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CIÊNCIA e NATURA

ISSN 2179-460X
Acesso aberto

Ci. e Nat., Santa Maria, v. 43, e87, 2021 • https://doi.org/10.5902/2179460X62685
Submitted: 06/11/2020 • Approved: 14/09/2021 • Published: 31/12/ 2021

Geo-Sciences

Soil degradation after the traffic of a military combat vehicle leopard 1A5BR

Degradação do solo após o trânsito de um veículo de combate militar leopardo 1A5BR

Müller, Cândida Regina[I], Pedron, Fabrício de Araújo[I], Barbosa, Beatriz Wardzinski[I], Rodrigues, Miriam Fernanda[I], Gubiani, Paulo Ivonir[I], Dalmolin, Ricardo Simão Diniz[I], Schenato, Ricardo Bergamo[I]

[I] Universidade Federal de Santa Maria, Santa Maria, RS, Brazil

ABSTRACT

Heavy vehicle traffic, especially large military combat vehicles, causes soil compaction, which reduces their physical quality and increases their susceptibility to soil erosion. A large contingent of the Brazilian Army conducts combat vehicle training at the Santa Maria Instruction Field (CISM), which has been caused degradation of the ecosystem. The aim of this study was to evaluate the effect of combat vehicle Leopard 1A5BR traffic on soil physical properties in an Abruptic Alisol with military vehicle traffic history. Two types of maneuvers were evaluated: (i) straight traffic with 0, 1 and 3 passes, and (ii) pivoting maneuver with 0, 1 and 2 pivots. Soil morphology, particle size distribution and organic carbon content were analyzed in the 0.00-0.10 and 0.20-0.30 m layers. Bulk density, total porosity, macroporosity, microporosity, saturated soil hydraulic conductivity, penetration resistance and preconsolidation pressure were evaluated in the 0.00-0.04, 0.10-0.14 and 0.20-0.24 m layers. The preconsolidation pressure of the surface layer indicated that the soil surface layer is susceptible to traffic compaction of Leopard 1A5BR. Only one pass (straight traffic) and one pivoting maneuver were sufficient to increase soil penetration resistance and bulk density and reduce the total porosity and macroporosity in the surface layer (0.00-0.04 m).

Keywords: Battle tank; Soil compaction; Soil precompression stress; Land degradation; Army

RESUMO

O tráfego de veículos pesados, especialmente veículos de combate militar de grande porte, causa compactação do solo, o que reduz sua qualidade física e aumenta sua suscetibilidade à erosão. Um grande contingente do Exército Brasileiro realiza treinamento de veículos de combate no Campo de

Instrução de Santa Maria (CISM), o que causou degradação do ecossistema. O objetivo deste estudo foi avaliar o efeito do tráfego de veículos de combate Leopard 1A5BR nas propriedades físicas de um Argissolo Vermelho-Amarelo com histórico de tráfego de veículos militares. Foram avaliados dois tipos de manobras: (i) tráfego em linha reta com 0, 1 e 3 passadas e (ii) manobra pivotante com 0, 1 e 2 pivotamentos. A morfologia do solo, a distribuição granulométrica e o teor de carbono orgânico foram analisados nas camadas de 0,00-0,10 e 0,20-0,30 m. Densidade aparente, porosidade total, macroporosidade, microporosidade, condutividade hidráulica do solo saturada, resistência à penetração e pressão de pré-consolidação foram avaliadas nas camadas de 0,00-0,04, 0,10-0,14 e 0,20-0,24 m. A pressão de pré-consolidação da camada superficial indicou que a camada superficial do solo é suscetível à compactação de tráfego do Leopard 1A5BR. Apenas uma passada (tráfego em linha reta) e uma manobra de pivotamento foram suficientes para aumentar a resistência à penetração e a densidade do solo e reduzir a porosidade total e a macroporosidade na camada superficial (0,00-0,04 m).

Palavras-chave: Tanque de guerra; Compactação do solo; Capacidade de carga; Degradação da terra; Exército

1 INTRODUCTION

Dense and continuous traffic from heavy vehicles can cause soil compaction. When the stress generated on the soil exceeds their internal resistance to deformation, the soil will be compacted (Richart et al. 2005). Compaction reduces the soil physical quality and increases its susceptibility to erosion due to the pores and water infiltration reduction. Negative changes in physical properties make it difficult for the soil to perform its functions properly (Aguiar 2008; Vennik 2019), like plant growth, flows of energy and matter, environmental filtration (Reichert et al. 2003) and biological activity maintenance (Cambi et al. 2015).

Compaction modifies the infiltration rate, decreasing soil aeration (Webb 2002), as it provides a decrease in macroporosity, its distribution and connectivity (Braunack and Williams 1993; Freddi et al. 2007; Beutler et al. 2009), which increases the resistance of penetration and soil density when subjected to loads (Carvalho et al. 2011; Barik et al. 2014). These changes are potentiated when vehicle traffic occurs in conditions of soil moisture favorable to soil compaction (Silva and Cabeda 2006; Drewry et al. 2008).

Changes in soil physical properties contribute to erosive processes (Van Donk et al. 2003), which are aggravated by the removal of vegetation cover by vehicle traffic maneuvers (Retta et al. 2013; Kane et al. 2013). Military activities with heavy combat vehicles have negative impacts on ecosystems, especially soils. Military technological development has produced heavy vehicles, increasing the potential for damage to vegetation cover and soils, promoting modifications and loss of natural habitats, reducing biodiversity and accelerates erosion processes (Thurow et al. 1993; Ayers 1994; Demarais et al. 1999; Prosser et al. 2000; Van Donk et al. 2003; Althoff and Thien 2005; Anderson et al. 2005).

Most combat vehicle studies have been conducted in the southwestern United States (Anderson et al. 2005), which limits the understanding of the impact of these vehicles on other environmental conditions. Few studies about military vehicle trafficability have been conducted in Brasil (Knob, 2010; Cordeiro 2018). Considering that soil compaction is conditioned by the integration of the vehicle effect (weight, type of wheelset, maneuvers performed and traffic number), soil (texture, mineralogy and organic matter) and environment (climate and native vegetation) (Althoff and Thien 2005; Retta et al. 2013), understanding the effect of these vehicles on the environment demands local research.

