant differences between layers. Lower SWSC index values (i.e. SWSC < 0.60) result in reduced microbial production of nitrate due to insufficient soil water, while greater SWSC index values (SWSC >0.70) cause reduced nitrate production because of insufficient soil air (REYNOLDS et al., 2009).

The PAWC in NT and CT systems was in the range considered “good” for roots growth and development (REYNOLDS et al., 2007, 2009), which is expected, due to the soil being classified as clayey, then having a high water retention and storage capacity. On the other hand, the ST system was within the range considered "limiting" for this indicator in both layers, which was not expected, since no severe restrictions were found in other indicators. There were significant differences between the systems, with the CT system obtaining the highest mean, mainly taking into account the average layer (0.00–0.30 m) (Table 6).

The ME found in this study was similar to that found by DE LIMA et al. (2022), considering almost the same silt plus clay contents, where the ME in relation to macro and microporosity was low. The authors reported that the volume of mesopores found could not be effective in conducting water after the macropores have become empty. CAVALCANTI et al. (2020) obtained significant differences in ME in a sandy loam Alisol, increasing the volume of these pores, where there was greater soil disturbance by tillage operations, in the 0.00–0.30 m layer, which did not occur in this study, i.e., the water and air fluxes did not improve as expected.

A value of Mac ≥ 0.10 m^3 m^{-3} has been recommended as the minimum for the development and production of crops without losses caused by oxygen deficits in the root zone, for fine texture soils, Mac ≥ 0.15 m^3 m^{-3} is necessary to compensate for the low gas diffusion rates and the respiratory demands of biological activity (REYNOLDS et al., 2007; WHITE, 2006). In this study, the three systems obtained mean values of 0.14 m^3 m^{-3} in the 0.00–0.15 m layer, and 0.16 m^3 m^{-3} in the 0.15–0.30 m layer, suggesting that Mac is not harming root growth.

The SAC index values in the 0.00–0.15 m layer were lower than the threshold value (SAC= 0.34) (REYNOLDS et al., 2002), and the 0.15–0.30 m layer obtained the value considered ideal, with no significant differences between layers.

Higher initial ρ_B influenced the SCC behavior, consequently, σ_P increased with increasing initial ρ_B, obtaining different mean values of soil load-bearing capacity between layers, mainly in the NT system. The results in the 0.00-0.15 m layer indicate a raised resistance to plastic deformation of the soil in the three systems, suggesting high soil load-bearing capacity. Values of σ_P higher than 150 kPa can be classified as extremely high by HORN and FLEIGE (2003), being found in NT and ST at the surface. According to those authors, values between $120 < \sigma_P < 150$ would be considered high, which corresponds to the values found in the subsurface layer for the three tillage systems. Besides no significant differences between treatments, the absolute differences between the mean values can be considered extremely high (Table 6). The lack of statistical differences between layers in ST and CT systems was influenced by a high coefficient of variation (CV), which for σ_P is usual at uniaxial compression tests (CAVALIERI et al., 2008). However, the intensive soil disturbing in CT promotes less soil load-bearing capacity in comparison with ST and NT mainly at the soil surface.

Besides these values being considered high or extremely high, the machinery traffic can generate plastic deformations in the soil. HORN and LEBERT (1994) suggest that the soil was susceptible to soil compaction by typical loads since agricultural machinery generally applies stresses ranging from 70 to 350 kPa, while transport equipment applies stresses of up to 800 kPa. HÅKANSSON et al. (1988) also reported that stress values applied to the soil, vary from 100 to 150 kPa for tractors, and from 200 to 300 kPa for harvesters. These results show that traffic by common tractors and other machines could cause further compaction to the soil since all tillage systems presented a range from 61 to 350 kPa and 51 to 190 kPa for NT, from 80 to 276 kPa, and 55 to 169 kPa for ST, and from 65 to 251 kPa and 62 to 212 kPa for CT, respectively for 0.00–0.15 and 0.15–0.30 m layers. The soil Ci had the same compressive behavior as the σ_P, there was a significant statistical difference between layers in the NT system. This result reveals a trend toward greater soil compressibility in the NT system at the 0.15–0.30 m layer, which is related to its lower initial ρ_B, in this layer, and the higher porous space available for particle arrangement. On the other hand, in this soil layer, the growth of the roots can be more efficient, due to the lower physical restrictions posed by the soil.

No significant differences were found between the systems (Fig. 6), presenting Sq_{VESS} of 2.52, 2.40, and 2.94, respectively for NT, ST, and CT, being considered as an intact structures, with aggregate sizes from 2 mm to 7 cm, rounded, without a clod present (GUIMARÃES et al., 2011). Although the value found in the CT system is close to the attention limit ($3 \geq Sq_{VESS} > 4$), considered a threshold for suitable root growth (BALL et al., 2007; CHERUBIN et al., 2017).

Regarding the Sq_{VESS} stratification, there was a greater diversity of soil structure quality in the NT compared to the ST and CT systems, being the only one in which there were different Sq_{VESS} for three layers, while for ST and CT there were different Sq_{VESS} for two layers. In addition, where there was a greater organic carbon content, also was found lower Sq_{VESS} (Fig. 6). The VESS method has been indicated as an SPQI that integrates several soil physical properties in a single score (GUIMARÃES et al., 2011). In addition, its use was important to analyze the soil resistance to degradation function, since this indicator can demonstrate soil structural quality degradation (CHERUBIN et al., 2017). The OC obtained in the three tillage systems is above what is considered usual for soils in this region, that is ≤ 25 g kg^{-1} (CASTRO LOPES et al., 2013). In the same way as Sq_{VESS}, no significant differences were found between tillage systems, being around 37, 39, and 38 g kg^{-1}, respectively for NT, ST, and CT. For the SI, due to the stratification of the OC, had the same behavior as the OC, obtaining mean values above 9 % in the three tillage systems. According to PIERI (1992), an SI > 9 % indicates a stable structure, i.e., by performing the more detailed analysis of the OC, a structure considered very good was obtained, with no significant differences between the tillage systems, and the NT obtained 11.35, followed by the ST= 10.84 and CT= 10.20 %.

As stated above, the SI takes into account the OC, which in the three systems has decreased in-depth, this decrease is frequently evidenced in Brazilian soils and consequently causes the decrease of SI in-depth as well. It is important to highlight that in other soil conditions, such as soils in Canada (REYNOLDS et al., 2007), the proposed optimal OC range would be 30 ≤ OC ≤ 50 g kg^{-1}, values found by stratifying the OC in this study, which, in any case, makes clear the importance of the organic matter in the soil structure stability in the most diverse conditions.

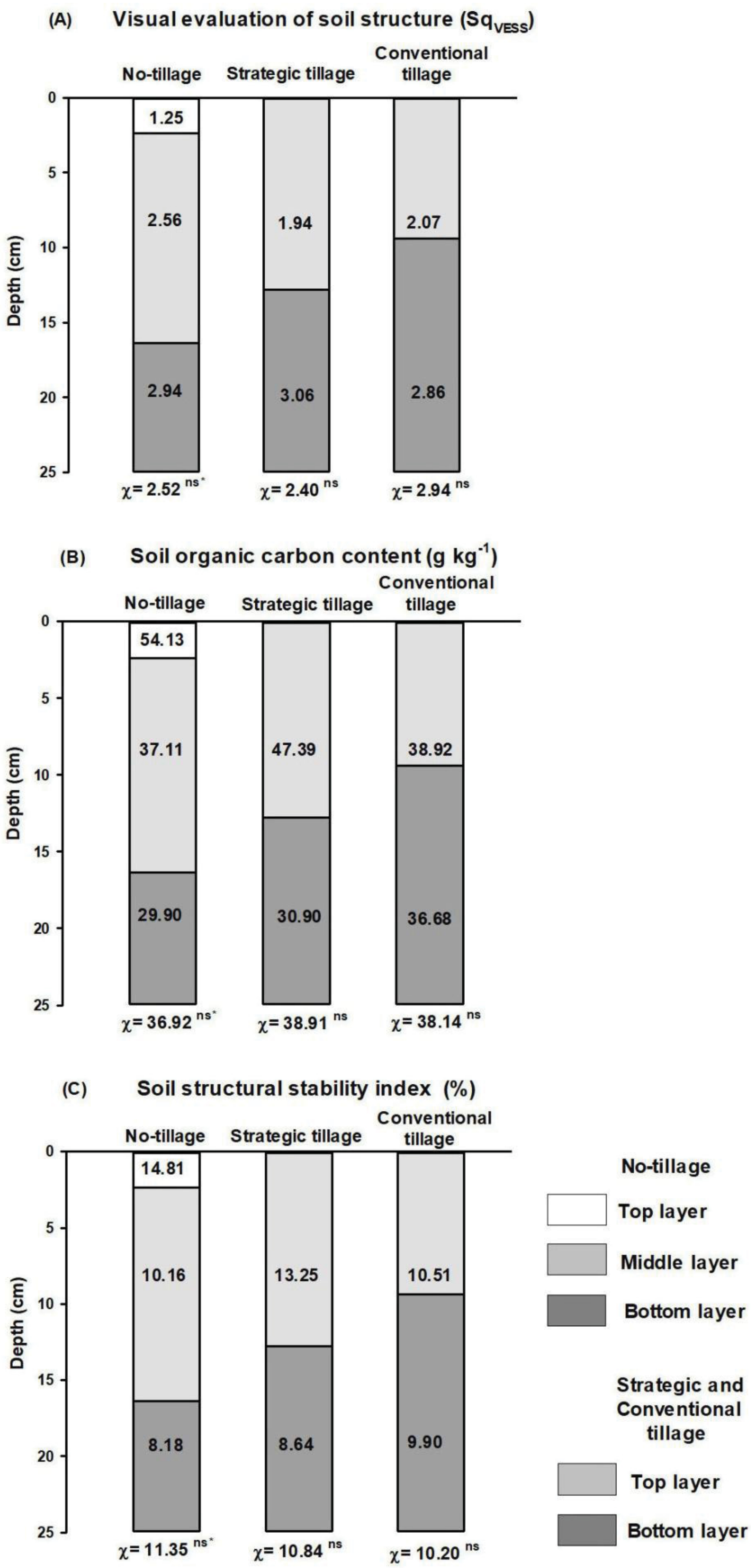


Figure 6: Depth of distinct layers of VESS scores, organic carbon and structural index in the three tillage systems. *ns= not significant by the F test (F). Sq_{VESS} F= 3.53^{ns}; OC F= 0.11^{ns}; SI F= $0,605^{ns}$.

