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Effects of long-term tillage systems on soil physical quality and crop yield in a Brazilian Ferralsol

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A R T I C L E I N F O

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A B S T R A C T

Long-term soil tillage trials can provide important knowledge about sustainable changes in soil physical quality and crop yield. This study evaluated soil physical quality indicators under different long-term tillage systems and examined the relationships between quality indicators and crop yield. The study was carried out on a Rhodic Ferralsol with three tillage systems established in 1989: conventional tillage (CT), strategic tillage (ST), and no-tillage (NT). All treatments had long-term crop rotation. The soil parameters evaluated were total organic carbon (TOC), bulk density (ρ_s), macro and microporosity (Mac and Mic), relative gas diffusivity (D/D_0), pore tortuosity (τ), relative field capacity (RFC), structural stability index (SSI), least-limiting water range (LLWR), and degree of compactness (DC, taking as reference the soil bulk density in which LLWR = 0). Soybean and maize yields in two consecutive summer seasons were measured. Conventional and strategic tillage provided higher ρ_s in the 0.15–0.30 m layer depth, leading to higher DC in CT. Using soil bulk density at LLWR = 0 as reference proved useful to assess soil DC and plant response. No-tillage provided lower DC in the 0–0.15 m (86 %) and 0.15–0.30 m (78 %) layers than CT (91 % and 94 %, respectively). The maize yield had a negative linear relationship to DC, with the lower values at DC > 87 %. All tillage systems affected D/D_0, even at similar porosity values. The better soil physical quality under NT provided 1211 kg ha^{-1} higher maize yield compared with CT. The differences in soybean yield between treatments were not significant, but NT provided 381 kg ha^{-1} more than CT. These findings indicate that NT is the best system studied. Our results strongly suggest that ST does not improve physical properties of soils under NT with crop rotation, and that a diversified crop rotation in NT was efficient to avoid soil physical degradation.

1. Introduction

Tillage causes changes in the soil pore system, affecting processes related to air and water fluxes and mechanical resistance to root growth. Conventional tillage generally promotes whole soil disturbance up to 0–25 cm depth, which predisposes soil, water, nutrient, and organic carbon losses due to erosion, organic carbon losses through faster mineralization, and subsurface soil compaction (Taboada et al., 1998). To counteract the harmful effects of conventional tillage on Brazilian soils, no-tillage was introduced in the 1970s. No-tillage is now used on around 33 million hectares in Brazil (Joris et al., 2016) and on 161 million hectares worldwide (Kassam et al., 2015). Despite the many advantages of adopting no-tillage, its sustainable usage is founded on crop rotation, minimal soil disturbance, and permanent soil covering (Joris et al., 2016; Conyers et al., 2019).

In no-tillage, seeds and fertilizers are applied through furrow-opening tools that only disturb the soil under the crop row (Dang et al., 2018). Due to this minimal soil disturbance, no-tillage provides benefits such as reduced soil and water losses as well as organic carbon accumulation (Medeiros et al., 2011; Garcia et al., 2013; Conyers et al., 2019), leading to soil structure improvement (Garcia et al., 2013; Girardello et al., 2014; Calonego et al., 2017; Conyers et al., 2019). However, surface compaction due to larger and heavier no-tillage machinery has been reported (Martínez et al., 2016), with possible damage to

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physical functionality of soil and root growth, ultimately compromising crop yield (Calonego et al., 2017).

To ameliorate soil surface compaction under no-tillage, strategic tillage can be used (Dang et al., 2018; Conyers et al., 2019), whereupon the soil under no-tillage systems is chiseled periodically to overcome any physical barriers to plant development (Dang et al., 2018; Conyers et al., 2019). However, the effects of chiseling on soil physical attributes do not last long (Nunes et al., 2015; Conyers et al., 2019), and the stage at which strategic tillage becomes necessary in no-tillage systems (Nunes et al., 2015; Dang et al., 2018) have not been widely studied for Brazilian soils. Nunes et al. (2015) found that the effects of chiseling in reducing soil bulk density and penetration resistance (PR) and increasing soil macroporosity disappeared after 18 months. Santos et al. (2019) reported that chiseling increased water infiltration 12 months after tillage, reducing runoff and penetration resistance in a very clayey dystroferric Rhodic Ferralsol, although it favored superficial root growth.

Nevertheless, the need for chiseling no-tillage soils has been questioned (Dang et al., 2018). While soil physical properties may indicate some compaction, the soil structure under no-tillage may still be favorable for soil physical functionality as well as agronomic and environmental functions (Meek et al., 1990; Cavalieri et al., 2009; Conyers et al., 2019). The continuous and well-connected biopores formed by decomposing roots and other biological activities provide better water infiltration (Meek et al., 1990; Conyers et al., 2019) and alternative pathways for growing roots (Calonego et al., 2017) under no-tillage soils. These beneficial effects are achieved mainly by no-tillage and diversified crop rotation, and they can be reversed by tillage (chiseling) used to relieve soil compaction (Moraes et al., 2014). It is well known that soils under no-tillage have greater aggregate stability (Nunes et al., 2015; Conyers et al., 2019), which preserves organic matter inside aggregates. Overall, the effects of tillage practices on tropical soils are best assessed in long-term experiments (Martínez et al., 2016).

This study tested the hypothesis that strategic tillage every three years in Rhodic Ferralsol provides better soil physical quality and crop yield that with continuous long-term CT or NT. Our objectives were to evaluate the effects of long-term tillage systems on soil physical quality in Rodic Ferralsol in Southern Brazil and to establish relationships between soil physical properties and soybean and maize yield in two consecutive cropping seasons.

2. Material and methods

The study was conducted in a long-term experiment in Ponta Grossa municipality, Parana State, Southern Brazil (25°5′42″S; 50°9′43″W). The climate at the study site is humid-temperate (Cfb), with mean temperatures of 16 °C and 22 °C in the coldest and warmest month, respectively, and frequent frosts in the winter. Mean annual rainfall is around 1800 mm, unevenly distributed between different months of the year (Fig. 1). The relief is smooth undulating (slope 2–4%), and the soil at the site is classified as a Rhodic Ferralsol (FAO, 1998) or "Latossolo Vermelho Distrófico típico" in Brazilian soil classification system (Santos et al., 2018). The soil is clayey in texture (Table 1), and the most common clay minerals are kaolinite and oxides; thus, the soil is non-expansive.

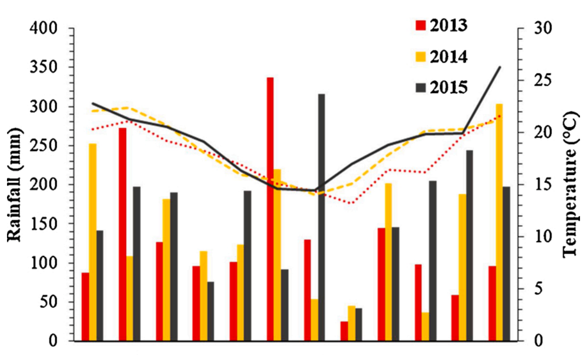

Fig. 1. Mean monthly rainfall and medium temperature at the long-term trial site during the study period (2013–2015).