In Brazil, the Santa Maria Instruction Field (CISM) is the most commonly used military training area for the mechanized infantry, using up to 60 Mg combat vehicles. Located in Santa Maria, Rio Grande do Sul state, southern Brazil, the CISM has an area of 5,867 hectares. Training is conducted throughout the year with approximately 140 armored combat vehicles plus a contingent of smaller vehicles. The Leopard 1A5BR has a combat weight of up to 42 Mg and is one of the most used vehicles in the CISM.

The intense use of the Leopard 1A5BR vehicle has promoted the degradation of roads, fields and watercourses at CISM. Some overused areas have become degraded (Pittelkow 2013; Fernandes 2015). Continuous training on the sandy loam soils has promoted compaction in virtually the entire CISM area. Information on changes in the physical properties of the soil and how it behaves with military vehicles traffic is of interest to the Brazilian Army and is important to other National

Armies as well, so that sustainable management and reclamation plans can be prepared. This information is also important for planning military practices outside the army's instructional fields when agricultural areas are exposed.

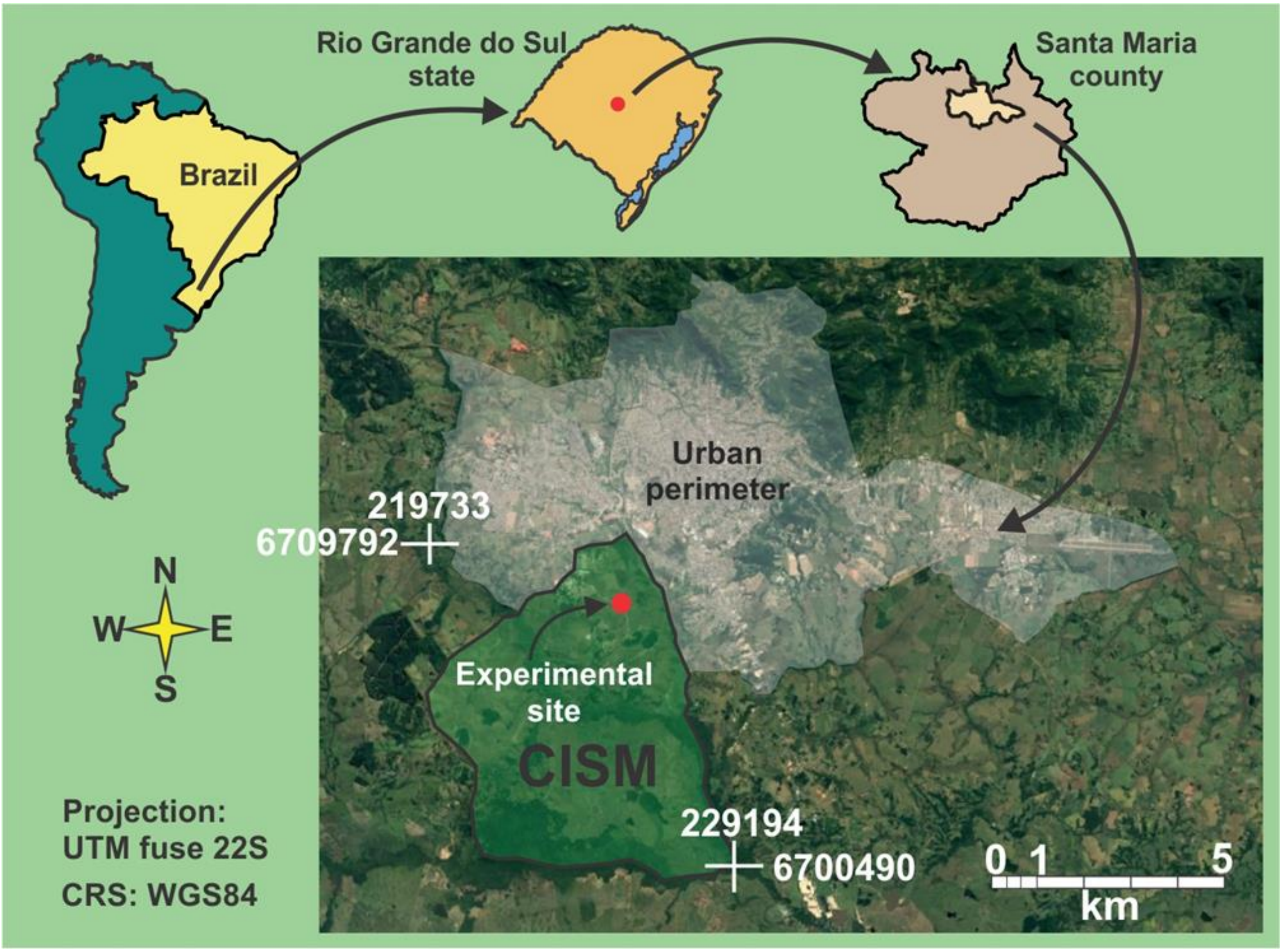
The aim of this study was to determine the effect of the straight and pivoted traffic intensity of the combat vehicle Leopard 1A5BR on the physical properties and advancement of the compaction state of a sandy loam soil with military vehicle traffic history.

2 MATERIAL AND METHODS

2.1 Study area

The study was conducted in an area located in the Santa Maria Instruction Field (CISM), which belongs to the Brazilian Army and has been used for military instruction with armored combat vehicles and troop transport. The CISM is located in the municipality of Santa Maria, state of Rio Grande do Sul, southern Brazil, between the geographic coordinates 29° 42' 31'' and 29° 47' 39'' south latitude 53° 48' 12” and 53° 53' 23'' west longitude (Figure 1). The experiment sampling was conducted in September, 2018.

Figure 1: Experimental area localization.



