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Structural change in an oxisol under dynamic loads and different tillage systems

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Abstract

This study aimed to analyse the structural changes of an oxisol under different loads using no-tillage (NT) and conventional till (CT) conditions. Experiments were conducted using a randomised design with a 2 x 5 factorial scheme, areas of oxisol under no tillage and conventional tillage and five loads (0, 50, 100, 150, and 200 kg), with 4 repetitions, totally 40 experimental units. Loads were applied by a traffic simulator to determine the surface tamping and the variables (cohesive intercept and friction angle), which obtained through shear-force equipment. The tillage systems and loads of traffic influenced the soil structure based on the variables analyzed. The highest values for surface tamping and compaction degree were observed in no tillage condition, while cohesive intercept and friction angle were higher on conventional tillage. The use of the above-stated load, which the soil can support, causes structural rearrangement. After the structural rearrangement, the soil tends to return to its initial state. The variation in friction angle associated with different applied loads is less in soil under no-tillage conditions.

Keywords: shear force, friction angle, superficial settling, traffic simulator.
Abbreviations: NT_No Tillage, CT_Conventional till.

Introduction

The main tillage systems in Brazilian farming are conventional tillage (CT) and no-tillage (NT). From an agronomic point of view, NT is more conservationist in terms of reducing soil and water loss, improving soil structure, and maintaining productivity (Reichert et al., 2016).
Intensive mechanization of farmland has increased the size of agricultural machines, with a consequent increase in their weights. While some adjustments have been made to reduce soil impact, stress risks remain (Augustin et al., 2019). Agricultural traffic has been identified as one of the main sources of soil compaction in agriculture (Md-Tahir et al., 2019). Given the search for increased productivity and improvement in soil physical, chemical and biological properties, more studies are needed to evaluate different tillage systems.
Changes in soil structure are correlated to agricultural traffic, which causes surface tamping and increases the degree of compaction, thus hindering crop growth (De Marins et al., 2018). Significant effects have been found in clayey soils, with visual differences in crop growth after only one year of changes in traffic levels (Emmet-Booth et al., 2020).
Surface soil tamping can occur due to pore volume reduction caused by compaction from unsuitable machine traffic conditions. Such parameters can be used to evaluate soil structure behaviour up to 0.30 m in depth (Mion et al., 2016) and compaction effects as a function of applied load (Alcantara, 2017). Bulk density can be used as a physical measure to detect soil compaction and changes in its structure. Degree of compaction and relative density are also used as important physical indicators of plant growth restriction, regardless of the soil texture (Lima et al., 2017). Void index relates the volumes of empty spaces and solid particles in a soil. It is an indicator of soil porosity that directly influences its density. Heavy traffic causes diverse changes in soil structure, reducing voids, clogging pores, and decreasing water permeability through soil (Reichert et al., 2016). Furthermore, increased resistance due to compaction influences shear resistance of soils, which is directly related to soil support capacity (Silva et al., 2004; Marasca et al., 2011). Compacted soils are more resistant to shear due to closeness between particles, which reduces voids and increases soil bulk density (Bachamann et al., 2006).
Soil resistance to shear stress can be obtained by parameters such as c and Φ, which represent the cohesion intercept between particles and internal friction angle, respectively. These are characteristics intrinsic to soil type, and vary with other properties such as texture, structure, organic matter content and bulk density (Rocha et al., 2002; Braja Das, 2015).
In this study, we hypothesized that no-tillage would have better structural conditions to support dynamic loads than conventional tillage, where an increase in load would negatively influence the soil structure. In this context, the objectives were to evaluate the influence of dynamic load on structural changes in an oxisol under two tillage systems and to test different loads under laboratory conditions.

Results and Discussion

Results of statistical analysis

Surface tamping, cohesive intercept, and friction angle showed significant differences for each tillage isolated. In turn, the loads applied in traffic simulation had a significant effect on all parameters evaluated (Table 3). Interaction between both tillage systems and among the applied loads showed statistical differences for surface tamping, compaction degree, cohesive intercept, and friction angle.

Traffic effects on soil compaction

Regarding soil surface tamping, the results indicate a linear and significant increase for both tillage systems (Figure 1). This interaction is statistically represented by the regression with a linear behaviour. The mathematical model shows that 98% of the changes in soil tamping can be explained by the loading in traffic simulations.