The experimental area was under native vegetation until 1967, when conversion to cropland occurred. During the first three years, the soil was cropped with rice (*Oryza sativa*) in the winter through conventional tillage (one plow and two harrows) and left fallow during the summer. In the third summer season, soybean (*Glycine max*) was planted and rice/soybean crop rotation continued until 1981, when the no-tillage was started with soybean and wheat (*Triticum aestivum*) as summer and winter crop, respectively. In 1989 the experiment started to be prepared and the last application of limestone was in 1994, details about fertilizing can be found in Pierri et al. (2019). The long-term trial was then established in randomized blocks with three treatments and three replicate plots, each approximately 8 m wide × 25 m long and with a border of 1.0 m on all sides. Black oats (*Avena strigosa*) were sown as a cover crop in May 1993 (Table 2). Since then, a crop rotation with maize (*Zea mays*), vetch (*Lathynus sativus*), and soybean as summer crops, and black oats, white oats (*Avena sativa*), and wheat as winter crops has been cropped (Table 2). The cover crops are killed-off with herbicides.

The studied soil tillage treatments were conventional tillage (CT), no-tillage with strategic tillage (ST), and continuous no-tillage since 1989 (NT). Under CT, the soil was tilled through conventional moldboard plow to 0.25 m depth and harrowed twice to 0.20 m depth before planting each crop. In treatment ST, the soil under NT was chiseled to 0.30 m depth every three years, always before the winter crop planting, with the last chiseling performed in May 2014. In NT, crops were sown using no-tillage seeder that disturbs only the soil under the crop row. Cover crops were sown at 0.17 m row spacing, using a small disc seeder. After kill-off of the previous cover crop, in the 2013/14 summer crop, season soybean (NA5909RG hybrid) was sown (approximately 315,000 plants ha^{-1}, 0.38 m row spacing rows) and harvested in April 2014, with ~759 mm accumulated precipitation during the season (Fig. 1). In the 2014/15 summer crop season, maize (hybrid P30F53YM) was planted (75,000 plants ha^{-1}, row spacing 0.80 m) and harvested in March 2015, with ~1258 mm accumulated precipitation during the crop season. The soybean crop received fertilizer dose of 300 kg ha^{-1} of 00–20-20 (NPK) at sowing, while the maize crop received 300 kg ha^{-1} of 12–32-00 (NPK) +1 kg ha^{-1} of Zn at sowing and a top-dressing of 320 kg ha^{-1} urea and 150 kg ha^{-1} KCl at start of flowering.

Soil sampling was conducted in early May 2014 before the tillage operations. Two trenches (0.22 m × 0.60 m × 0.30 m) were opened, avoiding the borders (~2 m) in each plot, and disturbed and undisturbed soil samples were collected in the middle of the 0–0.15 and 0.15–0.30 m soil layers. Six undisturbed samples were taken using stainless cores (0.035 m high, 0.05 m diameter) per trench and layer, totaling 216 samples. Disturbed soil samples were collected in each trench and layer (total 36 samples), oven dried for 48 h at 45 °C, and passed through a 2-mm-mesh sieve. Soil texture, chemical attributes, and particle density were determined on these samples (Table 1). Total organic carbon (TOC) content was determined by the wet oxidation method in potassium dichromate solution in sulfuric medium (Walkley-Black).

The undisturbed soil samples were water saturated for 48 h and weighed to determine volumetric water content at saturation (θ_S). For soil water retention curve (SWRC), all saturated samples were step by step equilibrated at −20, −60, and −100 hPa on a tension table. The samples were then divided into two groups of six samples, in which one group was desaturated to −250, −330, and −1000 hPa and the another to −5000 and −15,000 hPa water potentials in pressure chambers (Klute, 1986). Then, the samples were re-saturated and submitted to six drying times (0.34, 1.0, 3.0, 4.5, 6.0, and 7.5 h) in an oven at 45 °C, to create a soil water gradient to determine root penetration resistance (PR), following the procedures of Moreira et al. (2014). The PR was

Table 1
Average values of basic soil properties and chemical characterization of soil in the experimental area.

Sand			Silt	Clay	ρ_p	pH	P	Ca^{2+}	Mg^{2+}	K^+	Al^{3+}	CEC
Coarse	Fine	Total										
g kg^{-1}					g cm^{-3}		mg dm^{-3}	cmol$_c$ dm^{-3}				
0.00–0.15 m												
CT 183	192	375	106	519	2.59	4.65	4.30	2.88	1.25	0.25	0.22	10.60
ST 200	190	390	131	479	2.57	4.33	6.58	2.15	0.90	0.26	0.48	10.85
NT 196	185	381	90	529	2.62	4.80	9.80	2.62	1.32	0.24	0.50	9.63
0.15–0.30 m												
CT 167	181	348	121	531	2.58	4.93	1.61	2.55	1.20	0.32	0.06	8.95
ST 187	190	377	100	523	2.59	4.87	0.85	2.50	0.90	0.26	0.06	8.45
NT 175	175	350	70	571	2.61	4.98	1.95	2.45	1.17	0.26	0.18	8.60

CT = Conventional tillage; ST = Strategic tillage (one chiseling every three years); NT = No-tillage. Coarse sand; fine sand, Total, Silt and Clay: Bouyoucus densimeter method; ρ_p: particle density, modified volumetric flask method; pH in $CaCl_2$; P e K^+: Mehlich-1 extractor; Ca^{2+}, Mg^{2+}, and Al^{3+}: KCl 1 mol L^{-1} extractor; H + Al: 0.5 mol L^{-1} calcium acetate extractor at pH 7.0. CEC: cation exchange capacity at pH 7.0.

Table 2
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
2009	White oats	Cover crop	URS-3	Soybean	Grain Production	CD206
2010	Wheat	Grain Production	Supera	Soybean	Grain Production	CD06
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

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

determined using a laboratory electronic penetrometer described in Tormena et al. (1998). Finally, the samples were oven-dried at 105 °C for 36 h to obtain the soil dry mass for calculating the soil bulk density (ρ_s) and soil water content (θ). Total porosity (TP) was computed based on volumetric water content at saturation (θ_S), and microporosity (Mic) was taken as volumetric water content at matric potential −60 hPa (pores <50 μm). Macroporosity (Mac) was calculated as the difference between TP and Mic (Tables 2–4).