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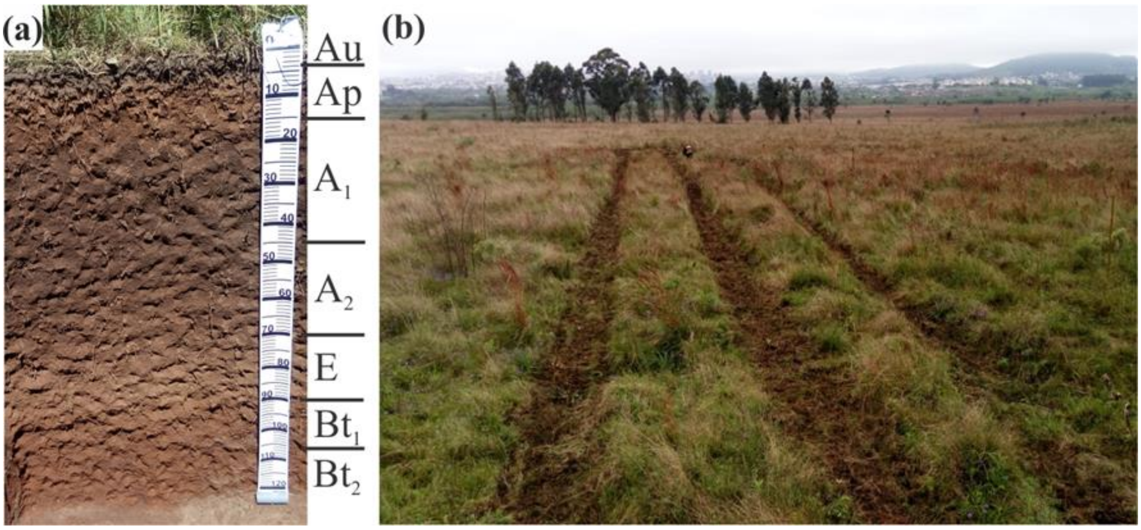
The relief of the area varies from plane to undulate (0-12% of slope) in the sedimentary hills and plane in the floodplains. In the experimental area, the geology is characterized by the Alemoa Member of the Santa Maria Formation, that are composed of clay siltstones and claystones (Sartori 2009).

The climate of the region is subtropical with a humid summer (Cfa), classified as humid mesothermal, according to the Köppen climate classification. The mean annual temperature ranges from 18 to 20°C, and the mean annual rainfall is 1750 mm (Alvares et al. 2013). Training with armored combat vehicles occurs in any weather condition. The traffic of those vehicles over the last 15 years has been intense. In the experimental area, the intense vehicle traffic was recorded in the years 2009, 2013, 2014 and 2018.

The soil in the area has been classified as Argissolo Vermelho-Amarelo Ta Distrófico abrúptico according to the Brazilian Soil Classification System (Santos et al. 2018), Abruptic Alisol (Densic, Differentic, Loamic, Profondic) (According to the World Reference Base for Soil Resources; IUSS Working Group WRB 2015) and Arenic Hapludult (According to the Soil Taxonomy; Soil Survey Staff 2014) (Figure 2).

Figure 2: Soil profile (a) and landscape of experimental site (b) (Au: anthropogenic A horizon; Ap: agricultural A horizon; A: natural A horizon; E: eluvial horizon; Bt: argillic horizon).



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The morphological description of the soil and landscape was performed according to the Manual of Description and Sampling of Soil in the Field (Santos et al. 2015), obtained from the Barbosa et al. (2020). The Au horizon has a layer of burnt vegetation residues and the Ap horizon corresponds to the effects of the annual plow due to agricultural use prior to the installation of the military instruction field. The Ap horizon has laminar/massive structure from 0.10 to 0.15 m (Table 1). The structure was predominantly moderate with subangular blocks, except for the Au and Ap horizons, which had granular and laminar structure, respectively. The soil presented textural class sandy loam to all horizons from Au to Bt1 and clay loam to Bt2.

Table 1: Morphological and grain size characterization of the Abruptic Alisol of the experimental site (Barbosa et al., 2020).

Structure: gr.: granular; lam.: laminar; ma.: massive; ang.: angular; sang.: subangular; mod.: moderate; wk.: weak.

Horizon	Depth (m)	Moist Color	Structure	Granulometry (g kg^{-1})			Textural class
				Sand	Silt	Clay	
Au	0.0-0.03	10YR 4.5/2	gr.; mod.	650	255	95	Sandy loam
Ap	0.03-0.15	10YR 3.5/6	lam./ma.; mod.	657	245	98	Sandy loam
A_1	0.15-0.45	10YR 3/1	ang./sang.; mod.	638	256	106	Sandy loam
A_2	0.45-0.70	10YR 3/2	ang./sang.; wk.	612	282	106	Sandy loam
E	0.70-0.90	10YR 4/3	ang./sang.; wk.	630	304	66	Sandy loam
Bt_1	0.90-1.05	5YR ¾	ang./sang.; mod.	551	289	160	Sandy loam
Bt_2	1.05-1.20+	5YR 3.5/3.5	ang./sang.; mod.	407	239	354	Clay loam

Source: Authors

The dry mass of the aerial part of the vegetation was 7.8, 9.7 and 10.6 Mg ha^{-1} in the locations with low, medium and high vegetation, respectively. The most common herbaceous and shrubby plant species found at the site were *Andropogon bicornis* L. and *Schizachyrium microstachyum* (Desv. Ex Ham.) Roseng, *Aristida jubata* (Arechav.) Herter, *Baccharis trimera* (Less.) DC., *Eryngium elegans* Cham. Et Schlecht; *Eryngium ciliatum* Cham. & Schltdl, *Desmodium incanum* (Sw.) DC, *Sida rhombifolia* L., *Eragrostis plana* Nees and *Paspalum notatum* Fluegge (Barbosa et al., 2020).

2.2 Vehicle data

The Leopard 1A5BR is a Brazilian version of the German military armored combat vehicle (battle tank). It is 7 m long (without the cannon), 3.4 m wide and 2.7

m high. The vehicle's wheelset is 0.55 m wide and 4.2 m long with two aligned rubber pads (Figure 3). It has a weight of approximately 40.2 Mg without load, reaching 42.2 Mg in the combat setup. The calculated static pressure on the soil is 87 kPa, which is only a reference value, considering that the pressure applied to the ground (dynamic pressure) was not monitored and the track pads' surface exerts higher pressure. Traffic occurred at an average speed of 15 km h^{-1}.