In both areas (NT and CT), tamping increased as load was raised. The highest values of deformability were observed for the 200 kg load, with values of 6.18 mm for no-tillage and 3.98 mm for conventional tillage. NT area showed higher tamping values compared to CT. However, there was no statistical difference by the test of means for the 50 kg load. Both areas showed a strong correlation with an average R^2 of 98%.

Regression analysis pointed to a quadratic behaviour of soil compaction degree after traffic. The equation in Fig 2 demonstrates that about 83% of the variation in degree of compaction can be explained by increasing loads. The highest soil compaction degrees were 87.81% and 87.14% in NT at 150 kg load and in CT at a 100 kg load, respectively. At 200 kg, degrees were 80.96% and 80.71% in NT and CT, respectively. By test of means, only the 150 kg load showed significant difference for compaction degree between NT and CT. The NT area showed higher values for compaction degree compared to CT (Figure 2).

Cohesive intercept had a quadratic relationship with the load, with higher values at 150 kg of 6.74 kPa for NT and at 8.14 kPa for CT, respectively. Final values were 5.32 kPa in NT and 4.21 kPa in CT. By test of means, the lowest loads, 0, 50 and 100 kg, had no significant difference between tillage systems. Yet for NT, the highest value was reached by applying 150 kg. Statistically, for the mean test, the values for cohesive intercept were larger in the NT condition (Figure 3).

Internal friction angle after application of different loads showed quadratic behaviour by regression analyses in both tillage systems. CT showed higher angles at all loads. The highest values were 26.43° at 150 kg and 32.90° at 100 kg in NT and CT, respectively. The highest load promoted friction angles of 21.9° and 25.25° in NT and CT, respectively, with a variation of 13.27%. Generally, the CT condition had larger values for friction angle (Figure 4).

Dynamic traffic changed soil compaction, evidenced by increased tamping in the topsoil, increased compaction degree, and cohesive intercept and friction angle alterations. Some similar values in some loads can be explained by the history of NT in the area being considered initial (only 2 years).

Both tillage systems showed increasing deformation in the upper soil as loads were increased. Difference in tamping between the areas was from the 100 kg load on. The area under NT had higher deformability values. This can be justified because the NT area had higher initial values of void index and porosity than CT area, which allows a significant structural rearrangement when greater loads are applied onto the soil. Similar results were obtained by Alcântara (2017) and Mion et al. (2016).

In both systems, compaction degrees increased as loads increased in both systems. They tended to be smaller in NT area, which was already expected due to bulk density changes. These findings are in line with those in the literature (Couto et. al, 2013; Lima et. al, 2017).

The cohesion value changes in this study tended to decrease from a 150 kg load in traffic simulation. Organic matter content is expected to influence soil cohesion. However, while the organic matter was not measured, NT (only 2 years) had a small amount of coverage at Cerrado conditions. The lack of significant differences between the systems indicates that organic matter had no effect on cohesion in the direct shear test (Braida, 2004).

Friction angles were higher in the CT area. The comparison of means showed that all loads promoted significant differences between management systems. In both tillage systems, friction angle was increased with the load. The lower angles in the NT area can be explained by an enrichment of organic matter in the soil surface (Braida, 2004).

The increase in friction angle at the first loads demonstrates that soil interaction forces tended to be higher at these loads. Such general trend of increasing traction forces and vertical tension can be associated with greater areas of contact between tire and soil with increased load applied (Wang et al., 2019).

Soil structural rearrangement

The results on compaction degree, cohesive intercept, and friction angle show the trend of soil structure to rearrange in both tillage systems. The same behaviour was observed at 150 kg in NT and at 100 kg in CT.

The trend of soil particles to rearrange can be seen by the quadratic relationship with the loads. This, in turn, behaves differently at 150 kg in NT and 100 kg in CT. This demonstrates soil proneness to rearrange structurally after receiving an above-capacity load. Such load could break soil structure, promoting a residual state, which can be inferred to happen on the soil after the load of 150 kg and 100 kg for NT for CT, respectively. In the same tillage system, the return to the average between initial and final means demonstrates proneness of soils to return to its residual state after rupture. Soil structural changes at a load of 150 kg in NT and 100 kg in CT demonstrating that NT tends to support heavier loads, validating its structural improvement under this system.