The SWRC data were fitted according to van Genuchten (1980) model:

$$\theta = \theta_R + \frac{(\theta_S - \theta_R)}{\{1 + [\alpha \,.\, |\psi|]^n\}^{1-1/n}} \tag{1}$$

where: θ = volumetric water content (m^3 m^{-3}); θ_S = volumetric water content at saturation (m^3 m^{-3}); ψ = water matric potential (|hPa|); and θ_R, α, and n are equation fitting parameters.

The soil resistance to penetration curve (SRPC) was defined as soil penetration resistance (PR) as a function of θ and ρ_s described in Eq. 2 according to Busscher (1990) and da Silva et al. (1994), which was linearized (Eq. 3) and rearranged to calculate the soil water content at the critical PR value (Eq. 4).

$$PR = a\,\theta^b \rho_s{}^c \tag{2}$$

$$lnPR = \ln a + (b\ln\theta) + (c\ln\rho_s) \tag{3}$$

$$\theta = \left[\frac{PRcritical}{(\exp a)(\rho_s{}^c)}\right]^{\frac{1}{b}} \tag{4}$$

where: $PR_{critical}$ = critical soil penetration resistance (MPa); θ = volumetric water content (m^3 m^{-3}); ρ_s = soil bulk density, and *a*, *b*, and *c* are model fitting parameters.

To compute the least-limiting water range (LLWR), we used the following soil water content values: soil water content at ψ=−100 hPa (field capacity, θ_{FC}); soil water content at ψ=−15,000 hPa (permanent wilting point, θ_{PWP}); soil water content at which soil resistance to root penetration limits root growth (θ_{PR}), here we used a critical PR limit of

2.0 MPa for CT, 3.0 MPa for ST, and 3.5 MPa for NT, based on Moraes et al. (2014); and soil water content at 10 % air-filled porosity (θ_{AIR}), according to Grable and Siemer (1968). Thus, LLWR was calculated for the following conditions: If $\theta_{AIR} \geq \theta_{FC}$ and $\theta_{PR} \leq \theta_{PWP}$: LLWR = θ_{FC} - θ_{PWP}; If $\theta_{AIR} \geq \theta_{FC}$ and $\theta_{PR} \geq \theta_{PWP}$: LLWR = $\theta_{FC} - \theta_{PR}$; If $\theta_{AIR} \leq \theta_{FC}$ and $\theta_{PR} \leq \theta_{PWP}$: LLWR = θ_{AIR} - θ_{PWP}; If $\theta_{AIR} \leq \theta_{FC}$ and $\theta_{PR} \geq \theta_{PWP}$: LLWR = $\theta_{AIR} - \theta_{PR}$.

Soil degree of compactness (DC) was determined using as reference the soil bulk density at which LLWR is zero:

$$DC = \left[\frac{\rho_s}{\rho_{reference}}\right] \times 100 \quad (5)$$

where: ρ_s = soil bulk density (g cm^{-3}); $\rho_{reference}$ = soil bulk density (g cm^{-3}) for each tillage system and depth, taken as ρ_s when LLWR = 0. For treatments that did not provide $\rho_{reference}$, values of ρ_s were simulated at intervals of 0.02 g cm^{-3} until LLWR was zero, and $\rho_{reference\ simulated}$ was used as the reference bulk density for calculating DC.

The relative field capacity (RFC) expresses the soil's capacity to store water and air relative to the soil's total pore volume (as represented by θs) (Reynolds et al., 2009), described in Eq. (6).

$$RFC = \frac{\theta_{FC}}{\theta_S} \quad (6)$$

where: RFC = relative field capacity (dimensionless); θ_{FC} = field capacity water content ($m^3\ m^{-3}$) taken at −100 hPa water potential, and θ_S = soil water content at saturation ($m^3\ m^{-3}$).

The SSI was calculated using soil organic carbon content (%) as well as clay and silt content (%) (Pieri, 1992). An SSI > 9% indicates stable structure, 7%<SSI ≤ 9% indicates low risk of structural degradation, 5%<SSI ≤ 7% indicates high risk of degradation, and SSI ≤ 5% indicates structurally degraded soil.

$$SSI = \left[\frac{1,724*OC}{Clay + Silt}\right]*100 \quad (7)$$

Where: SSI = structural stability index (%); OC = soil organic carbon content (%); and (Silt + Clay) = combined silt and clay content of soil (%).

The relative gas diffusivity (D/D_0) was estimated as proposed by Millington and Quirk (1961) and used by Lima et al. (2020), taking air-filled porosity at −60 hPa water potential and TP values calculated for each sample:

$$\frac{D}{D_0} = \frac{\varepsilon^{10/3}}{TP^2} \quad (8)$$

where: D/D_0 is the relative gas diffusivity (dimensionless); ε is air-filled porosity ($m^3\ m^{-3}$); and TP is total porosity ($m^3\ m^{-3}$).

The pore tortuosity (τ, dimensionless) was estimated from the TP data according to Yu and Li (2004):

$$\tau = 0.5*\left(1 + \left(0.5*\sqrt{1} - TP\right)\right) + \frac{\sqrt{1 - \left(\sqrt{1} - TP\right)^2 + \left(\frac{1-TP}{4}\right)}}{1 - \sqrt{1} - TP} \quad (9)$$

where TP is total porosity ($m^3\ m^{-3}$).

The soybean and maize yield data were obtained, respectively, for summer crop seasons in 2013/14 (soybean) and 2014/15 (maize). The crop yield was measured taking a useful area from each plot (138 m^2) and expressed in kg ha^{-1}, after correction to 13 % grain moisture.

Normality of the data (TOC, ρ_s, Mac, Mic, TP, D/D_0, τ, RFC, SSI, DC, and soybean and maize yields) was tested by Shapiro-Wilk's test at 5 % significance level, and those that were not normally distributed were transformed according to Box and Cox (1964). Analysis of variance (ANOVA) was performed to test the effect of tillage system on soil physical attributes, and means were compared by Tukey test ($p < 0.05$). Pearson correlation coefficient (r; $p < 0.05$) was calculated to identify paired correlations between soil physical attributes and crop yield by PROC CORR in SAS, while the SWRC and SRPC models were fitted by the PROC GLM and PROC REG routines (SAS, 2002).

3. Results and discussion

The long-term tillage systems did not show significant differences in TOC (Table 3). Several studies suggest higher TOC in topsoil (0.075 m layer depth) under no-tillage compared with conventional tillage, due to preservation of residues on the soil surface (Garcia et al., 2013). However, according to Tornquist et al. (2009), TOC values are rather "high" (>20 g dm^{-3}) in Southern Brazilian soils, despite the effects of climate and soil making accumulation of TOC in tropical and subtropical soils difficult. Moreover, the gentle slope at the study site leads to reduced soil erosion, preventing soil, water, and organic matter losses. In general, Brazilian soils have TOC content below the "optimum" level of 30–40 g dm^{-3} needed to avoid damage to soil structure (Garcia et al., 2013; Nunes et al., 2015).