Figure 3: Military armored combat vehicle “Leopard 1A5BR” used in the experiment: front view (a), wheeled track (b) and side view (c).

Source: authors

2.3 Methodology and experimental design

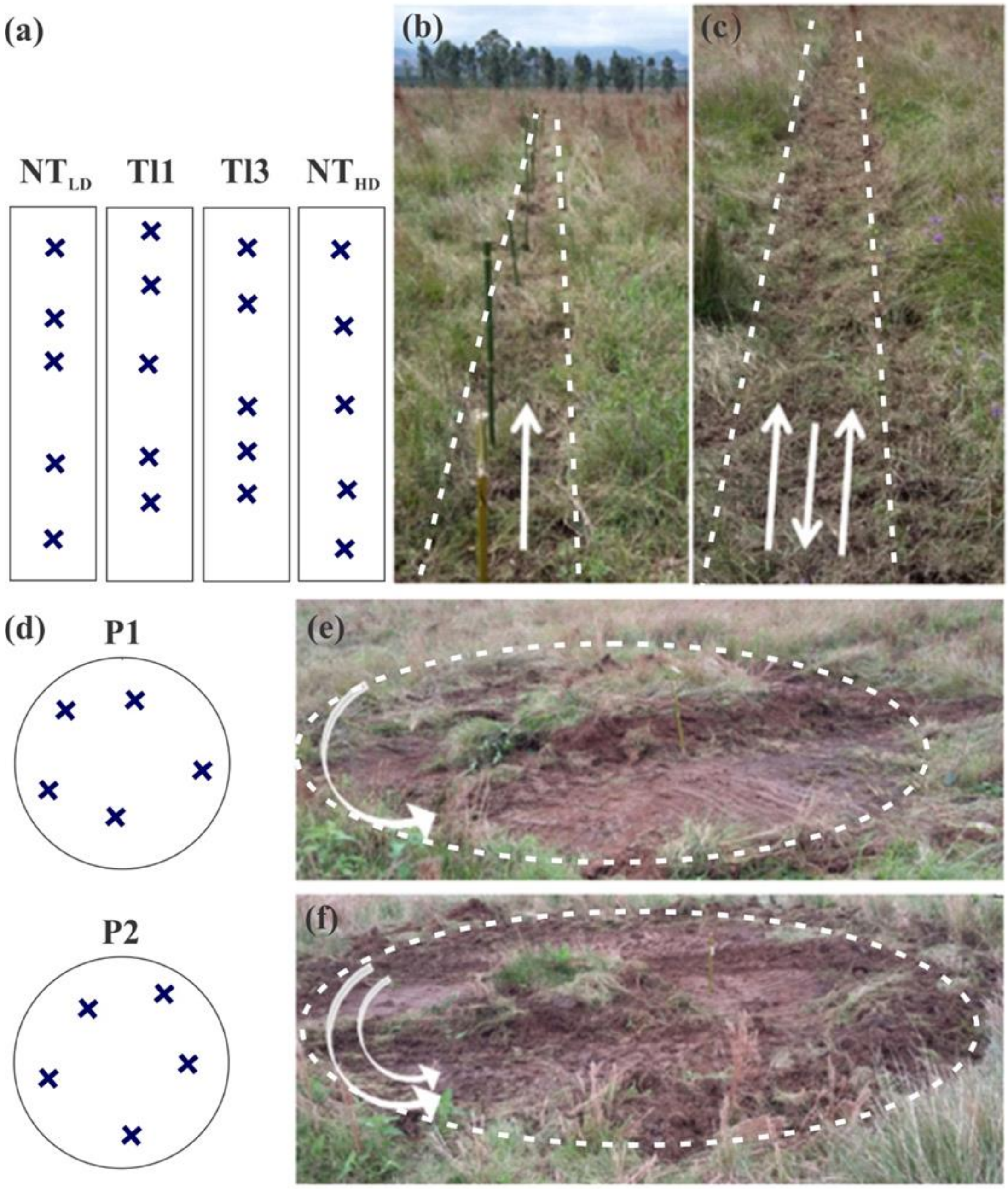
The traffic of the Leopard 1A5BR was carried out two days after a 89.8 mm rain (INMET 2019), when the mean volumetric water content of the soil was 0.30 m^3 m^{-3}, a condition close to the field capacity for this soil. The high moisture condition was chosen as a strategy in order to evaluate the effects of the traffic on the conditions most favorable to its degradation.

The area was divided into two independent experiments. One of the experiments consisted of straight traffic; the second in the pivoting maneuver (when one of the tracks locks and the vehicle moves around its own axis).

For the straight traffic (Figure 4) the traffic intensities were evaluated with one (TI1) and three (TI3) passes in the same place. Beside the straight traffic area, pivoting maneuvers were performed with one (P1) and two (P2) pivoting (Figure 4). Considering the variability in the soil due to the history of military vehicle traffic in the area, no-traffic treatment was sampled at two different sites, one on each side of the experimental area. Under conditions of high density (NT_{HD}), representing the common pre-compaction of land use in previous years, and another, under conditions of lower density (NT_{LD}), representing the situation closer to the natural, with lower density when compared to NT_{HD}. The option to use two treatments without traffic was based on greater than natural soil variability due to the history of traffic in the experimental area.

For the straight traffic experiment, the traffic intensities were applied in 18 m long and 0.4 m wide lanes, 1.8 m apart to each other. Each lane was divided into 18 plots of 1 m, from which five repetitions were randomly selected (Figure 4) to compose their experimental units. For the pivoting experiment, traffic intensities were evaluated with one (P1) and two (P2) pivots, each applied to a single point in the area. At each point, five plots were marked by lot on the vehicle trail to compose the sample units. Two no-traffic treatments were also considered in the pivoting experiment.