Materials and Methods

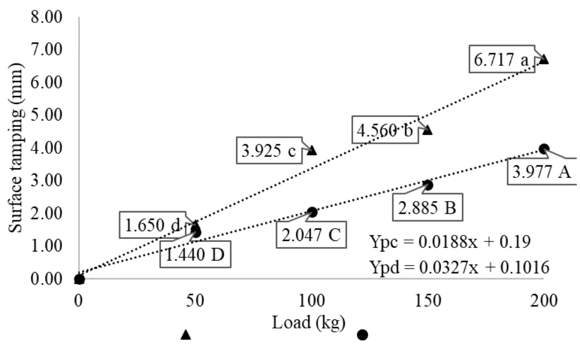
Area characterization

The study area was a Cerrado biome having Red Latosol soil type (EMBRAPA, 2006) or oxisol, located in the city of Anápolis-GO, Brazil, at the geographical coordinates of 16° 15' S and 49° 01' W, with an average altitude of 980 m. Annual means of rainfall and temperature were 1,400 mm and 24 ºC, respectively. In the present study, the area was divided the soil areas into tillage systems: no-tillage (NT) and conventional tillage (CT). Data were collected in the crop year of 2018/2019. Table 1 shows the summary of soil physical properties.

The NT area was cultivated with pasture until the 2014/2015 crop year. Thereafter, corn for silage was grown under

Table 1. Physical and mechanical characterization of oxisol under no-tillage (NT) and conventional tillage (CT).

Analysed properties	Values	
	NT	CT
Texture Analysis		
Sand content	160 ± 22 g kg^{-1}	240 ± 21 g kg^{-1}
Silt content	380 ± 31 g kg^{-1}	400 ± 29 g kg^{-1}
Clay content	460 ± 38g kg^{-1}	360 ± 33 g kg^{-1}
Physical indexes		
Water content(w)	27.72 ± 1.48 %	24.66 ± 1.09 %
Natural specific weight (δ)	2.72 ± 0.12 g/cm³	2.69 ± 0.05 g/cm³
Dry density (ρ)	1.08 ± 0.05 g/cm³	1.10 ± 0.03 g/cm³
Total porosity (η)	60.29 ± 0.39 %	58.45 ± 0.39 %
Consistency Limits		
Liquid Limit (LL)	44.83 ± 1.39 %	43.92 ± 1.12 %
Plasticity Limit (PL)	36.69 ± 2.36 %	34.32 ± 2.97 %
Contraction limit (CL)	26.64 ± 1.88 %	24.97 ± 1.72 %
Mechanical properties	1.37 ± 0.16 g/cm³	1.38 ± 0.16 g/cm³
Optimum water content (wot)	31.00 ± 1.84 %	31.8 ± 1.54 %
Compaction Degree (CD)	79.37 ± 0.8%	80.07 ± 0.8%



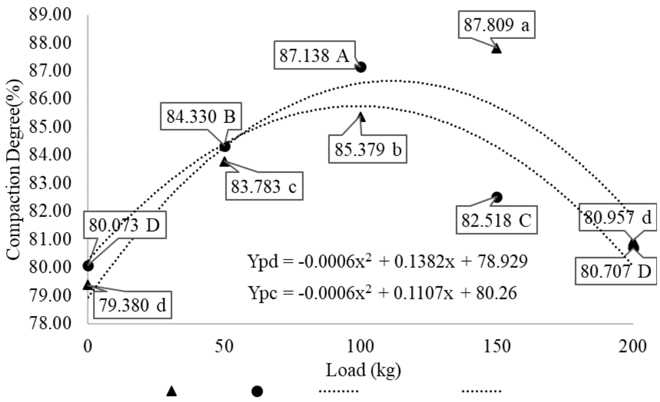
NT CT

Fig 1. Effect of different traffic loads applied by the simulator on soil surface tamping in the areas with no-tillage (NT) and conventional tillage (CT) systems. Deformation means followed by the same lowercase letter for NT and uppercase letters for CT do not differ according to Tukey's test ($p > 0.05$).

Table 2. Contact area (cm²) and average contact pressure (kPa) of the areas in each load.

Load (kgf)	Contact area (cm²)		Average contact pressure (kPa)	
50	21.875	d	215.018	d
100	26.604	c	381.563	c
150	28.243	b	512.988	b
200	30.062	a	689.973	a

* Means followed by the same letter in the row do not differ from each other by the Tukey's test ($p > 0.05$)



NT CT

Fig 2. Effect of different traffic loads applied by the simulator on compaction degree in soils of areas under no-tillage (NT) and conventional tillage (CT) systems. Means followed by the same lowercase letter for NT and uppercase for CT do not differ from each other by the Tukey's test ($p > 0.05$).