There was no significant differences in ρ_s and TP at the 0–0.15 m soil depth layer between tillage treatments; however, in the 0.15–0.30 m layer ρ_s was significantly lower in NT and CT than in ST (Table 3). Soil bulk density is generally considered to be sensitive to soil tillage practices and is one of the most easily measured indicators of structural degradation (Asgarzadeh et al., 2011). The non-significant differences in ρ_s in topsoil under the long-term tillage systems was due to high TOC (Table 3), and its impact on soil structure stability. In addition, TOC helps to prevent soil compaction (Reynolds et al., 2009), and different forms of carbon (particulate and associated to minerals) can provide differences in soil structure and pore size distribution. According to Pachepsky and Park (2015), ρ_s >1.24 g cm^{-3} in clay soils might limit root growth. In CT and ST treatments in the present study, ρ_s in both soil layers exceeded this value.

Although no difference was found for TP in the topsoil, macroporosity values were significantly lower in CT and ST than NT. On the other hand, microporosity values were higher in CT and ST than in NT, providing a potentially greater volume of plant-available water. Even though ρ_s and TP had no statistical difference at this layer, the pore distribution between macro and micropores was affected by tillage systems, due to different soil stress distribution by machines. Lamandé and Schjønning (2011) found significant differences of soil stress distribution for a tilled and not recently tilled soils on topsoil; however, no differences were found for soil bulk density and porosity. Reynolds et al. (2009) suggest that the macropore range between 0.09–0.13 $m^3\ m^{-3}$ is "ideal" for crop development. The values in all tillage treatments were within this range (Table 3), but slightly higher in NT, probably due to lower ρ_s and the biopores formed from decomposed roots (Williams and Weil, 2004) and edaphic fauna activity, as also suggested by Cavalieri et al. (2009) in a study carried out in the same soil. The lack of soil disturbance in NT allows the biopores to remain intact and provides better soil physical functionality over time.

The increased ρ_s values in no-till soils commonly reported for clay soils in Brazil (Suzuki et al., 2007) were not verified in this long-term study. In general, chiseling to 0.30 m deep in no-tillage is recommended to alleviate soil compaction effects (Conyers et al., 2019). Nonetheless, higher ρ_s values were found in the 0.15–0.30 m layer in the CT and ST treatments (although the chiseling in ST was done 36 months before sampling). According to Spoor et al. (2003), chiseling is necessary when impairment of plant root development due to reduced soil aeration and hydraulic conductivity is detected. Our results strongly suggest that ST does not improve physical properties of soils under NT with crop rotation, and that a diversified crop rotation in NT was efficient to avoid soil compaction.

Estimated relative gas diffusivity (D/D_0) was influenced by tillage treatment only on topsoil. Grable and Siemer (1968) and Pulido-Moncada and Munkholm (2019) reported that D/D_0<0.005 can limit the

Table 3
Mean values of total organic carbon (TOC), soil bulk density (ρ_s), macropores (Mac), micropores (Mic), total porosity (TP), relative gas diffusivity (D/D_0), pore tortuosity (τ), relative field capacity (RFC), and structural stability index (SSI) in the Rhodic Ferralsol at the study site under conventional tillage (CT), strategic tillage (ST), and no-tillage (NT).

Tillage system	TOC g dm^{-3}	ρ_s g cm^{-3}	Mac m^3 m^{-3}	Mic	TP	D/D_0 –	τ –	RFC –	SSI %
0–0.15 m									
CT	32.41	1.26	0.10b	0.45a	0.54	0.002b	1.63	0.79	8.94
ST	31.73	1.25	0.11b	0.45a	0.56	0.003b	1.64	0.86	8.97
NT	31.95	1.22	0.15a	0.42b	0.56	0.007a	1.62	0.72	8.89
F	0.02^{ns}	1.94^{ns}	6.39*	4.48*	1.18^{ns}	7.50*	0.97^{ns}	1.94^{ns}	0.30^{ns}
CV (%)	16.90	8.25	44.46	10.44	8.67	119.76	3.97	21.71	12.42
0.15–0.30 m									
CT	26.08	1.24b	0.12	0.40	0.53a	0.006	1.66b	0.76	6.89
ST	24.68	1.31a	0.11	0.39	0.50b	0.007	1.71a	0.76	6.83
NT	21.13	1.20b	0.12	0.43	0.55a	0.005	1.63b	0.72	5.68
F	1.74^{ns}	3.97*	1.19^{ns}	2.00^{ns}	5.16*	2.19^{ns}	2.23^{ns}	0.55^{ns}	0.86^{ns}
CV (%)	19.78	7.09	36.90	17.82	9.66	148.87	5.49	9.79	17.00

Means within columns followed by different letters are significantly different (Tukey test, $p < 0.05$). F = significance. CV = coefficient of variation.

development of maize roots. The estimated average D/D_0 values in CT and ST were lower than this limit value at 0–0.15 m soil layer, and NT kept adequate values in both layers (Table 3).

Tillage operations can destroy pore continuity, so pore tortuosity (τ) can be used as an indicator of detrimental impacts on soil functionality: the higher the τ, the lower the gas and water fluxes. Galdos et al. (2019) verified that higher τ leads to greater pore discontinuity, which reduces gas and water flow in the soil. A significant difference was only detected for the 0.15–0.30 m depth layer, for which ST had higher τ than NT and CT (Table 3). On the other hand, the similarity in τ in the 0–0.15 m layer between tillage methods may be due to biopores remaining functional after crop harvest, at the time sampling was performed. Biopores provide greater pore connectivity and continuity under NT, while the soil disturbance in CT and ST breaks the soil structure and pore network, decreasing pore connectivity, which may hamper root growth at deeper layers. In the present study, structure break-up in ST occurs only occasionally, but our results suggest that pore continuity had not been restored three years after soil disturbance. Moreover, CT with yearly disturbance can provide greater homogeneity of soil structure leading to similar τ mean values in this layer. Thus, periodic chiseling every three years in ST can be detrimental to soil physical quality, since the soil pore system takes longer to recover. It is worth mentioning that even with their similar porosity, the tillage systems provided different pore continuity verified by D/D_0 and τ, at different layers, which can affect water infiltration, gases fluxes, and root growth.

The treatments did not provide significant differences in relative field capacity, with all RFC values above the critical threshold of 0.70 at which aeration in the rhizosphere is reduced (Reynolds et al., 2009). Recently, Weninger et al. (2019) reported that RFC values of 0.724–0.900 hamper aeration of the root system of agricultural crops and affect crop yield. This RFC range was exceeded in all systems, except in NT. The favorable conditions in NT may be due to the highest macroporosity in the 0–0.15 m layer, and the lowest τ and highest TP associated with the lowest mean ρ_s (or mechanical impedance) in the 0.15–0.30 m layer. According to Reynolds et al. (2009), the essential premise of this criterion ($0.60 \leq RFC \leq 0.70$) is that rain-fed mineral soils have desirable water and air contents, for maximum microbial production of crop-essential nitrate.