Figure 4: Experimental area with the plots design (a), the Leopard 1A5BR track after one straight pass (b) and three straight passes (c). The plots design for the pivoting maneuver (d) and the field after 1 pivoting (e) and 2 pivoting (f). The white arrows indicates the traffic direction



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Bulk density (Bd, Mg m^{-3}), total porosity (TP, m^3 m^{-3}), macroporosity (Ma, m^3 m^{-3}), microporosity (Mi, m^3 m^{-3}) and saturated soil hydraulic conductivity (Ks, mm

h^{-1}) were measured in preserved soil samples collected in metal rings (0.04 m high and 0.057 m diameter) in the 0.00-0.04, 0.10-0.14 and 0.20-0.24 m layers. Disturbed soil samples were collected in the 0.00-0.10 and 0.20-0.30 m layers, due to the textural homogeneity of the soil surface horizons, for particle size analysis and total organic carbon content.

The particle size (sand, silt and clay content) was evaluated according to the procedure described by Gee and Bauder (1986), and dispersion according to Suzuki et al. (2015). Total organic carbon (TOC, g kg^{-1}) was quantified by the wet combustion process described by Nelson and Sommers (1982), using the Mebius method in the digester block (adapted by Teixeira et al. 2017).

The soil undisturbed samples were saturated for 48 h and submitted to Ks evaluation with a constant head permeameter (Teixeira et al. 2017). Subsequently, the samples were again saturated for 48 h, weighed and subjected to the tension of 6 kPa on a sand column (Reinert and Reichert 2006). Then, the samples were oven dried at 105 ºC until they reached constant weight for the determination of Bd (Blake and Hartge 1986). The TP was considered the volumetric water content at saturation; Mi was considered the volumetric content of water retained at a tension of 6 kPa; and Ma was calculated by the difference between TP and Mi (Danielson and Sutherland 1986).

Mechanical soil penetration resistance (PR) was evaluated in the field with a digital penetrometer with an automatic data collector. The constant penetration velocity was 2 cm s^{-1} with a 1 cm diameter cone and 60º angle. Data were obtained every 0.010 m, up to 0.5 m deep, with five measurements by traffic intensity and pivoting maneuver. Concomitant with the measurement of soil mechanical resistance to penetration, disturbed soil samples were also collected, weighed and oven dried at 105 ºC until reaching constant weight. The gravimetric water content of these samples was multiplied by the corresponding layer bulk density to determine the volumetric water content of the soil.

The soil precompression stress (σp) was evaluated in another set with 36 undisturbed samples (12 samples per soil layer) collected in metal rings 0.03 m high and 0.057 m in diameter, at the 0.00-0.04, 0.10-0.14 and 0.20-0.24 m layers in the NT_{LD} (treatment with less soil alteration).

These samples were divided into four groups containing nine samples per group, three samples from each soil layer per group, to ensure Bd variation within the groups. All samples were saturated and then the water content of each group was decreased by applying suction: groups one and two were submitted to a sand column device at 6 and 10 kPa (Reinert and Reichert, 2006), respectively, group three was subjected to 100 kPa using a pressure-plate extractor (Klute, 1986) while group four was also subjected to 100 kPa and then more water loss was allowed by evaporation, to obtain samples drier than those of group three.

After equilibrating the sample water suction of each group, the samples were weighed to determine the volumetric water content (θ, m^3 m^{-3}) and subjected to consecutive static loads of 0, 12.5, 25, 50, 100, 200, 400, 800 and 1600 kPa, for a period of 5 minutes for each load (Silva et al. 2000), in a uniaxial compression press. A loading time of 5 min was chosen based upon the observations by Silva et al. (2000) on the same type of soil of this study, in which 98% of the final settlement was reached for all loading steps after 5 min and earlier. We did not noticed saturation during the tests, which indicated that the interference of positive pore water pressure could be absent or negligible. At the end of the compression test, the samples were oven dried at 105 ° C, until they reached constant weight, to determine the Bd.

The σp was determined in each sample by the Casagrande method (1936) using the SCC supplement (Gubiani et al. 2017). A nonlinear model ($\sigma p = aBd^b\theta^c$; a, b and c correspond to the fit parameters) described by Busscher (1990) was fitted to the data set.

2.4 Statistical analyses

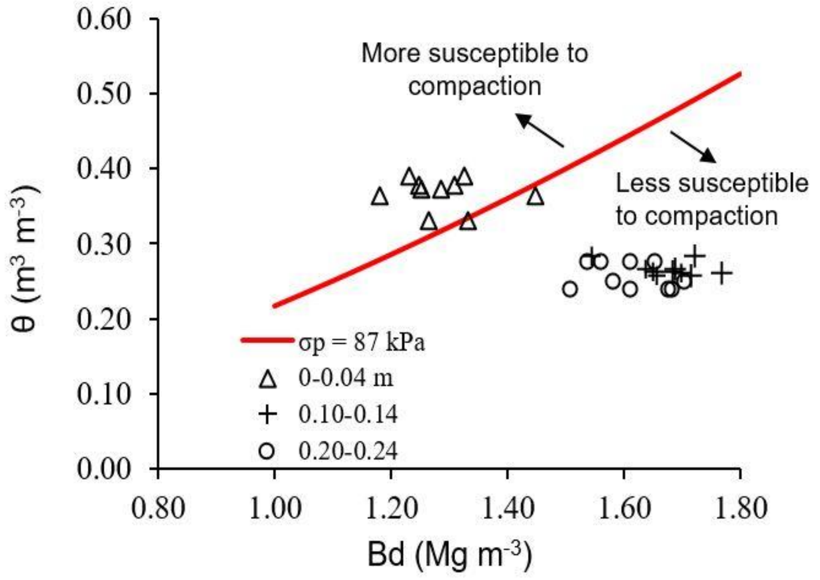
TOC and soil particle size were analyzed using descriptive statistics. The other data (Bd, TP, Ma, Mi, Ks, PR and θ) were submitted to statistical variance analysis and when there were significant differences, the means were compared by Tukey test at 5% probability of error. Square root transformation was applied to variables without adherence to normal distribution.