Table 3. Summary of analysis of variance of soil surface tamping (ST), compaction degree (CD), cohesive intercept (CI), and friction angle (Φ).

FV	GL	ST	CD	CI	Φ
Area	1	16.913*	1.939	13.769*	400.056*
Load	4	33.517*	61.955*	10.170*	65.602*
Area*Load	4	2.712*	15.665*	5.649*	18.102*
Residue	30	0.222	2.205	0.238	0.756
Total	39				
CV (%)		17.32	1.78	7.92	3.36
Average		2.72	83.223	6.165	25.842
*Significant at 5% probability by the test F					
CV: coefficient of variation (%)					
GL: Degrees of freedom					

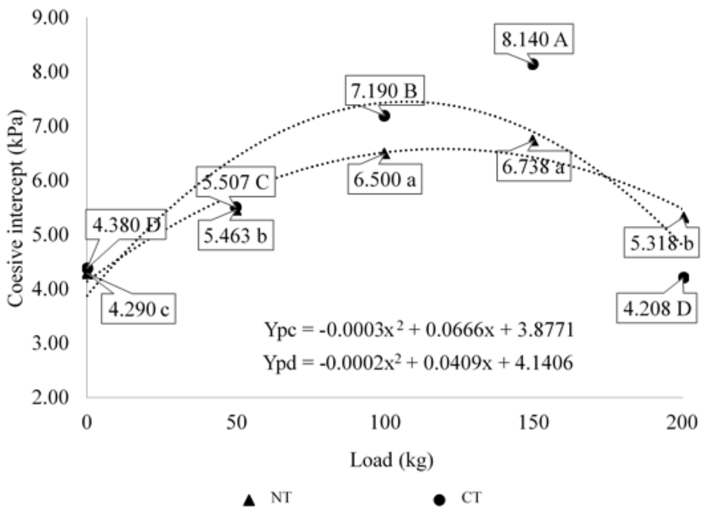
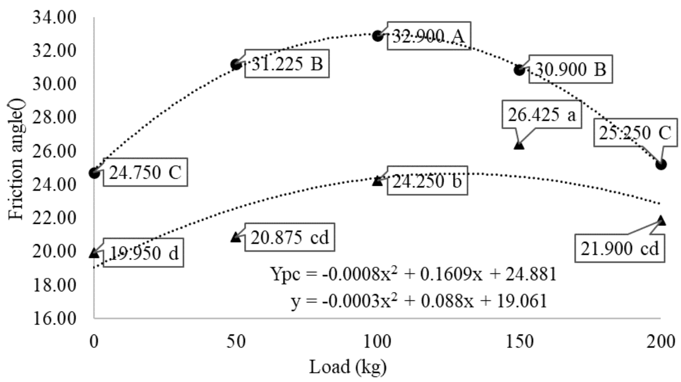


Fig 3. Effect of different traffic loads applied by the simulator on cohesive intercept for areas under no-tillage (NT) and conventional tillage (CT) systems. Means followed by the same lowercase letter for NT and uppercase for CT do not differ according to Tukey's test (p > 0.05).



NT CT

Fig 4. Effect of different traffic loads applied by the simulator on soil friction angle for areas under no-tillage (NT) and conventional tillage (CT) systems. Means followed by the same lowercase letter for NT and uppercase for CT do not differ according to Tukey's test (p > 0.05).

conventional preparation in the first year and NT from the following year onwards. A conventional planting area was grown with pasture until the 2015/2016 crop year. Afterwards, corn for silage was cropped under conventional preparation until data collection. The areas were homogeneous and had 0.25 hectares (50 x 50 m) for each planting system. From these, undisturbed soil samples were collected. The collections were made along the dry branch of the soil compaction curve, with moistures of 27.72% and 24.66% for NT and CT, respectively.

Sampling of undisturbed soil

Undisturbed samples for laboratory tests were removed from the depth of 0.00-0.20 m, with the dimensions 0.20 x 0.20 x 0.40 m (height, width, and length). Twenty samples were taken in the NT area and 20 in the CT one.

Samples were collected according to the NBR 9604 standard (ABNT, 1986b) and stored in a humid chamber, at the Laboratory of Soil Mechanics, State University of Goiás, to maintain their field humidity conditions until testing.

Linear traffic simulator test

A linear traffic simulator was used to evaluate traffic effects on soil physical and mechanical properties under laboratory conditions. The use of the simulator to reproduce field conditions in the laboratory was validated technically by Couto et al. (2013).