Structural stability index was not significantly different between treatments. The SSI values were >7% in the 0.0–0.15 m layer, indicating a low risk of structural degradation (Reynolds et al., 2009) favored by the high TOC in this layer in all tillage treatments. The SSI values for the 0.15–0.30 m layer (>7%) suggest a low risk of structural degradation, which is especially worrying in both CT and ST, due to the mechanical soil disturbance of this layer.

Soil compaction at the 0.15–0.30 m layer is recurrent in chiseled systems (Nunes et al., 2015; Dang et al., 2018; Santos et al., 2019), due to working depth of the chisel generally being deeper than that of harrow and plow tools (Nunes et al., 2015). The chisel breaks the soil structure, cracking soil but not completing disturbing it in CT. Thus, the soil under chiseling can become more compressible than the soil under no-tillage, which favors compaction when the soil is trafficked under favorable soil moisture levels such as near field capacity. Additionally, aggregate compression by the chisel results in lower total porosity, thus increasing ρ_s, as seen for the 0.15–0.30 m layer in ST. Spoor et al. (2003) claims that if the soil is trafficked just after chiseling, the pressure applied can be transmitted to the deeper layers, as verified by Tormena et al. (1998) in our study area. Those authors suggest that topsoil firmness can protect deeper layers, as stronger layers can play an important role in absorbing compaction stresses.

The SWRC and SPRC adjusted parameters are presented in Table 4. Regardless of soil tillage system, the adjusted parameters were significant since the confidence interval did not include zero (Glantz and Slinker, 1990).

The penetration resistance (PR) of soil was positively influenced by ρ_s and negatively by θ, as widely reported in studies worldwide. The

Table 4
Equations obtained for soil water retention curve (SWRC) and soil resistance to root penetration curve (SPRC) in two soil layers under conventional tillage (CT), strategic tillage (ST), and no-tillage (NT).

	0–0.15m	0.15–0.30m
SWRC		
CT	$\theta = 0.099\ (0.547–0.099)/[(1+(0.021\ \psi)^{1.432}]^{0.301}$ $R^2 = 0.99$ F = 4212***	$\theta = 0.100\ (0.529–0.100)/[(1+(0.047\ \psi)^{1.354}]^{0.262}$ $R^2 = 0.99$ F = 4804***
ST	$\theta = 0.153\ (0.555–0.153)/[(1+(0.021\ \psi)^{1.407}]^{0.289}$ $R^2 = 0.99$ F = 4629***	$\theta = 0.146\ (0.506–0.146)/[(1+(0.039\ \psi)^{1.380}]^{0.275}$ $R^2 = 0.99$ F = 2314***
NT	$\theta = 0.087\ (0.565–0.087)/[(1+(0.047\ \psi)^{1.383}]^{0.277}$ $R^2 = 0.99$ F = 3204***	$\theta = 0.145\ (0.550–0.145)/[(1+(0.035\ \psi)^{1.378}]^{0.274}$ $R^2 = 0.99$ F = 6558***
SPRC		
CT	$RP = 0.026\ \rho_s^{6.059}\ \theta^{-2.319}$ $R^2 = 0.78$ F = 59.16***	$RP = 0.062\ \rho_s^{6.14}\ \theta^{-1.406}$ $R^2 = 0.57$ F = 21.63***
ST	$RP = 0.035\ \rho_s^{7.180}\ \theta^{-2.060}$ $R^2 = 0.82$ F = 78.6***	$RP = 0.055\ \rho_s^{3.956}\ \theta^{-2.213}$ $R^2 = 0.83$ F = 78.6***
NT	$RP = 0.066\ \rho_s^{5.989}\ \theta^{-1.613}$ $R^2 = 0.82$ F = 73.6***	$RP = 0.071\ \rho_s^{2.712}\ \theta^{-2.253}$ $R^2 = 0.79$ F = 62.1***

θ = volumetric water content (m^3 m^{-3}); ρ_s = soil bulk density (g cm^{-3}); ψ = soil water matric potential (hPa). F = significance of the model, *** = significance ($P < 0.001$). R^2 = determination coefficient, R^2 = [1-(Sum Square Residue/Sum Square Model)].

greater influence of ρ_s on SPRC is associated with the change in the soil structure under intense tillage or machinery traffic, which increases the contact of clay-clay particles, favoring soil cohesion and compaction (Medeiros et al., 2011). Our results suggest that less soil disturbance can enhance the effect of ρ_s on PR in the topsoil due to more compact soil packing caused by machinery traffic; however, its effects are decreased in underlying layers. Moreover, the yearly soil disturbance in CT provided similar effects in both layers, mainly because plow working depth breaks soil structure. Another finding is that soil water content has less influence on PR at topsoil for NT and at 0.15–0.30 m layer for CT, suggesting that even under wetter soil conditions, high ρ_s, as observed in CT and ST, can offer some mechanical restrictions to plant roots by PR, affecting soil physical functionality.

The higher PR in the 0–0.15 m layer (Fig. 2) in NT can be attributed to age-hardening of soil aggregates (Medeiros et al., 2011; de Moraes et al., 2017). This occurs due to the conditions favorable for cohesion of soil particles under NT, such as root action and non-disturbance of the soil. de Moraes et al. (2017) found that, under the same conditions of θ and ρ_s in Ferralsols, NT provides higher PR than CT since soil hardening due to aging favors connection of particles and consequently increased PR. Those authors concluded that the particular soil physical conditions in each tillage system mean that critical limits for PR should be set according to the management or tillage system used. For the 0.15–0.30 m layer, the higher PR, almost all range of ρ_s for ST, may be linked to structural changes due to stress from machine traffic on soil, contributing to particles closer together, causing soil compaction and a higher ρ_s (Table 3). The NT system kept PR lower and more stable with increasing ρ_s in the 0.15–0.30 m layer, with resistant to structural damage induced by traffic and alleviating mechanical resistance to roots. This was attributable to the presence of channels (biopores) formed by roots and edaphic fauna at the surface contributing to deeper growth and development of roots without mechanical impedance, as corroborated by the high Mac and D/D_0 values.