3 RESULTS

3.1Traffic effects on the soil physical properties

The coefficients were significant ($p \leq 0.05$) in the adjusted model $\sigma p = 13.22526Bd^{1.85651}\theta^{-1.23313}$ (Equation 1), with a determination coefficient of $R^2 = 0.74$. At 87 kPa σp, which is the static load of Leopard 1A5BR, the combinations of Bd and θ that generate a curve in the orthogonal plane θ-Bd (Fig. 5). Above the line are combinations (θ; Bd) for which the combat vehicle traffic would compact the soil; below the line are combinations (θ; Bd) for which traffic would not compact the soil. Although traffic occurred with θ close to field capacity (10 kPa), the combinations of θ and Bd determined in NT_{HD} plots at the time of application of traffic in other plots (points in Figure 5) indicate that the traffic occurred on soil condition unfavorable to compaction by the vehicle in the layers of 0.10-0.14 and 0.20-0.24 m and favorable for compaction in the layer of 0.00-0.04 m.

Figure 5: Combinations of Bd e θ that results in a σp = 87 kPa (static load of the Leopard 1A5BR) according to the equation 1, with the parameters set to the soil of the experiment



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3.2 Leopard 1 A5BR straight traffic

Bd differed significantly between traffic intensities in the 0.00-0.04 m and 0.20-0.24 m layers (Figure 6). Bd differed significantly between NT_{LD} and TI1 and TI3 at the 0.00-0.04 m layer. NT_{HD} differed only from TI3 in the same layer. The areas submitted to one and three passes did not differed from each other. The Bd increased from 1.25 to 1.51 Mg m^{-3} in the surface layer (0.00-0.04 m) after three passes of the vehicle. The 0.10 to 0.14 m layer had the highest Bd for all traffic intensities, with approximate 1.70 Mg m^{-3}, and did not differed significantly from the passes treatments. At the 0.20-0.24 m layer, NT_{LD} differed significantly from the other traffic intensities.

TP had a significant difference among traffic intensities for the three layers analyzed. The TP was higher in the surface (0.00-0.04 m), where it was reduced from 0.52 to 0.40 m^3m^{-3} after three passes. The second layer had TP reduced from

0.35 to 0.31 cm^3 cm^{-3} after the three passes. Statistical difference occurred among TI3 and non-traffic treatments (NT_{HD} and NT_{LD}). TI1 differed only from NT_{LD}. The third layer had TP difference among NT_{LD} and the other treatments. In the three soil layers TP decreased after trafficking three times in the soil when compared to NT_{LD}.

Ma was different for treatments only in the surface layer. The amount of macropores in the NT_{LD} in the first layer (0.17 m^3 m^{-3}) is higher than the other traffic treatments. NT_{HD} did not differed from NT_{LD} and TI1. Similarly, TI1 did not differed from NT_{HD} and TI3, but TI3 differed from the two non-traffic treatments. The lowest Ma values were found in the second layer, with no difference among treatments. Mi had difference only in the second layer. The highest values of micropores were found in the surface layer (0.00 to 0.04 m). In the 0.10-0.14 m layer, TI3 was different from the no-traffic treatments. TI1 was only different from NT_{LD}.

Ks values only differed in the third layer. NT_{LD} was above 80 mm h^{-1} and decreased to below 20 mm h^{-1} in the other treatments. The PR differed significantly in all layers (Figure 7a), what did not occur with the volumetric moisture (Figure 7b). PR increased from the surface to the maximum value in the 0.10-0.20 m layer and then decreased with increasing depth. From 0.00 to 0.20 m, the highest PR values were for TI1 and TI3 compared to NT_{HD}. In the 0.20 to 0.30 m layer the lowest PR was for TI3.

In the 0.00-0.05 m layer, PR started at 1 MPa for NT_{HD} and with straight traffic the values increase to 1.7 MPa. In the 0.05-0.20 m layers, PR values for NT_{HD} were greater than 2 MPa and reached approximately 4 MPa at 0.15 m depth. In the 0.20-0.50 m layer, the PR decreased, not exceeding 2.5 MPa, but was over 1.6 MPa.

Figure 6: Soil bulk density (Bd) (a), total porosity (TP) (b), macroporosity (Ma) (c), microporosity (Mi) (d) and saturated hydraulic conductivity (Ks) (e) in treatments with no traffic (NTLD and NTHD) and after 1 and 3 passes (TI1, TI3) of Leopard 1A5BR in straight line. Averages followed by the same letter do not differ from each other by Tukey's test (5%). ns = not significant by Tukey test (5%)