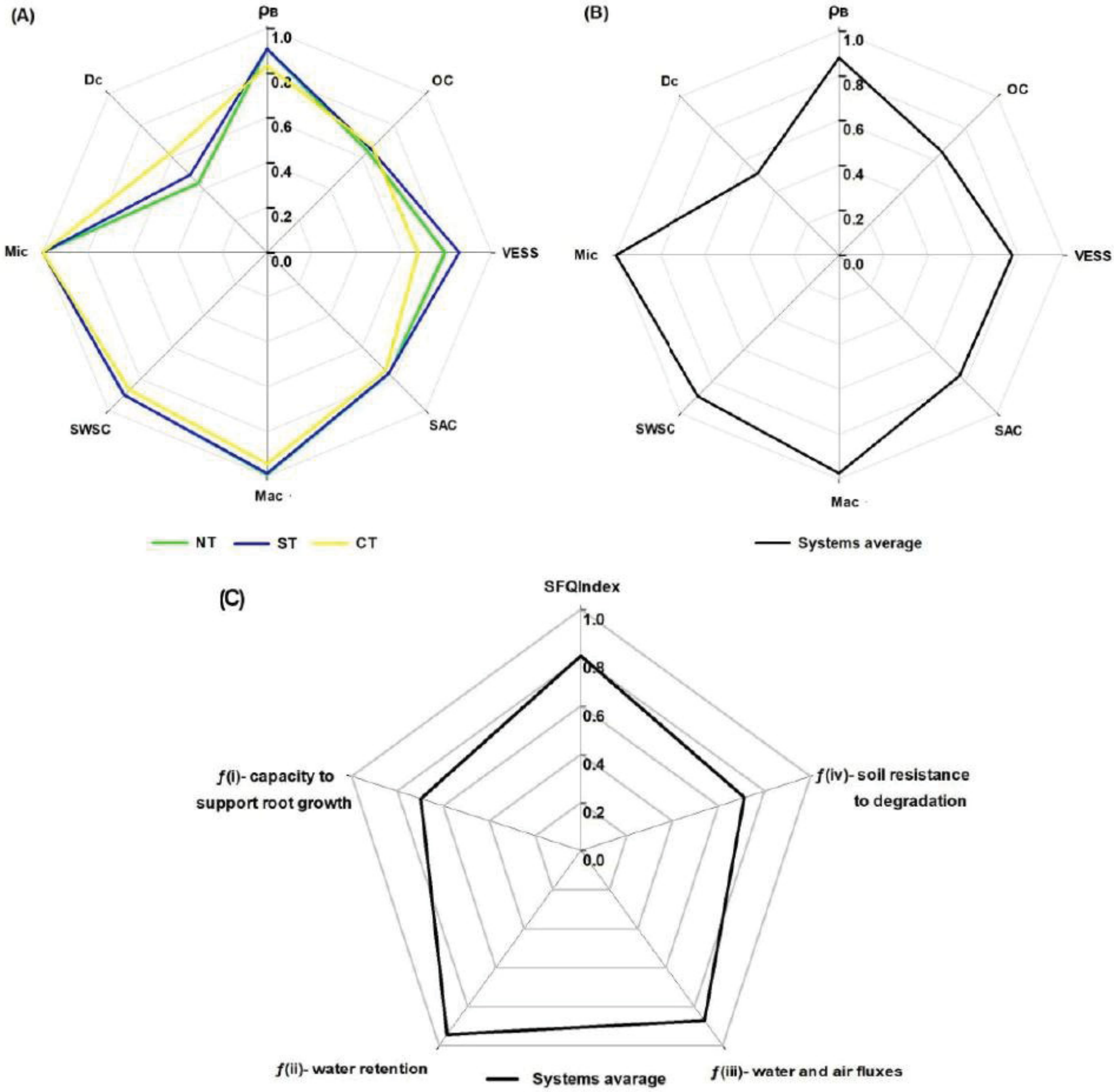
1.3.3. Soil physical quality index

The scores of SPQI, soil functions, and SFQ_{Index}, are shown in Figure 7. The systems were similar for most of SPQI (Fig. 7A). Those with the better scores were micropores (Mic), 1.00, and macropores (Mac), 0.97, respectively and those with the lower scores were degree of compactness (Dc), 0.51, and soil total organic carbon content (OC), 0.65, respectively. The soil water storage capacity (SWSC) had a score of 0.89, soil bulk density (ρ_B), 0.88, visual evaluation of soil structure (Sq_{VESS}), 0.77, and soil aeration capacity (SAC), 0.76, (Fig. 7B).

The function f(ii) water retention had the best score, 0.95, followed by the function f(iii) water and air fluxes, 0.87, (iv) soil resistance to degradation, 0.71, and (i) capacity to support root growth, 0.70. The SFQ_{Index} had a score of 0.81. The four soil functions and the SFQ_{Index} had no significant difference between the tillage systems according to the F test ($P<0.05$) (Fig. 7C).

The Dc and OC influenced the lowest scores obtained in functions (i) and (iv), respectively, since their scores, were lower concerning the other indicators (Fig. 7 AB).

The overall of the four soil functions indicates that the three tillage systems evaluated are within the limits considered "good" for plant development, although there were differences in the absolute mean values of yield between the systems.



Tillage systems	Soil physical quality functions				SPQ_{Index}
	ƒ(i)	ƒ(ii)	ƒ(iii)	ƒ(iv)	
No-tillage	0.67 a	0.95 a	0.88 a	0.71 a	0.80 a
Strategic tillage	0.70 a	0.95 a	0.88 a	0.75 a	0.82 a
Conventional tillage	0.73 a	0.93 a	0.86 a	0.67 a	0.81 a

Figure 7: Scores for each soil physical quality indicator used in each system (A), the same for systems average (B), and the contribution of each soil function in the SFQ_{Index} under no-tillage, strategic tillage, and conventional tillage (C). Mean values within each soil function followed by the same letter do not differ statistically by Tukey's test ($P<0.05$).

1.3.4. Pearson's correlation among soil physical quality indicators and yield

Correlations were performed for wheat, and soybean, against SPQI (Table 7). It was observed that only some SPQI, from functions linked to capacity to support root growth, Dc (r = -0.81), and soil resistance to degradation, Sq_{VESS} (r = -0.76), and Ci (r = 0.78), were significantly correlated with wheat yield.

The Sq_{VESS} were significantly correlated with the Dc (r = 0.82), FR_p (r = -0.70), PAWC (r = 0.67), and Ci (r = -0.67). As for the soil quantitative physical parameters, significant correlations were obtained mainly between ρ_B and Dc (r = 0.78); ρ_B and FR_p (r = -0.85) and Dc and FR_p (r = -0.82), (Table 6), i.e., all functions linked to capacity to support root growth obtained significant correlations with FR_p.

Significant correlations were obtained as well, between ME and ρ_B (r = -0.93), DC (r = -0.68), and FR_p (r = 0.93), showing a close correlation between the capacity to support root growth -*f(i)* and water and air fluxes -*f(iii)*. CARTER (1990) found a correlation between cereals yields and D_C in sandy soils and obtained the maximum grain yield when Dc remained between 0.77 and 0.84, according to the author, 68.6% (R^2=0.67) of the expected variation in the yield was attributed to Dc.

Besides the Dc having had a negative influence on ME, the Mac was not affected, suggesting that the changes in pores size happen distinctly due to the soil compressive behavior. The Ci was correlated to Dc, evidencing that the nature and properties of pore size influence the compressibility, which may be an effect of persistent biopores presence in the systems with lower disturbance.

Table 7: Pearson's correlation coefficients among soil physical quality indicators and yield for the soil tillage systems, no-tillage (NT), strategic tillage (ST) and conventional tillage (CT).

	ρ_B	Dc	FR_p	Mic	SWSC	PAWC	ME	Mac	SAC	σ_P	Ci	Sq_{VESS}	SI	OC	Wheat 2016	Soybean 16/17
ρ_B	1.00															
Dc	0.78*	1.00														
FR_p	-0.85*	-0.82*	1.00													
Mic	-0.35	-0.45	0.65	1.00												
SWSC	0.44	0.23	-0.02	0.68*	1.00											
PAWC	-0.06	0.32	-0.41	-0.58	-0.59	1.00										
ME	-0.93*	-0.68*	0.93*	0.46	-0.24	-0.09	1.00									
Mac	-0.02	-0.15	-0.14	-0.63	-0.67*	0.31	-0.12	1.00								
SAC	-0.44	-0.23	0.02	-0.68*	-1.00*	0.59	0.24	0.67*	1.00							
σ_P	0.69*	0.42	-0.56	-0.05	0.48	-0.31	-0.70*	-0.47	-0.48	1.00						
Ci	-0.75	-0.88*	0.73*	0.51	-0.16	-0.25	0.61	-0.06	0.16	-0.32	1.00					
Sq_{VESS}	0.52	0.82*	-0.70*	-0.50	-0.06	0.67*	-0.48	0.16	0.06	-0.05	-0.67*	1.00				
SI	0.12	0.05	0.06	-0.09	0.06	-0.16	0.04	0.04	-0.06	0.07	-0.42	-0.13	1.00			
OC	0.03	0.01	0.16	0.10	0.17	-0.16	0.16	-0.14	-0.17	0.04	-0.36	-0.16	0.97*	1.00		
Wheat	-0.41	-0.81*	0.48	0.34	-0.08	-0.43	0.24	0.17	0.08	-0.05	0.78*	-0.76*	-0.38	-0.39	1.00	
Soybean	-0.39	-0.57	0.58	0.28	-0.06	-0.22	0.47	0.04	0.06	-0.29	0.49	-0.39	-0.08	0.00	0.49	1.00

ρ_B= soil bulk density; Dc= degree of compactness; FR_p= fine roots pores volume; Mic= microporosity; SWSC= soil water storage capacity; PAWC= plant-available water capacity; ME= mesopores volume; Mac= macroporosity; SAC= soil aeration capacity; σ_P= precompression stress; Ci= compression index; Sq_{VESS}= VESS; SI= structural stability índex; OC= Soil total organic carbon content.

* indicate significant differences at ($p < 0.05$ %).