The results depicted in Fig. 3 indicate the soil water content at the limiting values for FC, PWP, PR, and AFP. The upper limit of LLWR was mostly defined by water content at field capacity (θ_{FC}), indicating that long-term tillage did not compromise soil air-filled porosity, as also evidenced by the Mac values (Table 3). However, higher values of θ_{FC} in the 0–0.15 m layer in ST, compared with other tillage systems, allowed the water content that maintained adequate aeration (θ_{AIR}) to become the upper limit of LLWR for ρ_s greater than 1.28 g cm^{-3}, which reflects potential limitations for soil aeration at field capacity up to this ρ_s. The lower limit of LLWR for both layers and all tillage practices was defined by the water content where PR was limiting (θ_{PR}). This may cause root growth limitation (Gonçalves et al., 2014), especially in drier periods. Knowledge about the regional influence of soil management/tillage system and of crops is essential to define the most appropriate limiting PR value (Leão et al., 2006; Moraes et al., 2014). Using the same PR values for soils or management situations that provide different conditions may lead to misinterpretations about soil physical quality, since soil mechanical behavior may be different under different soil tillage systems.

The most widely limiting value in the literature is PR =2.0 MPa (da Silva et al., 1994; Tormena et al., 1998; Asgarzadeh et al., 2011). However, in no-tillage systems, a biopore network is formed and preserved in the absence of tillage, favoring water flow and leaving channels with reduced soil resistance to root growth (Meek et al., 1990), even under high ρ_s conditions (Cavalieri et al., 2009; Medeiros et al., 2011; Moraes et al., 2014). These biopores provide low-resistance paths allowing roots to grow and develop, even within a soil matrix with high penetration resistance. Thus, Moraes et al. (2014) recommend PR =3.5 MPa as limiting for root development in no-tillage and PR =2.0 MPa for conventional tillage, but also suggest if the soil is closer to the structural conditions of no-tillage, the limiting PR is 3.0 MPa. Another issue to be considered when considering critical PR values is the crop and its root system. According to Leão et al. (2006), the limiting PR value can be higher for grasses, because the plants have an abundant and aggressive root system and grow satisfactorily under high PR conditions. For crops with pivoting root systems, such as soybean, the critical value of PR should be lower than that for grasses (Girardello et al., 2014). The limiting PR value may also be higher for a diverse crop rotation, with different root systems growing over time in summer and winter seasons, where plant roots can grow and develop more easily than under monocropping.

The water content of LLWR in the ρ_s range (hatched area in Fig. 3) was lower than available water ($AW=\theta_{FC}-\theta_{PWP}$) due to the suppressing effect of PR. In the CT, ST, and NT system, 8.5, 2.7, and 2.7 % of ρ_s values, respectively, exceeded the critical soil bulk density ($\rho_{reference}$) in the 0–0.15 m layer. Medeiros et al. (2011) took 2.0 MPa as the limiting PR and observed that $\rho_{reference}$ in a Rhodic Ferralsol was 1.10 g cm^{-3} in both no-tillage and conventional tillage systems, but with better structural conditions under no-tillage. The highest $\rho_{reference}$ in NT indicates that soil physical quality is degraded only when ρ_s >1.42 g cm^{-3}, and only one such ρ_s value was observed in the NT system. This suggests that long-term NT did not impair soil physical quality in topsoil. There were greater physical constraints in CT and ST, with their higher ρ_s values. In addition, even with similar frequency of $\rho_s>\rho_{reference}$ to NT, the LLWR for ST indicated that soil structural conditions were dependent on regular rainfall distribution during the cropping cycle to maintain soil moisture at levels favorable for growth and crop development. In the 0.15–0.30 m layer, CT had the largest range of ρ_s, providing null LLWR above 1.33 g cm^{-3}while, for ST and NT, ρ_s values above $\rho_{reference}$ were not detected.

The LLWR results indicated that CT gave the lowest soil physical quality. This is linked to the working depth of agricultural implements, which favors soil compaction and decreases physical quality in the underlying layers (Taboada et al., 1998). The CT soil had similar soil bulk

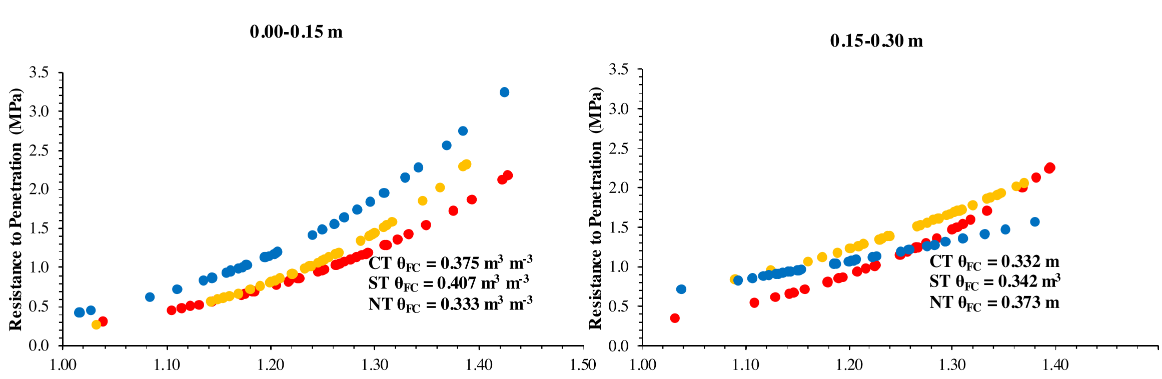

Fig. 2. Resistance to penetration at water content close to field capacity (θ_{FC}, $\psi = -100$ hPa) as a function of soil bulk density (ρ_s) measured in (left) the 0–0.15 layer and (right) the 0.15–0.30 layer under conventional tillage (CT), strategic tillage (ST), and no-tillage (NT).