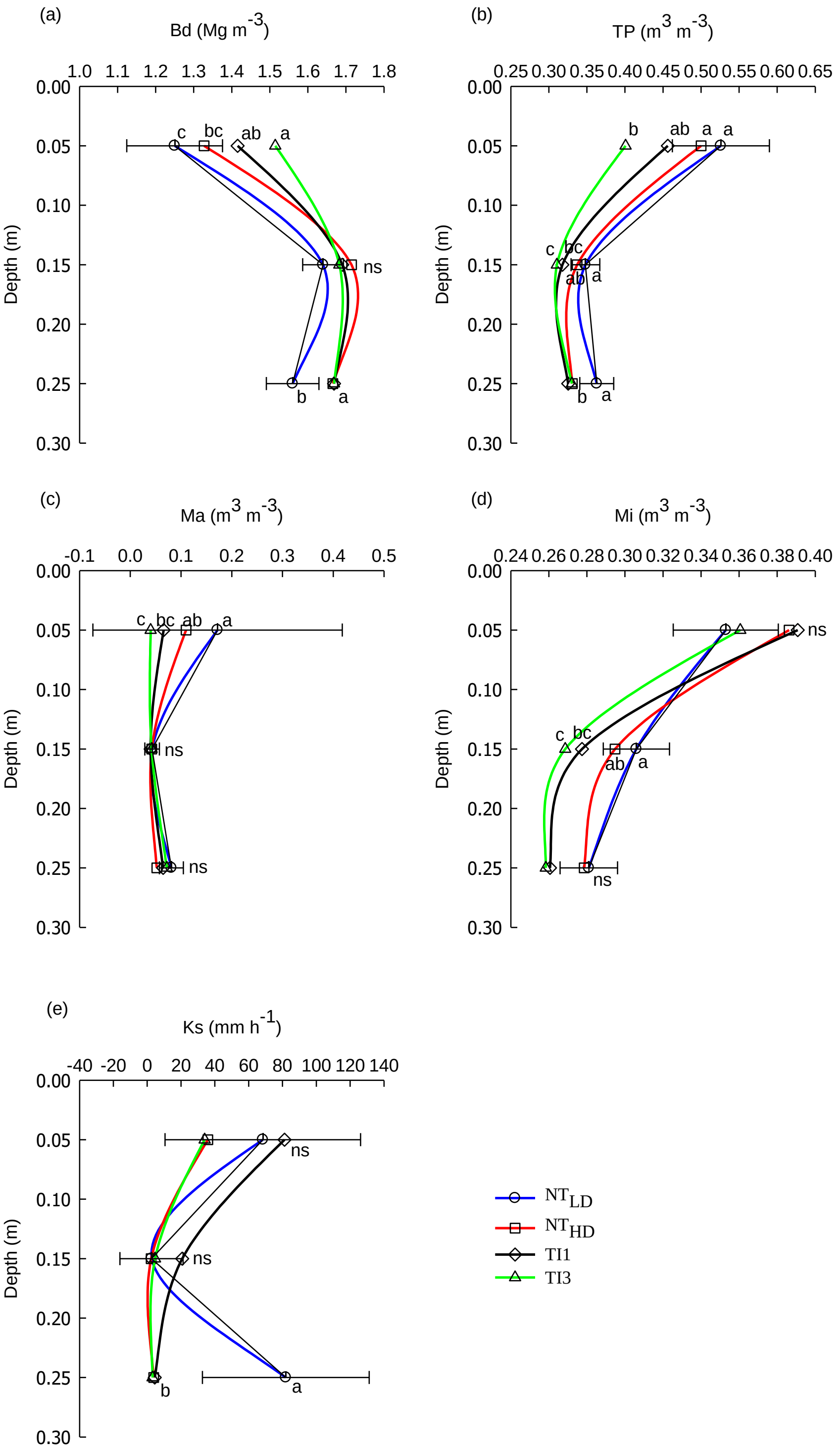

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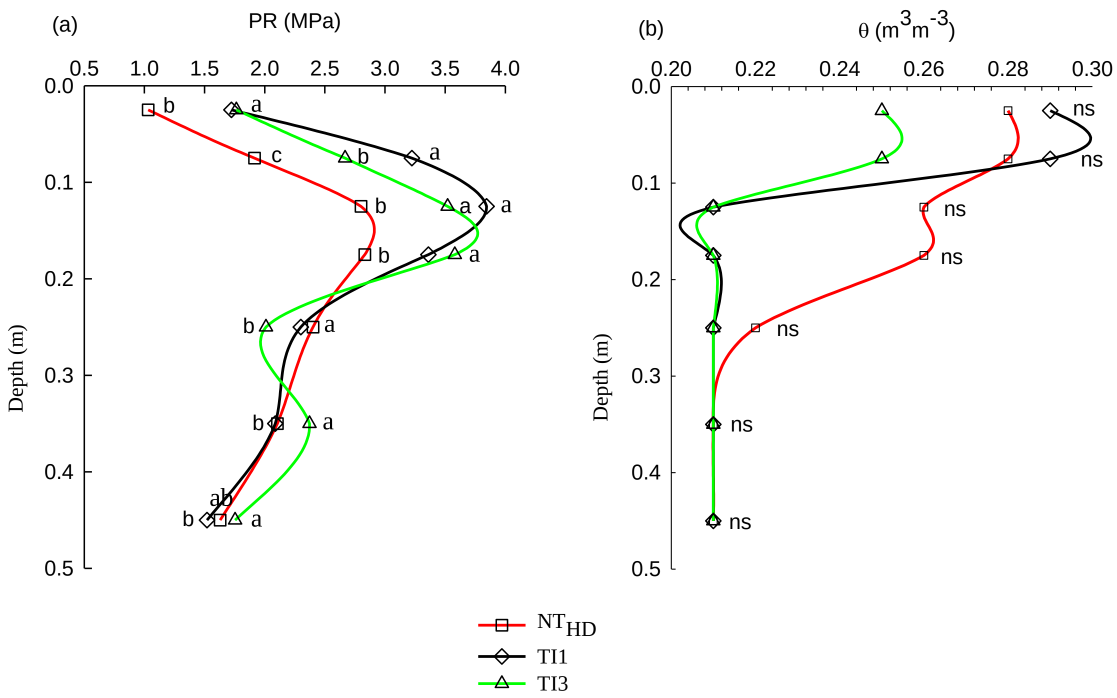
Figure 7: Soil penetration resistance (PR) (a) and volumetric water content (θ) (b) in treatments with no traffic (NTHD) and after 1 and 3 passes (TI1 e TI3) of Leopard 1A5BR in straight line. ns = not significant by Tukey test (5%)



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3.3 Leopard 1A5BR pivoting maneuver

The Bd had a significant difference between pivoting treatments in the first and second layer (0.00-0.04 and 0.10-0.14 m) (Figure 8a). In the first layer Bd increased with the maneuver from 1.25 to 1.45 Mg m^{-3}. Only NT_{LD} and P1 differed from each other. In the 0.10 to 0.14 m layer the Bd values were above 1.60 Mg m^{-3}. The significant difference occurred only between NT_{HD} and P1. In this layer the treatments NT_{LD} and P2 did not differ from each other or from the other treatments. Only NT_{HD} and P1 treatments differed, with NT_{HD} showing the highest density value. In the 0.20-0.24 m layer the variation of Bd data was not significant.

Only the first soil layer had a difference in TP (Figure 8b), which decreased from 0.52 to 0.42 m^3 m^{-3} with pivoting maneuvers. NT_{LD} differed from pivoting treatments, and P2 differed from the two no-traffic treatments. The subsurface layers had the lowest TP values.