It was verified that the NT was more productive than others (4,474 Kg ha^{-1}), followed by ST (4,412 Kg ha^{-1}), and CT (4,281 Kg ha^{-1}). Thus, taking into account that the soybean commercialization is carried out in 60 kg bags and that the difference between NT and CT was 193 kg ha^{-1}, it can be inferred that there is a considerable loss of financial resources considering the price of the soybeans bags. The difference in wheat yield also is relevant, NT was more productive than others again (7,029 Kg ha^{-1}), followed by ST (6,849 Kg ha^{-1}), and CT (6,543 Kg ha^{-1}), with the difference between NT and CT of 486 kg ha^{-1}.

1.4. Conclusions

There was few significant difference in SPQI between the tillage systems. However, the pore size distribution curve presented a raised frequency of fine root pores and mesopores for NT. In addition, CT had the highest Dc in the 0.15-0.30 m of depth, on the other hand, presented the highest PAWC in both layers studied.

The SPQI linked to the capacity to support root growth -*f(i)*: Dc, and soil resistance to degradation -f(*iv*): Sq_{VESS}, were significantly correlated with wheat yield, but none correlated with soybean yield. These indicators were efficient to show the effects of tillage systems on crop yield.

The physical functions that deal with the balance between water fluxes and soil water retention, despite being closely related to root growth and development, may not correlate with yield, under favorable water supply conditions, provided by the weather, but the pore size classes distribution and their functions in draining, redistributing and retaining water in the soil profile, must be more investigate because they are very important to optimize yield.

The NT system was considered the best tillage system, after 23 years of experiment, in the studied conditions, which kept all soil physical functions adequate, besides mostly contributing to soil conservation.

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APPENDIX 1 – CHAPTER 1

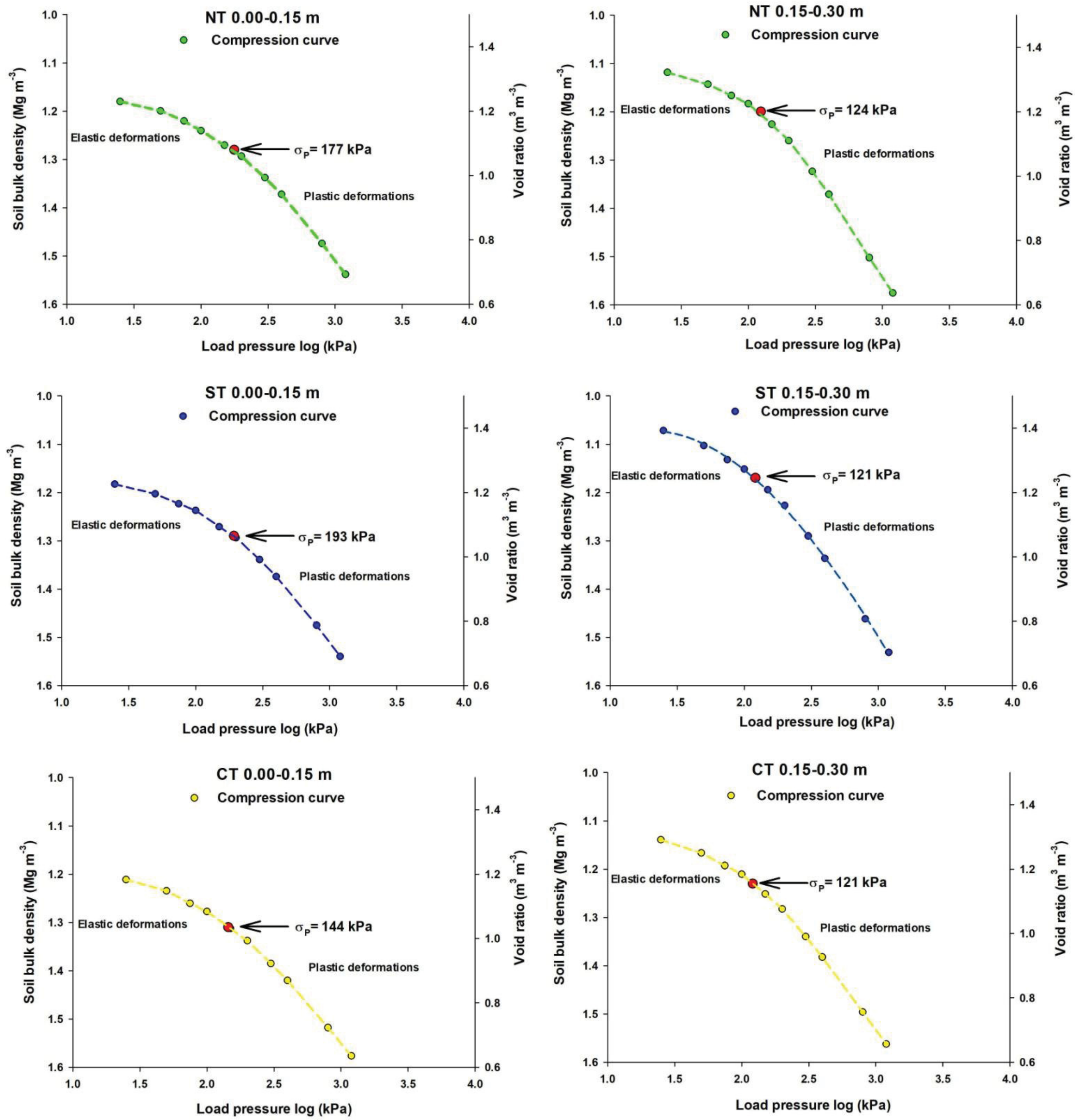
Table 1: Crop rotation used in the experimental area from 1989 to 2015.

Year	Winter	Function	Cultivar	Summer	Function	Cultivar
1989[1]	Black oats	Cover crop	Common	Soybean	Grain Production	BR16
1990	Lupine	Cover crop	Common	Maize	Grain Production	P3072
1991	White oats	Cover crop	UPF-5	Soybean	Grain Production	BR16
1992	Wheat	Grain Production	BR23	Soybean	Grain Production	BR16
1993[1]	Black oats	Cover crop	Common	Maize	Grain Production	P3072
1994	White oats	Cover crop	UPF-5	Soybean	Grain Production	BR16
1995	Wheat	Grain Production	BR23	Soybean	Grain Production	BR16
1996[1]	Vetch	Cover crop	Common	Maize	Grain Production	P3072
1997	Black oats	Cover crop	Common	Soybean	Grain Production	BR16
1998	Wheat	Grain Production	BR23	Soybean	Grain Production	BR16
1999[1]	Black oats	Cover crop	Common	Maize	Grain Production	P30F33
2000	White oats	Cover crop	Orla 9420	Soybean	Grain Production	BRS133
2001	Wheat	Grain Production	BRS120	Soybean	Grain Production	BRS133
2002[1]	Black oats	Cover crop	Common	Maize	Grain Production	P30F33
2003	White oats	Cover crop	UBS-3	Soybean	Grain Production	CD216/Abyara
2004	Wheat	Grain Production	CD105	Soybean	Grain Production	CD206
2005[1]	Black oats	Cover crop	Common	Maize	Grain Production	DKB214/WAXY
2006	White oats	Cover crop	URS-3	Soybean	Grain Production	CD206
2007	Wheat	Grain Production	CD105	Soybean	Grain Production	CD206
2008[1]	Black oats	Cover crop	Common	Maize	Grain Production	DKB214

2011[1]	Black oats	Cover crop	Common	Maize	Grain Production	DKB214
2012	White oats	Cover crop	Guapa	Soybean	Grain Production	CD206
2013	Wheat	Grain Production	Quartz	Soybean	Grain Production	CD206
2014[1]	Black oats	Cover crop	Common	Maize	Grain Production	30F53
2015	White oats	Cover crop	Guapa	Soybean	Grain Production	NA5909
2016	Wheat	Grain Production	Tbio	Soybean	Grain Production	M 5917

1 = year in which the chiseling occurred in the ST treatment, before sowing the winter crop.

Figure 1: Soil compression curve obtained from samples performed in 2016.



σ_P= precompression stress, the transition between elastic to plastic deformations.

CHAPTER 2- ESTIMATE OF ADVERSE PHYSICAL-MECHANICAL STRESSES IN THE SOIL LINKED TO CROP YIELD

Abstract

Studies that relate the different soil physical indicators such as soil water retention curve (SWRC), soil compression curve (SCC), and least limiting water range (LLWR) are still scarce. Both LLWR and SCC depend on water content and soil bulk density (ρ_B), and that can translate into management effects on soil. Besides that, they can fit in an SWRC, and give information about soil pores size distribution. Data obtained from SWRC, SCC, and LLWR, such as adverse limits in which the soil compaction poses structural changes, can provide soil adverse stress values that affect the plant's growth and, then, crop yield. Aiming to find a soil adverse physical-mechanical stress range, this study analyzed and integrated soil data under different long-term tillage systems and crop yield, on a Rhodic Ferralsol, with a clayey texture, located in Southern Brazil. Two samplings were performed in the area, in 2014, and 2016, at the depths of 0.00–0.15 and 0.15–0.30 m. The SWRC parameters and the LLWR were determined by 2014 data, and the SCC, as well as the $\rho_{B,}$ were done in 2016. From the SRWC parameters, obtained the pore size distribution curve, updated by ρ_B sampled in 2016, classifying the size of pores with diameters between 30 µm $_{(h\ -100\ hPa)}$ and 100 µm $_{(h-\ 30\ hPa)}$ as mesopores. To define a soil adverse volume frequency of mesopores ($\Phi_{MesAdverse}$) for plant growth, linear regressions between the mesopores volume frequency and the accumulated crops yield were performed. Thus, establishing as adverse the one that obtained the best fit. With the SCC, the precompression stress (σ_P) was obtained, as soil load-bearing capacity, and other indicators, such as bulk density alert value (ρ_{BA}) and critical soil bulk density ($\rho_{BCritical}$) obtained by the LLWR. Integrating the indicators, a soil adverse physical-mechanical stress range could be proposed to suggest deleterious effects on the water availability in the soil, even without providing soil plastic deformations or conditions of high physical degradation. For this, relationships between accumulated yield for the period of 2014 to summer 2017, and critical values, such as $\Phi_{MesAdverse}$, $\sigma_{P,}$ $\rho_{BA,}$ and $\rho_{BCritical}$ were performed. The relationships between the $\Phi_{MesAdverse}$, and the $\rho_{BCritical}$ with the accumulated crop yield were found, being possible to describe them as a linear model. Soil adverse physical-mechanical stress range developed in this study

proved to be applicable, with the integration of SWRC, SCC, and LLWR, considering not only the stress that causes additional compaction to the soil but also the water availability to roots and its influence on yield. Soil adverse volume frequency of mesopores can be used as one indicator of water availability, with effects on the yield presented by different long-term tillage systems. The NT showed the highest accumulated yield among the three systems, having a significantly negative relationship with the highest frequency of mesopores volume of 0.07 m^3 m^{-3} ($\Phi_{MesAdverse}$), and a positive relationship with $\rho_{BCritical}$.