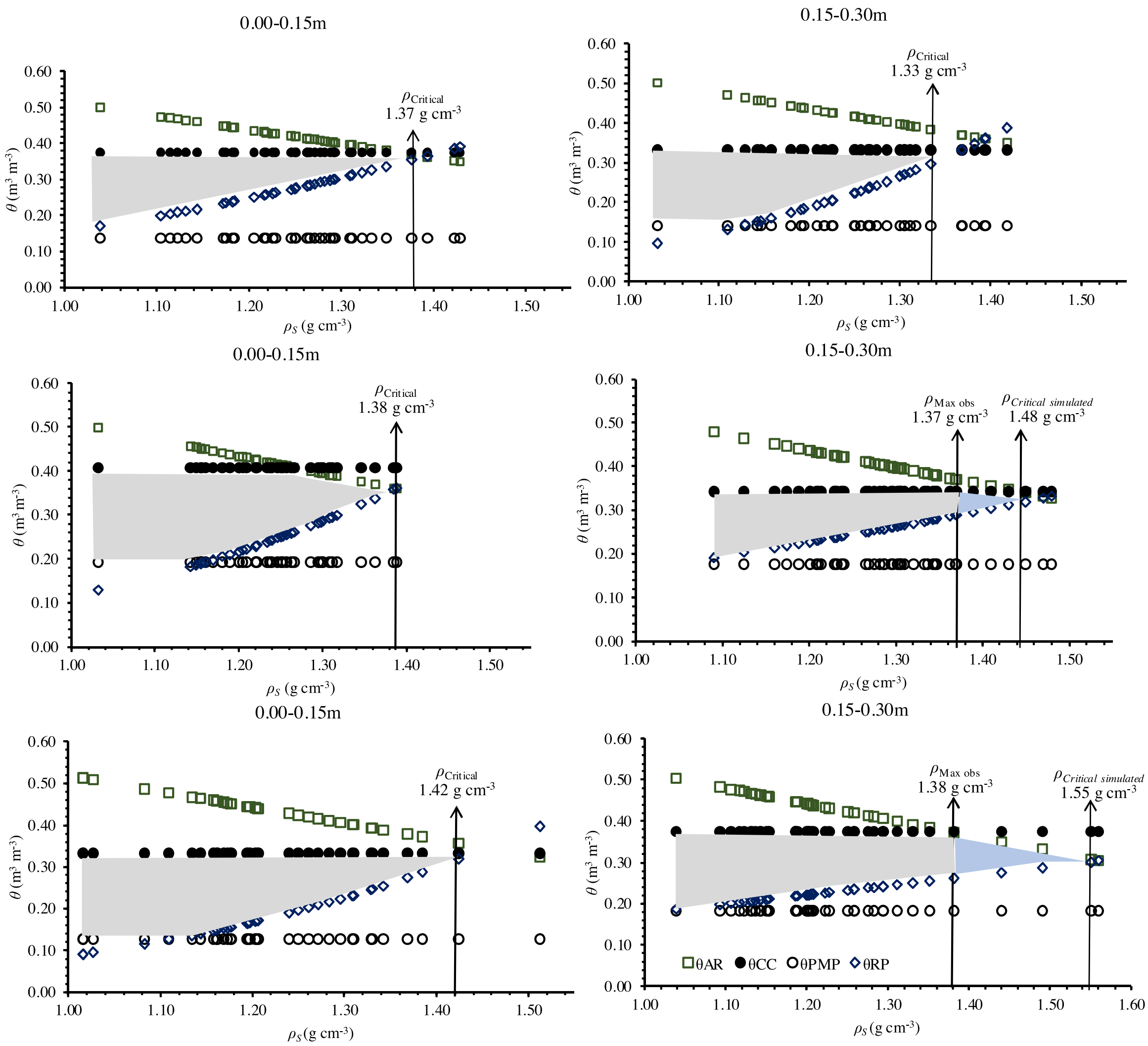

Fig. 3. Graphical representation of the least limiting water range (LLWR) in (left) the 0–0.15 layer and (right) the 0.15–0.30 layer under (A & B) conventional tillage (CT), (C & D) strategic tillage (one chiseling every three years) (ST), and (E & F) no-tillage (NT).

density in both layers studied, but its influence on PR was greater in the 0.15–0.30 m layer (Fig. 2), which can affect root development and crop yield. The CT soil had a higher frequency of ρ_s values above $\rho_{reference}$, indicating soil physical degradation after 25 years of the long-term experiment. Use of LLWR to monitor soil physical quality based on ρ_s was effective in diagnosing negative effects of soil physical quality on crop yield. For treatments in which no $\rho_{reference}$ was found, higher ρ_s values were simulated from the highest value measured until LLWR became zero.

The tillage treatments affected DC in both layers. In the 0–0.15 m layer, the highest average DC was found in CT (91 %), followed by ST (90 %) and NT (86 %). In the 0.15–0.30 m layer, the average DC values were 94 %, 85 %, and 78 % for CT, ST, and NT, respectively. DC values <70 % indicate very loose soil, which impedes soil-seed contact and water retention, probably reducing crop yield (Asgarzadeh et al., 2011). Suzuki et al. (2007) concluded that DC < 86 % is adequate for soybean grown on Ferralsols, but that DC > 91 % impairs soybean and bean (*Phaseolus vulgaris*) yield, due to reduced aeration (macroporosity) and hydraulic conductivity and increased PR. In our study, only NT provided favorable conditions for crops and CT provided the worst conditions in both soil layers. These results suggest that under NT combined with a diverse crop rotation, compaction does not impair soil physical quality.

The average soybean yield taken in this study was 3923, 4016, and 4304 kg ha^{-1}, respectively, for CT, ST, and NT. These mean values were not statistically significant, but NT had 381 kg ha^{-1} more grain yield than CT. For maize, the average yield was 10,815, 11,639, and 12,026 kg ha^{-1}, respectively, for CT, ST, and NT; maize yield in NT was significantly higher than in CT. Santos et al. (2019) suggest that soybean growth is less sensitive to tillage practices, as found on our study. According to Girardello et al. (2014) soybean yield may be more sensitive to weather changes than soil physical changes. In our study, rainfall during the season was higher (Fig. 1) than that required by soybean (530–800 mm cycle^{-1}; Ochsner et al., 2018), which under lower D/D_0 could have negatively affected the gases flux, and cause yield losses in CT and ST. The soybean obtained higher yield (experimental average 4081 kg ha^{-1}) than observed by Girardello et al. (2014) in similar soil under no-tillage (3699 kg ha^{-1}) and chiseling (3790 kg ha^{-1}), and by Santos et al. (2019) under no-tillage (3235 kg ha^{-1}) and chiseling (2751 kg ha^{-1}). The latter concluded that chiseling every three years does not increase soybean yield, corroborating our results.

For maize, NT produced about 1200 kg ha^{-1} more than CT, while ST produced 825 kg ha^{-1} more than CT and 387 kg ha^{-1} less than NT. Precipitation during the season supplied the water requirement of maize (350–550 mm cycle^{-1}; Ochsner et al., 2018); thus, the observed differences were caused by the tillage systems. Maize growth is sensitive to changes in soil physical quality (Girardello et al., 2014), with intense plow-based tillage reducing maize yield by 8–21 % (Wasaya et al., 2017). Our results indicated losses of maize yield in CT of around 10 and

8% compared with NT and ST, respectively. A significant relationship was found between soil physical attributes and crop yield (Fig. 4).

The significant relationship between DC and RFC shows that increasing soil compaction impaired soil D/D_0, which can compromise crop yield, under wet seasons. With values of DC > 86 % and 0.6 ≤ RFC≤0.7, CT and ST impaired aeration and compaction, restricting root development. The greater DC negatively affected Mac, due to the closer arrangement of soil particles promoted by soil compression from agricultural machinery. The recurring soil disturbance in CT provided an ephemeral increase in Mac, without persistent effects on soil physical quality beyond one cropping season. The DC determined using $\rho_{reference}$ detected the long-term effect of tillage system on yield, with 8.5 % of ρ_s values in CT presenting null LLWR. Although the negative correlation with yield was significant only for maize, soybean yield losses at DC > 86 % also occurred, especially in CT. The linear reduction in maize yield from DC > 78 % corroborates findings by Suzuki et al. (2007).