Load applied on soil samples from NT and CT areas consisted of four passes of the simulator tire, based on a study by Silva et al. (2011), Couto et al. (2013) and Md-Tahir et al. (2019). Tire inflation pressure was 96.5 kPa, and was constant for all treatments, according to Couto et al. (2013).

Vertical load application on the soil surface was done using a hydraulic jack. The applied load was monitored by a load cell positioned between the simulator support plate and hydraulic jack. The loading was applied until the soil samples were subjected to values of: 0 kg (control), 50 kg, 100 kg, 150 kg, and 200 kg. These loads were based on Couto et al. (2013) which used the load of 58.04 kg. This inflation pressure was used to approach the field conditions obtained with the tractor. Considering the load variations that can be used in the field, the proportional increase in the load was adopted from the control sample. The control sample had no traffic simulation, referring to the field condition. Contact pressures applied to the soil were calculated using the following equation:

$$Pm = \frac{W}{S}$$

Where:

Pm is the average pressure applied to the soil by the wheelset (kPa); W is the load supported by the wheelset (kgf); and S is the wheelset contact area (cm^2).

Tire and soil contact area was measured by recording the undisturbed sample block surface through a camera adjusted to the proportional scale and calculating the areas using the AutoCAD program, according to Mazetto et al. (2004), adapted. Table 2 shows the results for contact area and average contact pressure for each load.

Direct shear test

Samples for direct shear testing were taken from the soil blocks used in traffic simulator. Three undisturbed samples were taken from each block, totalling 60 samples for NT and 60 for CT. Samples were moulded directly using a pattern (0.06 x 0.06 x 0.02 m) and placed, with the aid of a stamp, into a two-part direct shear machine (Sheartronic).

Shear testing was performed according to the American standard ASTM D3080, applying static pressures of 25, 50, and 100 kPa. Loads lasted 30 minutes, horizontal displacement speed was 0.10 mm min-1 as in Bishop and Henkel (1962), was a maximum horizontal displacement of 10 mm.

Analysed parameters

Soil surface tamping

Machinery traffic effect on tamping of soil surface was evaluated by the photographic reading method, as described by Bueno (1987) and used by Taghavifar and Mardani (2012), Couto et. al (2013), Feitosa (2015), and Alcântara (2017).

Compaction degree and bulk density

Deformed soil samples were taken from all areas to determine soil maximum density (ρd max) using Proctor's model, performed according to the standards of ABNT (1986). Degree of compaction was calculated according to the following equation:

$$CD = \frac{\rho d\ field}{\rho d\ reference}\ 100$$

Where:

CD is the soil compaction degree (%);

ρd field is the dry density obtained in the field; and *ρd reference* is the maximum dry apparent density obtained in laboratory (Normal Proctor Test).

The *ρd field* was obtained in each undisturbed sample block after traffic simulation. The sample was moved from the soil to the direct shear mould, which had a known volume and weight, thus permitting calculation of sample density.

Cohesive intercept and friction angle

Cohesive intercept and friction angle were obtained by direct shear testing. The shear stresses applied to the soil along the vertical displacement, for each normal stress (25, 50 and 100kPa), were recorded in an Excel spreadsheet. A graph was plotted for shear stress envelope and normal stress up to a displacement of 10 mm (100%).

Using the shear stress envelope graph, a trend line was added to provide the linear equation that represents the line. Using the equation values, it was possible to obtain the cohesive intercept and calculate the friction angle using the arctangent of the portion a of the equation, multiplied by 180 and divided by pi to obtain a value in degrees.

Statistical analysis

Laboratory experiments were conducted under a randomized design and arranged in a 2 x 5 factorial scheme, consisting of 10 treatments with four repetitions each, totalling 40 plots. These consisted of two experimental areas (NT and CT) and five applied loads: 0 (control), 50, 100, 150, and 200 kg.

A bidirectional analysis of variance (ANOVA) was used to test differences among treatments, at a 95% confidence interval.

Conclusions

Both the tillage systems and the loads of traffic influenced the soil structure. The highest values for surface tamping and compaction degree was observed on no tillage. Cohesive intercept and friction angle were higher on conventional tillage. The use of the loads noted above, which the soil can support, causes statistically significant structural rearrangement; after the structural rearrangement the soil tends to return to initial state. The variation in friction angle associated with different applied loads is less in soil under no-tillage conditions.

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