Keywords: soil conservation, pore size distribution, mesopores, precompression stress, least limiting water range.

2.1. Introduction

Understanding and quantifying soil compaction has been one of the main concerns of researchers in soil physics. Since the mechanization in agricultural areas has been increasingly intensified due to the need to produce more in less time (KELLER et al., 2019; NUNES et al., 2015; REICHERT et al., 2009).

Mechanization in agriculture has resulted in a steady increase in the mass of farm vehicles, tractor wheel loads have increased from about 1.5 Mg, in 1960, to 4.0 Mg, in 2000, and harvesters from about 1.5 Mg, in 1960, to 9.0 Mg currently, increasing soil bulk density levels (ρ_B), and a decrease in hydraulic conductivity (KELLER et al., 2019). NUNES et al. (2019) reported that one of the main factors of compaction of agricultural soil, under no-tillage, is the use of agricultural machines and implements, that generally apply pressures greater than the soil load-bearing capacity, causing additional compaction to the soil. This additional compaction influences the size and distribution of soil pores, which have different functions and are quantified through the soil water retention curve (SWRC) (VAN GENUCHTEN, 1980), including mesopores, very fine and fine macropores that may be responsible for water absorption by roots and its redistribution in the soil profile (BREWER, 1964; KOOREVAAR et al. 1983; LAL and SHUKLA, 2004).

The soil load-bearing capacity can be quantified using the soil compression curve (SCC), through precompression stress (σ_P), which indicates the memory of the stresses to which the soil was subjected (LARSON et al., 1980). According to CASAGRANDE (1936), SCC can be divided by σ_P into two parts, recoverable and non-recoverable. Application of lower stresses promotes elastic deformation into the soil (recoverable), whereas higher stresses cause plastic deformations (non-recoverable) (HOLTZ and KOVACS, 1981). The type and magnitude of soil deformation depend on external factors that determine the applied pressure, as well as on soil's physical and mechanical properties, in which texture, organic matter content, and water content exert the greatest influence and control the physical degradation, that soils will undergo (ALEXANDROU and EARL, 1998; IMHOFF et al., 2016).

The least limiting water range (LLWR) is a soil physical quality indicator that incorporates relevant measurable sources of critical stresses that the soil poses on plants growth, such as soil penetration resistance, aeration, and water contents at field capacity and permanent wilting point (DA SILVA et al., 1994; LIMA et al., 2021; TORMENA et al., 1999). Generally, the increase in ρ_B results in a reduction in LLWR, in the direction of ρ_B values where LLWR can reach zero, this ρ_B is called critical soil bulk density ($\rho_{BCritical}$) (SILVA et al., 1994; TORMENA et al., 1999). Besides $\rho_{BCritical}$, the bulk density alert value (ρ_{BA}) can also be identified, that matches the value of ρ_B which the limit of water available in the soil is defined by water content under the excessive penetration resistance (θ_{PR}) or the reduced air-filled porosity (θ_{AFP}). The ρ_{BA} is obtained when LLWR becomes smaller than the plant-available water capacity (GUIMARÃES et al., 2013; NASCIMENTO et al., 2019). The LLWR is sensitive enough to point out the differences between different textures and management systems (DE OLIVEIRA et al., 2019), indicating physical restrictions on plants growth (DE MOURA et al., 2021; IMHOFF et al., 2016; LI et al., 2020).

Both the SCC and the LLRW depend on the soil water content and ρ_B, the latter can translate some effects of soil management, which can be included in the SWRC (DA SILVA and KAY, 1997), responsible for the distribution of pores as a function of their size and matric potentials with which it retains water.

NUNES et al. (2019) mention that the relationship between soil compressive properties and plant growth is insufficiently studied under different tillage systems, and that soil mechanical properties might be correlated with both plant development and soil attributes, that affect plant’s growth, as water and organic matter contents, soil texture, and ρ_B. In this way, IMHOFF et al. (2001) related σ_P and LLWR in different water contents, using the $\rho_{BCritical}$ as a limiting factor. In addition, IMHOFF et al. (2016) reported that the determination of relationships between the LLWR, σ_P, and compression index, and their dependence on intrinsic soil properties would be very useful to assess soil tillage systems. The authors still indicate that the maximum acceptable stress to be applied during tillage operations can be calculated by introducing the estimated values of $\rho_{BCritical}$ for plant growth in the model of the compression curve.

2.1.1. Theory

2.1.1.1. Soil mechanical properties

Soil compression curve (SCC) provides information about the soil mechanical behavior (HÅKANSSON and VOORHEES, 1998). This curve is represented graphically by the relationship between the logarithm (base 10) of the applied stress, in kPa, and the void ratio (ε) or soil bulk density (ρ_B). The ε decreases and ρ_B increases with the stress applied, but both determinate soil strain. The most common indicator obtained by SCC is soil load-bearing capacity through σ_P, in specific water tension, i.e., related to field capacity, and indicates the stress applied capable to promote soil plastic deformations, called additional compaction (Fig. 1).

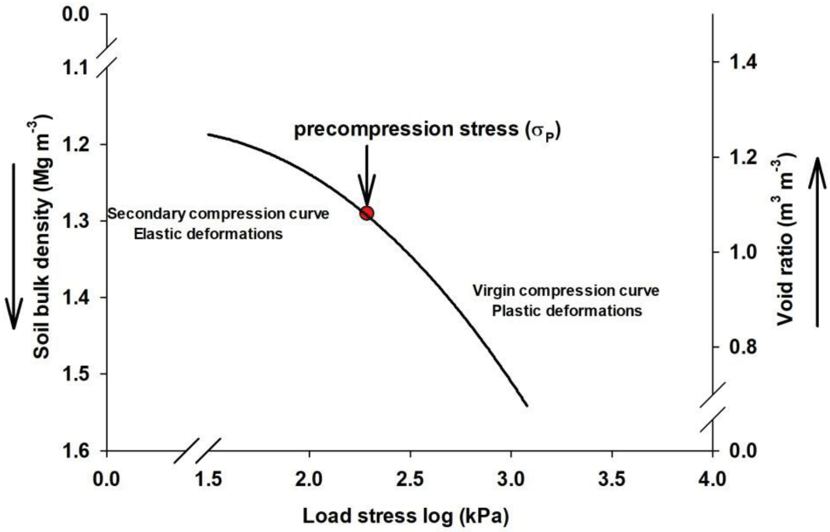


Figure 1: Soil compression curve and precompression stress (σ_P), the transition between elastic to plastic deformations.

Nonetheless, the σ_P indicator allows obtaining the ρ_B in which the soil deformation ceases to be elastic and becomes plastic, but is not possible to infer how much this stress is changing ρ_B at a point to damage plant growth and development. In addition, sometimes the soil presents elevated ρ_B that already caused some negative effect on the roots, and in which SCC cannot present, due to its lower ρ_B value is the initial ρ_B from the curve.

2.1.1.2. Soil water distribution

The classification of the pores used in this study is in agreement to KOOREVAAR et al. (1983) that defined as equivalent pores diameter in according to its function: macropores > 100 µm $_{(h\ -30\ hPa)}$; mesopores (100 µm $_{(h\ -30\ hPa)}$ - 30 µm $_{(h\ -100\ hPa)}$); and micropores < 30 µm $_{(h\ -100\ hPa)}$.

Macropores would be functionally related to water conduction during flooding and pounding rain, it’s responsible for the conduction of fast-draining water in the soil profile, consequently affecting the aeration and drainage of the soil (KOOREVAAR et al., 1983). Mesopores are responsible for drainage, hysteresis, and the gravitational driving force for water dynamics, which means their importance to the redistribution of water into the soil, mesopores would be effective in conducting water also after the macropores have become empty (KOOREVAAR et al., 1983; LUXMOORE, 1981), and storage pores or micropores has equivalent pore diameter between 0.5 and 30 µm and its function is the retention of water against gravity and release BREWER (1964); LAL and SHUKLA (2004).

To find the soil adverse volume frequency of mesopores ($\Phi_{MesAdverse}$), the mesopores volume frequency is plotted as a function of soil bulk density (ρ_B), aiming to find the highest frequency volume of mesopores, in which this class of pores affects yield, by the best fit, and the respective ρ_B in which this occurs.

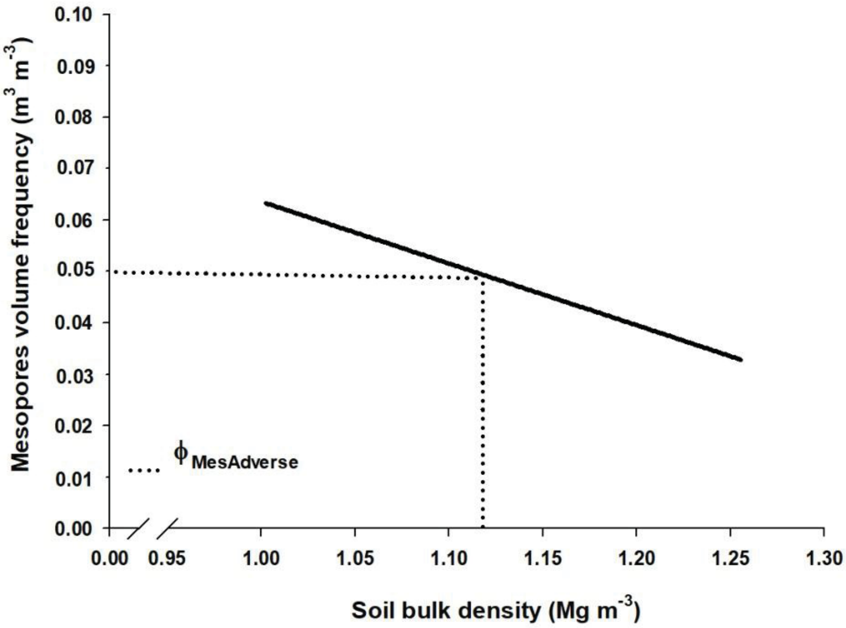


Figure 2: Relationship between mesopores volume frequency, and soil bulk density. $\Phi_{MesAdverse}$= adverse mesopores volume indicating its respective soil bulk density.