Pore tortuosity negatively affected soybean and maize yield, although not significantly for maize. The lower pore connectivity in ST and CT suggests the lack of pre-formed channels for root growth (Galdos et al., 2019), requiring root to break barriers to grow. Soybean is sensitive to increased PR (Leão et al., 2006), and higher τ means greater mechanical impedance, mainly in the 0.15–0.30 m layer, corroborating the PR data obtained (Fig. 2). For maize, the higher τ values were not sufficient to affect maize yield significantly, probably due to its vast root system that can exploit a large volume of soil.

Since the long-term trial was established, there has been no water deficit, especially in the period 2004–2014. Thus, under adequate rainfall distribution and crop nutrition, the deleterious effects of soil physical degradation do not always translate into significant depletion of crop yield. Under NT, soils with good fertility and a diverse crop rotation have greater soil biological activity, which improves soil physical quality. In this study, long-term no-tillage maintained healthy soil, providing high crop yields.

4. Conclusions

The soil physical properties measured in this study indicate that soil physical quality was better under NT than ST and CT, refuting the hypothesis that in the long term strategic tillage every three years in Rhodic Ferralsol provides better soil physical quality and crop yield. All three soil tillage systems, which had been running for 25 years, did not promote significant changes in most soil physical quality indicators.

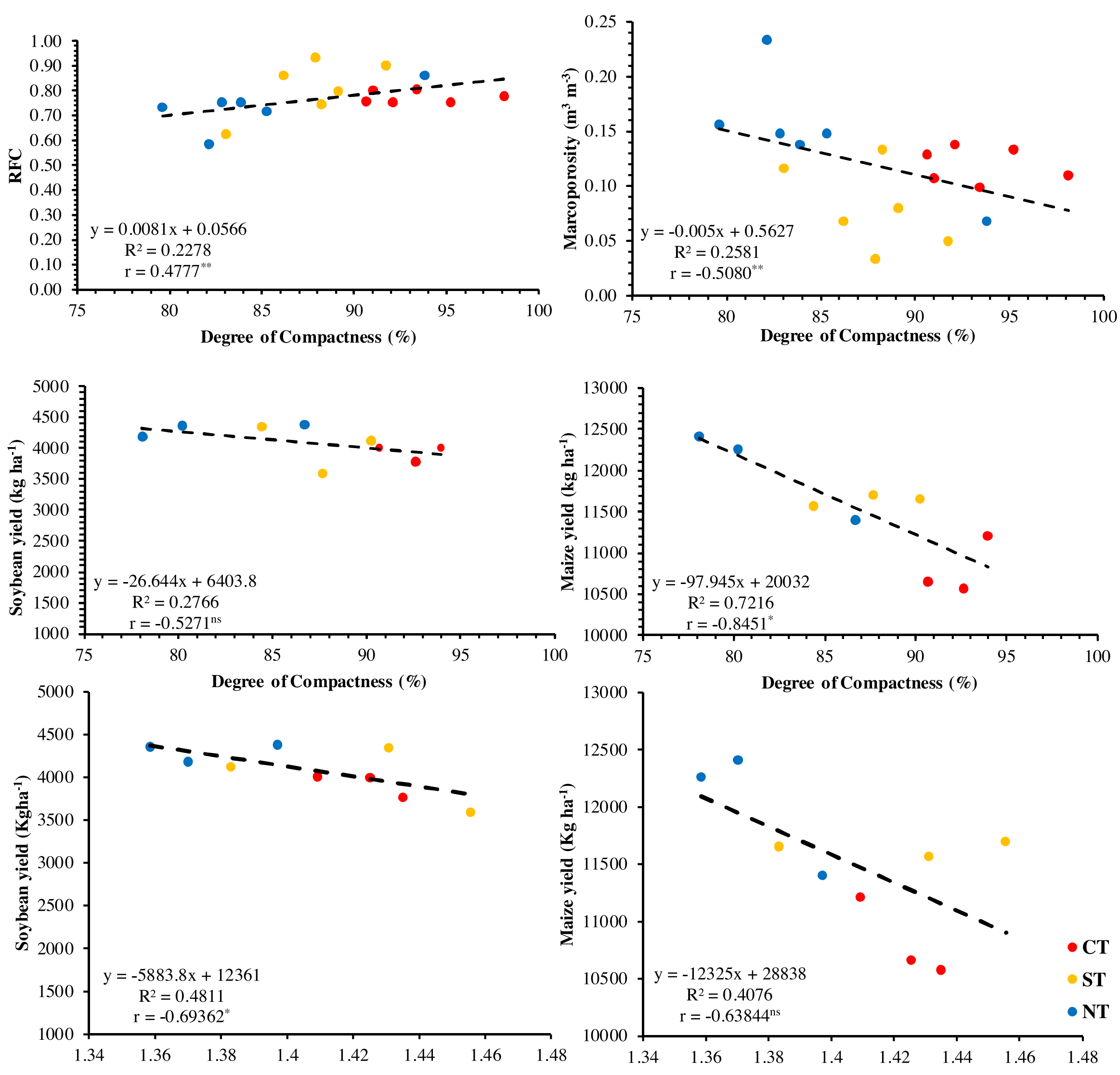

Fig. 4. Relationship between degree of compactness (DC) and: a) relative field capacity (RFC), b) macroporosity, c) soybean yield, and d) maize yield; and relationship between pore tortuosity (τ) and yield of e) soybean and f) maize in a Rhodic Ferralsol under conventional tillage (CT), strategic tillage (ST), and no-tillage (NT). *P < 0.05; **P < 0.01; ns = not significant by the F test. R^2 = coefficient of determination. r = Pearson correlation coefficient.

However, significant effects on soil aeration on topsoil and soil bulk density at subjacent layer were verified, with inadequate values for ST and CT for both macroporosity and gas diffusivity as well as for RFC, although the latter was not significant. Moreover, CT presented 8.5 % of $\rho_s > \rho_{reference}$, providing DC of 91 and 94 %, respectively, for 0–0.15 and 0.15–0.30 m layers, considered harmful for yield of soybean and maize crops. Soybean yield was significantly reduced with increasing pore tortuosity and, maize yield decreased linearly with degree of compaction, with crop yield losses of ~13 % at DC > 94 %. These physical attributes were sensitive indicators of negative impacts of long-term CT and ST on crop yield, even under favorable weather conditions.

Soil chiseling every three years under no-tillage (ST) did not improve soil physical quality, but instead had detrimental effects on crop yield compared to NT. Our results strongly suggest that ST does not improve physical properties of soils under NT with crop rotation. In addition, NT carried out under a diversified crop rotation did not have its physical quality limited by soil compaction, indicating that long-term, under the studied conditions, NT maintained healthier soil than CT and ST, providing high crop yields.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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