2.1.1.3. Soil physical quality properties

The LLWR is related to soil physical quality for plant growth, and is determined by the soil water retention curve (SWRC), soil penetration resistance curve (SRC), and soil air porosity. Then, is possible to monitor, along time, soil structure using the ρ_B as an indicator, and compare it against $\rho_{BCritical}$ (LLWR = 0). In addition, bulk density alert value (ρ_{BA}), which starts some detrimental by air porosity or penetration resistance under the limits of soil available water (AW), also can be used. Fig. 3A presents the limits of LLWR, in which the upper limit is the drier soil water content of either field capacity (θ_{FC}) or 10 % air porosity (θ_{AFP}) whereas the lower limit is the wetter soil or with more water content of either the permanent wilting point (θ_{PWP}) or penetration resistance (θ_{PR}). As reported above we can obtain two bulk densities considered important in the identification of soil physical degradation, the ρ_{BA} and $\rho_{BCritical}$ (Fig. 3A), in agreement with GUIMARÃES et al. (2013); SILVA et al. (1994). When LLWR becomes smaller than the plant-available water capacity (ρ_{BA}), and by the intersection of θ_{FC} with θ_{PR} or θ_{AFP} with θ_{PR} ($\rho_{BCritical}$) (Fig. 3A, B), used by the time to monitor the area due to the possibility of soil structure degradation.

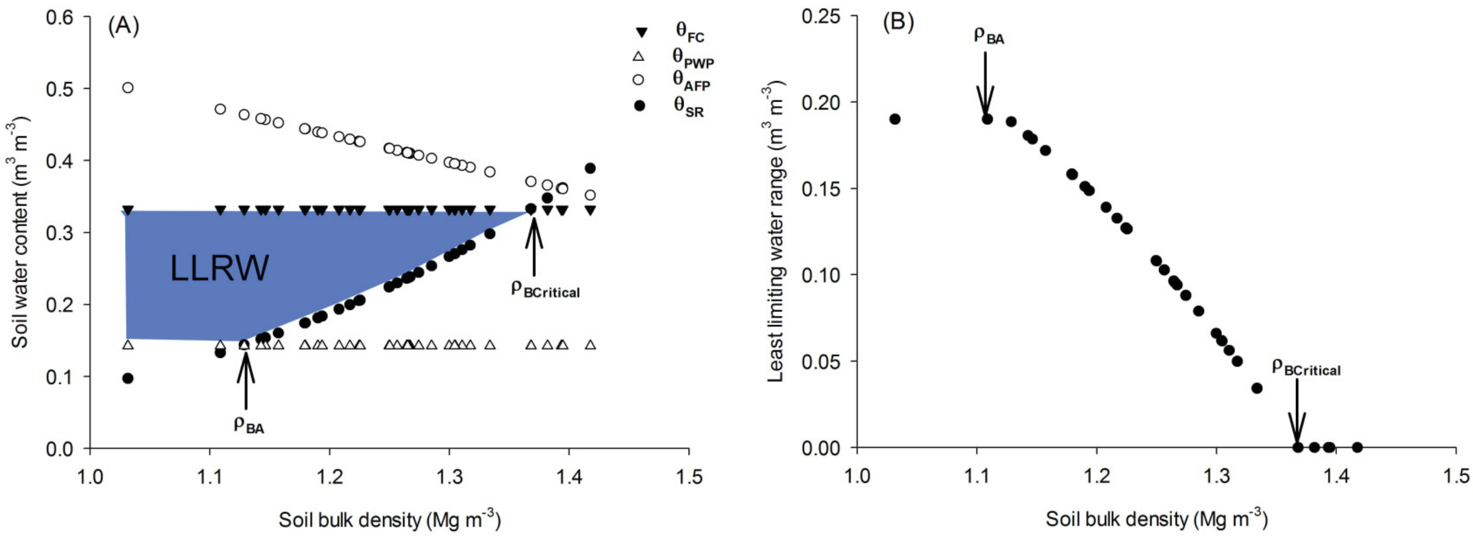


Figure 3: (A) Soil water content variation (θ) in the function of soil bulk density at the critical values of field capacity (θ_{FC}), permanent wilting point (θ_{PWP}), air-filled porosity (θ_{AFP}), and penetration resistance (θ_{PR}). The least limiting water range (LLWR) is the crosshatched area; (B) LLWR is a function of soil bulk density. ρ_{BA} is bulk density alert value, and $\rho_{BCritical}$ is critical soil bulk density.

2.1.1.4. Integration of soil physical properties to indicate adverse stresses for plant's growth

The soil's physical properties can be integrated into SCC by regressions estimating adverse physical-mechanical stresses that could affect, not only soil structure but also plant growth. This can be possible because those parameters determined by SWRC, SCC, and LLWR have in common the indicators ρ_B and soil water content. Thus, the concepts of the adverse volume of mesopores, σ_P, $\rho_{BA,}$ and $\rho_{BCritical}$, were used to define soil adverse physical-mechanical stress range (Fig. 4).

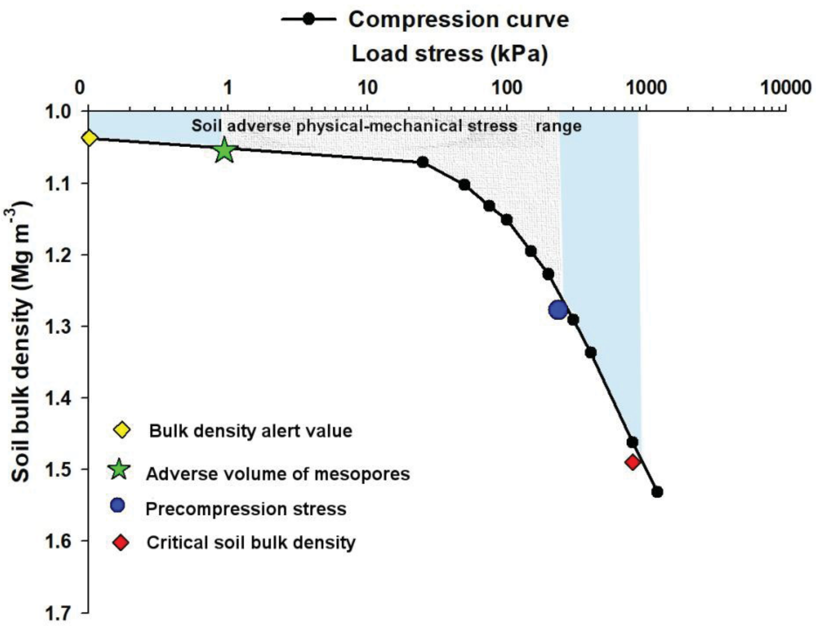


Figure 4: Soil adverse physical-mechanical stress range for the plants' growth.

This could suggest unfavorable or critical physical conditions that affect plants' growth, and consequently, the yield. Besides indicating unfavorable conditions to the soil structure, even the soil had submitted to only elastic deformations. This stress range can be a useful index to prevent or avoid deterioration of soil physical quality.

Parameters obtained by SWRC, SCC, and LLWR can provide estimates of soil stress values, in which the soil compaction poses structural changes affecting plant roots and, then, crop yield, besides soil plastic deformations. The objectives of this study were: a) to establish a relationship between limiting soil physical indicators and accumulated crop yield to define adverse indicators for plants growth through SCC; b) to integrate parameters dependent on soil bulk density, to find out harm effects to the plants' growth and soil strength and c) to define an adverse physical-mechanical stress range, under different long-term tillage systems.

2.2. Material and Methods

2.2.1. Experimental area

Details of the Experimental area are described in Chapter I, Item - 1.2.1. Experimental area.

2.2.2. Crop yield

The soybean and maize yield data were obtained, for summer crop seasons in 2013/14 (soybean), 2014/15 (maize), 2015/16 (soybean), and 2016/17(soybean) harvest, while the wheat data was obtained in the winter crop season in 2016. The crop yields were measured taking a useful area from each plot (138 m^2), 1 m of all borders of the plot was not used, and expressed in kg ha^{-1}, after correction to 13 percent of moisture content. The harvest was semi-mechanized without plant desiccation.

Table 1: The accumulated yield was considered the sum of the five harvests, for each tillage system.

Crop	Soybean	Maize	Soybean	Wheat*	Soybean	Accumulated
Year/harvest	2013/14	2014/15	2015/16	2016	2016/17	yield
Systems	(kg ha^{-1})					
No-tillage	4,304	12,026	4,292	7,029	4,474	32,125
Strategic tillage	4,015	11,639	4,246	6,849	4,412	31,161
Conventional tillage	3,923	10,815	4,040	6,543	4,281	29,602

* winter crop

2.2.3. Soil sampling and analysis

The soil samples used in this chapter were performed in 2014 and 2016 and are described in Chapter I, item - 1.2.2. Soil sampling and analysis.

2.2.4. Soil pore size distribution and adverse volume frequency of mesopores

The pore size distribution (PSD) varies in agreement with ρ_B inserted into the SWRC fit, then is possible to monitor the behavior of pores distribution, over time. For the experimental area, PSD for the three tillage systems can be observed in Fig. 5.

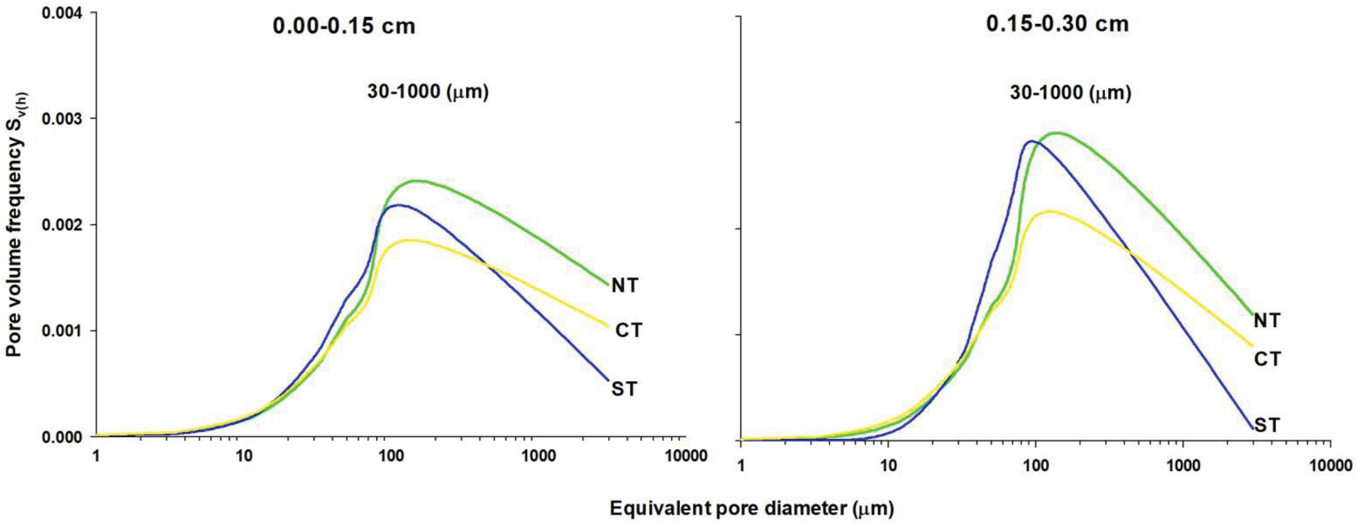


Figure 5: Soil pore volume frequency plotted against equivalent pore diameter (μm), on a log10 scale in two soil layers under no-tillage (NT), strategic tillage (ST) and conventional tillage (CT). The same figure of Chapter 1 (Figure 4).

To define the soil adverse volume frequency of mesopores ($\Phi_{MesAdverse}$) for plant growth, it was calculated the total of samples with mesopores volume lower than a minimum value of 0.06, 0.07, and 0.08 m^3 m^{-3} to establish the higher frequency of those mesopores that affect adversely the redistribution of water into the soil. Then, this frequency was regressed against the accumulated crop yield, from 2014 to 2017, seeking to find the $\Phi_{MesAdverse}$, which can mostly affect the crop yield (Fig. 6). The best fit indicates that the increase in the occurrence that volume of the $\Phi_{MesAdverse}$ is closely related to the decrease in accumulated crop yield.

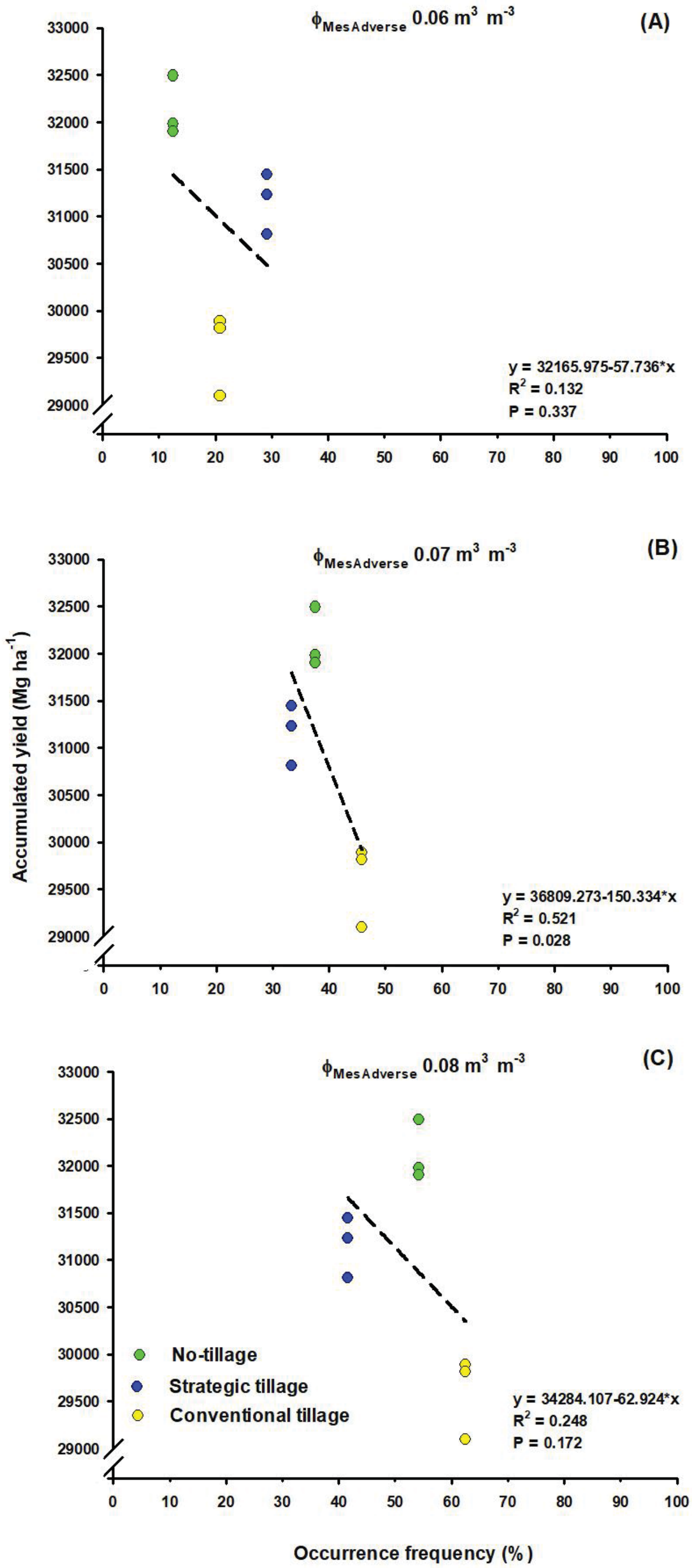


Figure 6: Relationship between accumulated yield (from 2014 to 2017) and frequency of mesopores volume considered limiting (A) 0.06 m^3 m^{-3}, (B) 0.07 m^3 m^{-3}, and (C) 0.08 m^3 m^{-3}. The dashed line is the fit model; R^2 = coefficient of determination; P = probability.

After being identified the $\Phi_{MesAdverse}$ as 0.07 m^3 m^{-3}, was proceeded the respective soil bulk density, in which the $\Phi_{MesAdverse}$ occurred, by regressions between mesopores volume and soil bulk density, for each tillage system, considering both soil layers (Fig. 7), named $\rho_{MesAdverse}$.

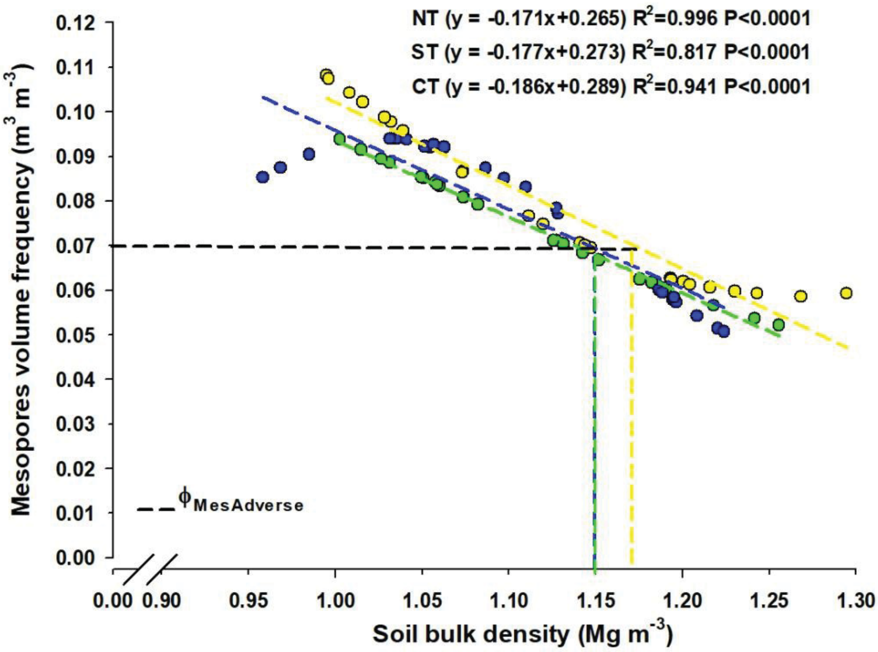


Figure 7: Relationship between mesopores volume and soil bulk density at the 0.00-0.30 cm soil depth, under no-tillage (NT), strategic tillage (ST), and conventional tillage (CT). $\Phi_{MesAdverse}$ = Adverse mesopores indicating their respective bulk densities.

2.2.5. Soil compression curve (SCC) and Precompression stress (σ_P)

Details of the determination of this item are described in Chapter I, Item - 1.2.3. Soil compression curve (SCC) and Precompression stress (σ_P).

2.2.6. Parameters of least limiting water range (LLWR)

It adopted critical soil penetration resistance (θ_{PR}) of 3.5, 3.0, and 2.0 MPa for no-tillage (NT), strategic tillage (ST), and conventional tillage (CT), respectively (MORAES et al., 2014). The LLWR as a function of ρ_B showed that, in the range of values of ρ_B obtained, NT and ST have not reached critical density (LLWR=0) in the 0.15–0.30 m layer, so these values were estimated using regression equations (VIZIOLI et al., 2021). The values of bulk density alert value (ρ_{BA}) was obtained when

LLWR became smaller than the plant-available water capacity (GUIMARÃES et al., 2013; NASCIMENTO et al., 2019).

2.2.7. Critical stress values

The parameters derived from the soil water retention curve and soil compression curves, such as $\Phi_{MesAdverse}$ and σ_P, were regressed to find their respective bulk density, and then, named as $\rho_{MesAdverse}$ and $\rho\sigma_P$. After this procedure, the values of ρ_{BA}, $\rho_{BCritical}$, $\rho_{MesAdverse}$, and $\rho\sigma_P$ were regressed by a fourth-order polynomial curve from the soil compression curve (SCC), for each tillage system, in both soil layers. Thereafter the adverse physical-mechanical stress values were obtained.

2.2.8. Statistical analysis

The data were submitted to the Shapiro-Wilk test, to verify the normality. Then ANOVA was performed, when the F test was significant ($p < 0.05$) the differences between tillage systems or layers, were compared by the Tukey test ($p < 0.05$). In addition, for fitting curves was used linear and non-linear regression techniques using Sigma Plot program, and the statistical program SAS.

2.3. Results and Discussion

2.3.1. Initial soil bulk density

The mean values of soil bulk density (ρ_B) were 1.16, 1.15, and 1.18, respectively for NT, ST, and CT, at 0.00-0.15 m, and 1.07, 1.05, and 1.09 Mg m^{-3} for 0.15-0.30 m layer.

The ρ_B had no significant difference between the tillage systems according to the F test ($P < 0.05$). Although, between layers, within each system, showed differences in the three systems, with the 0.00-0.15 m being statistically higher than the 15-30 cm layer.

All systems presented ρ_B values lower than the critical limit, which is approximately 1.40 Mg m^{-3}, for clayey to loamy clay soils. Values between 1.40 and 1.50 Mg m^{-3} are often the minimum value at which root restriction may be observed (DADDOW and WARRINGTON, 1983; USDA-NRCS, 1996). In according t REYNOLDS et al. (2007), in soils with fine and medium texture, the ρ_B considered adequate for maximum crop production would be between 0.90 to 1.20 Mg m^{-3}, values below 0.90 Mg m^{-3}, which could cause production losses due to inadequate plant anchorage and low capacity to provide water and dissolved nutrients to the roots. In this study both layers analyzed were below 1.20 Mg m^{-3}, even in the 0.00–0.15 m layer, where the highest value of ρ_B was obtained, indicating that the ρ_B in the studied systems probably did not compromise the capacity to support root growth.

2.3.2. Adverse parameters for plant growth and soil strength

Soil bulk density is considered adverse for plants growth and soil strength when is associated to the least limiting water range (LLWR), soil pore size distribution, and precompression stress. Those that affect plants growth were indicated as the $\rho_{BCritical}$, in which the LLWR is equal to zero, and are associated with severe soil physical degradation (SILVA et al., 1994). While $\rho_{MesAdverse}$ is linked to a minimum frequency of mesopores with a volume of 0.07 m^3 m^{-3} for “optimal” water redistribution into the soil. If the soil presents a high frequency of this mesopores volume ($\Phi_{MesAdverse}$), the plants cannot supply water to the roots efficiently. The close relationship of both these adverse parameters with accumulative crop yield can be observed in Fig. 8.

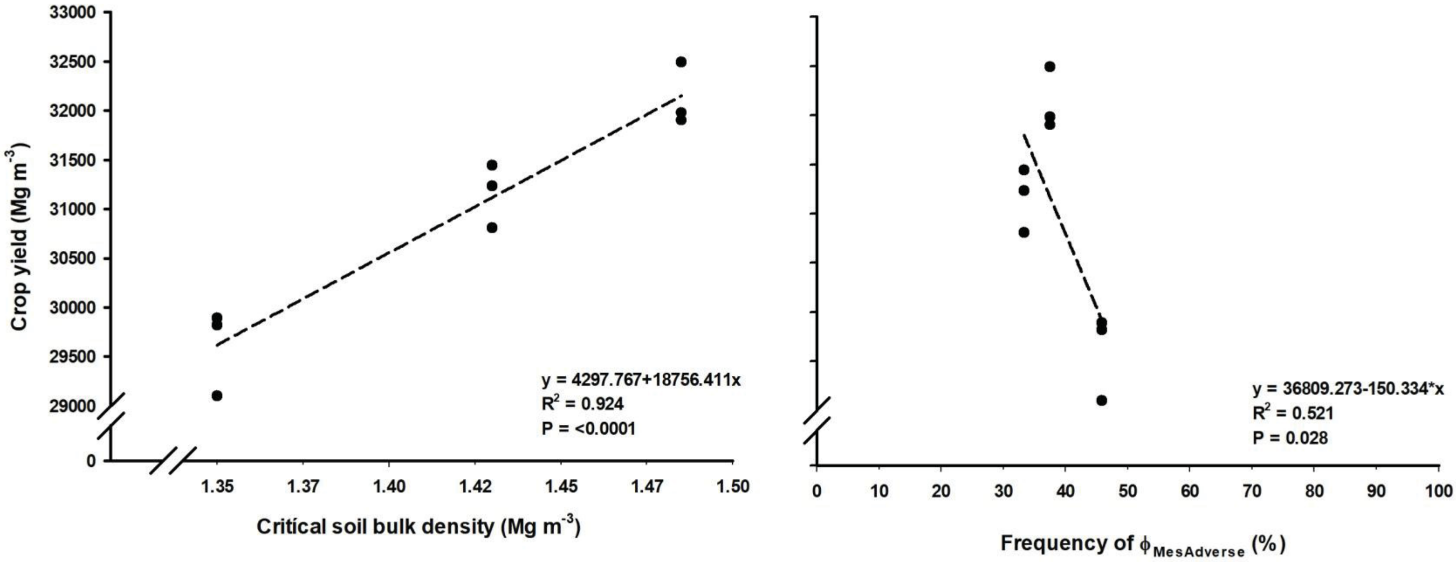


Figure 8: Relationship between critical soil bulk density and frequency of adverse mesopores volume (0.07 m^3 m^{-3}) and yield.

The soil bulk density at the adverse volume of mesopores was defined in this study, as 0.07 m^3 mesopores per m^3 of soil, through a linear regression between the frequency of mesoporosity volumes at different values against the accumulated crop yield for the period of 2014 to 2017 (Fig. 6). Since founding the $\Phi_{MesAdverse}$, the bulk densities corresponding to it for the tillage systems occurred at about 1.12, 1.12, and 1.16 Mg m^{-3}, for NT, ST, and CT (Fig. 7).

2.3.3. Soil compression curve and soil adverse physical-mechanical stress range

Soil structure starts to show physical degradation in LLWR by the bulk density alert value (ρ_{BA}), while the additional soil compaction is verified in SCC by the precompression stress (σ_P) is surpassed.

The models used to find the stress values under soil bulk densities as $\rho_{MesAdverse}$, ρ_{BA}, $\rho_{BCritical}$, as well as $\rho\sigma_P$ are shown in the Table 2.

Table 2: Polynomials obtained from soil compression curve, coefficient of determination (R^2), and F test value (p<0.05), in two soil layers under no-tillage (NT), strategic tillage (ST), and conventional tillage (CT).

	0.00–0.15 m
NT	ρ_B= -5.5E-13x^4 + 1.49E-09x^3 - 1.5E-06x^2 + 0.000937x + 1.15819 R^2 = 0.783 F = 94.96**
ST	ρ_B= -4E-13x^4 + 1.16E-09x^3 - 1.3E-06x^2 + 0.000882x + 1.16182 R^2 = 0.768 F = 95.31**
CT	ρ_B= -6.1E-13x^4 + 1.7E-09x^3 - 1.8E-06x^2 + 0.001067x + 1.18683 R^2 = 0.786 F = 105.46**
	0.15–0.30 m
NT	ρ_B= -1.5E-13x^4 + 5.98E-10x^3 - 1E-06x^2 + 0.001007x + 1.09469 R^2 = 0.876 F = 185.39**
ST	ρ_B= -5.4E-13x^4 + 1.57E-09x^3 - 1.8E-06x^2 + 0.001225x + 1.04483 R^2 = 0.916 F = 285.74**
CT	ρ_B= -4.3E-13x^4 + 1.32E-09x^3 - 1.6E-06x^2 + 0.00112x + 1.11413 R^2 =0.756 F = 73.50**

ρ_B= soil bulk density values. **= significance ($P < 0.0001$). R^2= determination coefficient, R^2= [1-(Sum Square Residue/Sum Square Model)].

Mean values of soil bulk density under field conditions and adverse parameters are presented in Table 3, with their respective estimated adverse stresses. It was observed that the mean bulk densities at the surface layer, for all tillage systems surpassed the ρ_{BA}, indicating that some deleterious effects on soil structure already have happened. In relation to reaching the $\rho_{MesAdverse}$ in this layer, the same results were obtained in the three systems as well, all systems had implications also on $\Phi_{MesAdverse.}$ Thus, evidencing negative physical effects on soil structure, consequently also for plant roots. Then any applied stress to the soil could maintain or damage even more, due to the initial soil bulk density (ρ_B) that is higher than the threshold established by $\rho_{MesAdverse}$. No-tillage, strategic tillage, and conventional tillage had an initial mean value of 1.16, 1.15, and 1.18 Mg m^{-3}, and the mean $\rho_{MesAdverse}$ was 1.12, 1.12, and 1.16 Mg m^{-3}, respectively. This result suggests that for these systems, at the surface layer, the soil structure already is being degraded, which could negatively influence the soil water dynamics.

Table 3: Values of densities and applied stress regarding to bulk density alert value, adverse mesopores, precompression stress, critical soil bulk density and soil adverse stress range in two soil layers under no-tillage (NT), strategic tillage (ST) and conventional tillage (CT).

	Layers (m)	ρ_{BA} (Mg m^{-3})	stress (kPa)	$\rho_{MesAdverse}$ (Mg m^{-3})	stress (kPa)	$\rho\sigma_P$ (Mg m^{-3})	stress (kPa)	$\rho_{BCritical}$ (Mg m^{-3})	stress (kPa)	stress range (kPa)
NT	0.00–0.15	1.14	0	1.12	0	1.28	177	1.42	560	0-560
NT	0.15–0.30	1.09	0	1.12	21	1.21	124	1.55	1004	0-1004
ST	0.00–0.15	1.16	0	1.12	0	1.29	193	1.38	406	0-406
ST	0.15–0.30	1.09	35	1.12	63	1.17	121	1.48	846	35-846
CT	0.00–0.15	1.04	0	1.16	0	1.31	144	1.37	248	0-248
CT	0.15–0.30	1.14	20	1.16	39	1.23	121	1.33	271	20-271

ρ_{BA}= bulk density alert value; $\rho_{MesAdverse}$= bulk density of adverse mesopores; $\rho\sigma_P$= bulk density of precompression stress; $\rho_{BCritical}$= critical soil bulk density.

The soil adverse stress range was considered the interval between the minimum value found of ρ_{BA} or $\rho_{MesAdverse}$, and the maximum value found of $\rho\sigma_{P}$ or $\rho_{BCritical}$, i.e., the stresses in which start to change bulk densities by reducing the water content, by changes on soil structure (ρ_{BA}), or increasing the frequency of mesoporosity at 0.07 $m^3\ m^{-3}$ volume, $\Phi_{MesAdverse}$, and those stresses where increase soil bulk density leading to additional soil compaction by plastic deformation ($\rho\sigma_{P}$) or leading to severe water content restrictions to the roots ($\rho_{BCritical}$), consist in critical stress range applied to the soil (Fig. 9).

The range for the 0.00–0.15 m layer was smaller than the 0.15–0.30 m layer, due to the higher ρ_{B} at the surface for the three tillage systems (Table 3). This finding suggests a greater effect on root plants and soil structure in this layer.

For the 0.15–0.30 m layer, applied stress to achieve the $\Phi_{MesAdverse}$ was 21, 63, and 39 kPa for NT, ST, and CT, respectively. Presenting that in this layer, there is a better condition for the water availability to the plants in the three systems (Table 3). However, there may be changes in the volume of mesopores by machine traffic on the three systems. HORN and LEBERT (1994) suggest that the soil was susceptible to soil compaction by typical loads since agricultural machinery generally applies stresses ranging from 70 to 350 kPa, while transport equipment applies stresses of up to 800 kPa. HÅKANSSON et al. (1988) also cited stress values applied to the soil, which varied from 100 to 150 kPa for tractors, and from 200 to 300 kPa for harvesters.

In the NT system, the stress applied to reach the $\rho_{BCritical}$, at both layers were higher than the ST and CT (Table 3), demonstrating that, although there were no significant statistical differences between the tillage systems for soil load-bearing capacity, under soil water potential of -100 hPa, the NT system showed greater resilience with the increase of applied stresses, as the CT showed the lowest resilience.

These results indicate that the 0.00–0.15 layer, is less susceptible to additional compaction than the 0.15–0.30 m layer when posed to low loads, mainly in the NT, where the σ_{P} was statistically different between the studied layers, but with the increase in applied loads, this behavior can be changed in according to the results of the estimates made to achieve the $\rho_{BCritical}$, in which the greatest resilience occurred in the subsurface (Fig. 9).

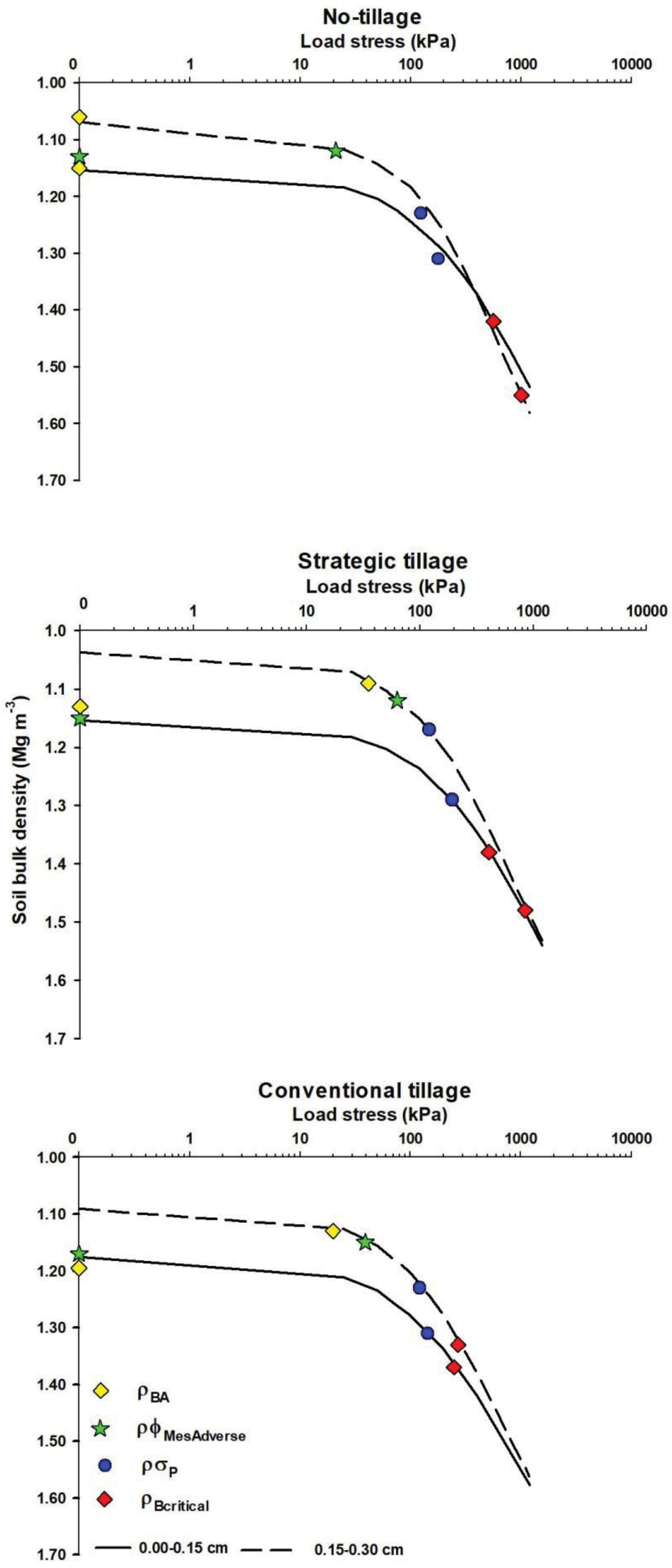


Figure 9: Lines represent the means of soil compression curves in two soil layers under no-tillage, strategic tillage and conventional tillage systems.

IMHOFF et al. (2001) found a value of 360 kPa to achieve the $\rho_{BCritical}$ in the soil water potential of -100 hPa (field capacity), corresponding to a soil water content of 0.18 $m^3\ m^{-3}$, in an Acrisol with 19 % of clay content, relating the LLWR and the σ_P. The authors used the LLWR $\rho_{BCritical}$ (1.70 Mg m^{-3}) as a reference to the critical stress that can be applied to the soil. This result is closer to the CT system (Table 3).

In another research, IMHOFF et al. (2016) found in soil with 32 % of clay content $\rho_{BCritical}$ of 1.48 Mg m^{-3}, whereas the soil with 25 % of clay had $\rho_{BCritical}$ of 1.55 Mg m^{-3} and concluded that the stress applied to the soil by the agricultural machinery must be less than 150 kPa for the former and less than 300 kPa for the latter, in order to maintain adequate soil conditions to plant growth, using the estimated $\rho_{BCritical}$ for plant growth in the model of the compression curve.

Considering that σ_P is an indicator of the maximum stress that must be applied to the soil to avoid additional compaction (CASAGRANDE, 1936; LARSON et al., 1980), the stresses values between ρ_{BA} or $\Phi_{MesAdverse}$ and σ_P could be applied under the conditions of this study, without causing severe restrictions to plant's growth and additional compaction to the soil. However, the water absorption capacity by the plants and its redistribution in the soil would already be decreasing, it may harm the yield.

The stress necessary to reach $\rho_{BCritical}$ was high mainly in the NT system, thus, the possibility of reaching severe soil physical degradation conditions is low. Probably due to the non-disturbing or minimal disturbance of the soil, demonstrating how management influences, not only susceptibility to additional compaction, but also its physical degradation.

In the study by VIZIOLI et al. (2021), the results of some physical indicators, such as ρ_B, pore tortuosity (τ), and total porosity in the 0.15–0.30 m layer indicated a physical degradation in the ST system, which could affect the water infiltration, gases fluxes, and root's growth. In the present study, better results for those attributes were not verified in this system, at this layer as well, suggesting that, chiseling is not providing the expected benefits, with the mechanical chisel to a depth of 0.30 m. In general, chiseling to 0.30 m deep in no-tillage is recommended to alleviate soil compaction effects (CONYERS et al., 2019; VIZIOLI et al., 2021), but in this study, this practice is not recommended.

Taking into account the results obtained from the soil physical indicators, and that the no-tillage system avoids some agricultural operations and reduces the energy cost in relation to strategic tillage and conventional tillage (MÜLLER et al., 2017; SANTOS et al., 2020), this would be the system more indicated, also recommending crop rotation, as the benefits indicated by the physical quality indicators are consistent in terms of soil functionality.

2.4. Conclusions

In this study, $\Phi_{MesAdverse}$ indicated deleterious effects on water availability, even without promoting plastic deformations (non-recoverable) or conditions of high physical degradation ($\rho_{BCritical}$). Thus, relationships between the $\Phi_{MesAdverse}$, and the $\rho_{BCritical}$ with the accumulated crop yield were found, being possible to describe them as a linear model. The NT showed the highest accumulated yield among the three systems, having a significantly negative relationship with the highest frequency of mesopores volume of 0.07 m^3 m^{-3} ($\Phi_{MesAdverse}$), and a positive relationship with $\rho_{BCritical}$.

Soil adverse physical-mechanical stress range developed in this study proved to be applicable, with the integration of parameters from the soil water retention curve, least limiting water range, and the soil compression curve. It was possible to obtain not only the stress that causes additional compaction to the soil (plastic deformations) but also the water availability to plants and its influence on yield.

Besides $\rho_{BCritical}$ is a useful tool to define severe physical degradation that plants are submitted, mainly under drier and/or unfavorable soil conditions, soil adverse volume frequency of mesopores can be used as an important indicator of water distribution in the soil affecting its availability, under favorable conditions. Then effects on the crop yield can be attributed to the soil water distribution that ends up not being efficient, despite its supply seeming suitable, mainly under favorable water conditions.

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3.1. Conclusões finais

1. Os sistemas de preparo do solo apresentaram poucas diferenças significativas entre os indicadores de qualidade física.
2. Os indicadores ligados à capacidade de suporte ao crescimento radicular (Grau de compactação) e à resistência do solo à degradação (VESS) foram significativamente correlacionados com a produtividade do trigo, mas nenhum com a produtividade da soja.

3. A distribuição das classes de poros de acordo com suas funções de drenagem, redistribuição e retenção de água no perfil do solo, são muito importantes em otimizar a produtividade.
4. O intervalo de pressões físico-mecânicas adversas no solo desenvolvido neste estudo indicam efeitos deletérios na disponibilidade de água no solo, mesmo sem promover deformações plásticas ou condições de alta degradação física do solo.
5. O sistema plantio direto apresentou o maior rendimento acumulado entre os três sistemas, tendo relação significativamente negativa com a maior frequência de volume de mesoporos de 0,07 m^3 m^{-3} ($\Phi_{MesAdverso}$), e positiva com a densidade do solo crítica ($\rho_{scrítica}$), podendo ser considerado o melhor sistema de preparo do solo, após 23 anos de experimento, nas condições estudadas.
6. Como conclusão final, verificamos a necessidade de realizar mais pesquisas em relação à distribuição das classes de poros de acordo com suas funções, assim como, a integração da curva de retenção de água no solo, intervalo hídrico ótimo e curva de compressão do solo e relacioná-las a produtividade das culturas em diferentes sistemas de preparo do solo e ambientes de produção.

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