The Ma was significant for the first and third layer treatments. The amount of macropores in NT_{LD} in the first layer is higher than the other treatments, with 0.17 m^3 m^{-3} and decreased with the first pivoting maneuver to 0.06 m^3 m^{-3}. Only NT_{LD} was different from the other treatments. In the 0.20-0.24 m layer only NT_{HD} differed from pivoting maneuvers.

The Mi was different only in the surface layer (0.00-0.04 m). Pivoting maneuvers decreased Mi compared to NT_{HD}. Only NT_{HD} differed from the other treatments. The Ks was different in surface layer (0.00-0.04 m), decreasing with the maneuvers. Only NT_{LD} was different from the pivoting treatments.

Soil PR had a significant difference in the 7 layers for pivoting maneuvers (Figure 9a), and there was no difference in relation to volumetric water content (Figure 9b). The PR increased from the surface to the maximum value in the layer from 0.05 to 0.15 m and then decreased with increasing depth. From 0.00 to 0.10 m the highest PR were from P1 and P2, and from 0.15 to 0.50 m the highest PR values were from NT_{HD}. In the 0.00-0.05 m layers only NT_{HD} was different from the pivoting maneuvers. In the 0.05-0.10 m layer the difference occurred among all treatments. In the 0.10-0.15 m layer P1 had the highest PR and differed from the other treatments. In the 0.15-0.30 m layer the significant difference occurs among P3 and the other treatments.

In the surface layer (0.00-0.05 m) PR values start at 1 MPa for NT_{HD} and after the pivoting maneuver the values increase up to 2.5 MPa. In the 0.05-0.20 m layer, the RP values for NT_{HD} are greater than 2 MPa and reach almost 3.5 MPa at 0.10 m. In the 0.20-0.50 m layer the values decrease, not exceeding 2.5 MPa, but still greater than 1.5 MPa.

Figure 8: Soil bulk density (Bd) (a), total porosity (TP) (b), macroporosity (Ma) (c), microporosity (Mi) (d) and saturated hydraulic conductivity (Ks) (e) in treatments with no traffic (NTLD and NTHD) and after 1 and 2 pivoting maneuver (P1 and P2) of Leopard 1A5BR. Averages followed by the same letter do not differ from each other by Tukey's test (5%). ns = not significant by Tukey test (5%)

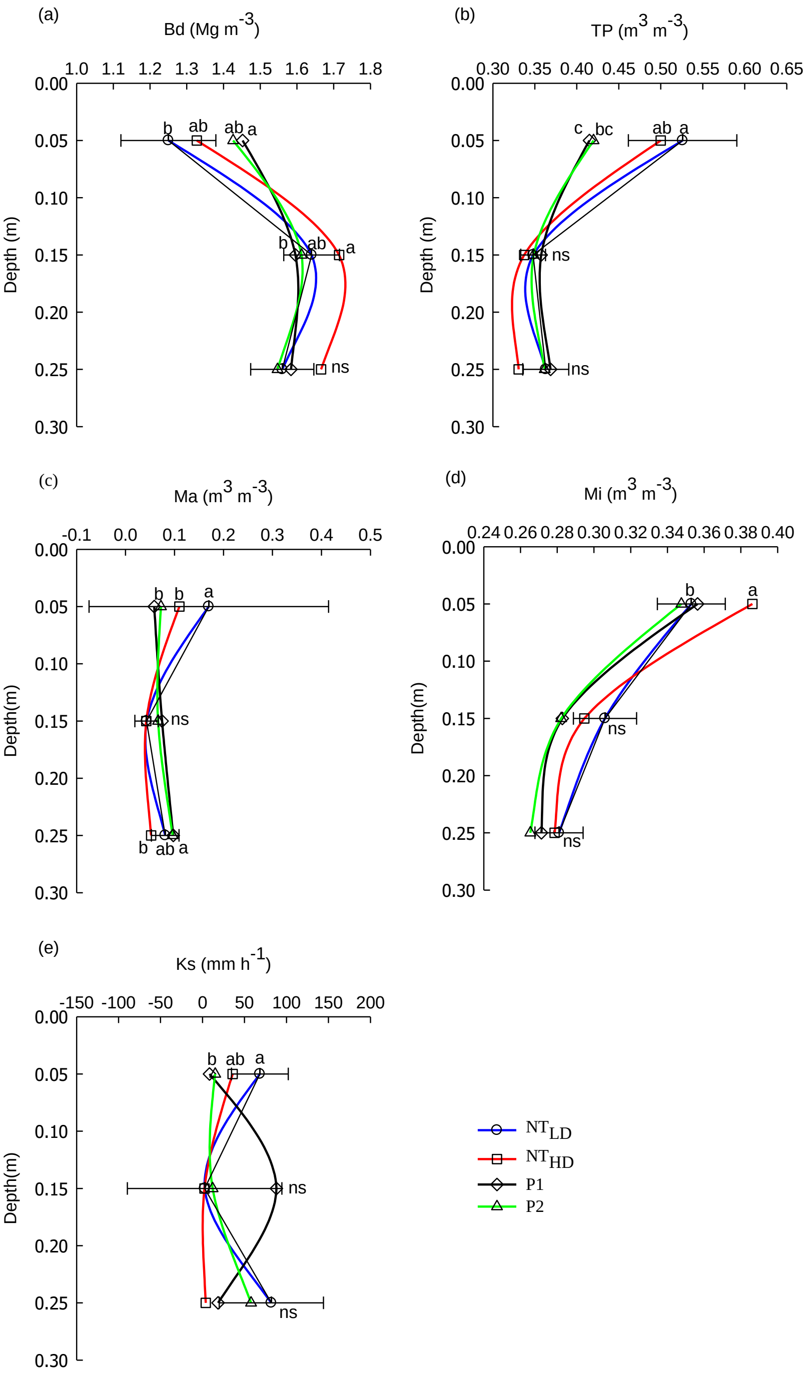

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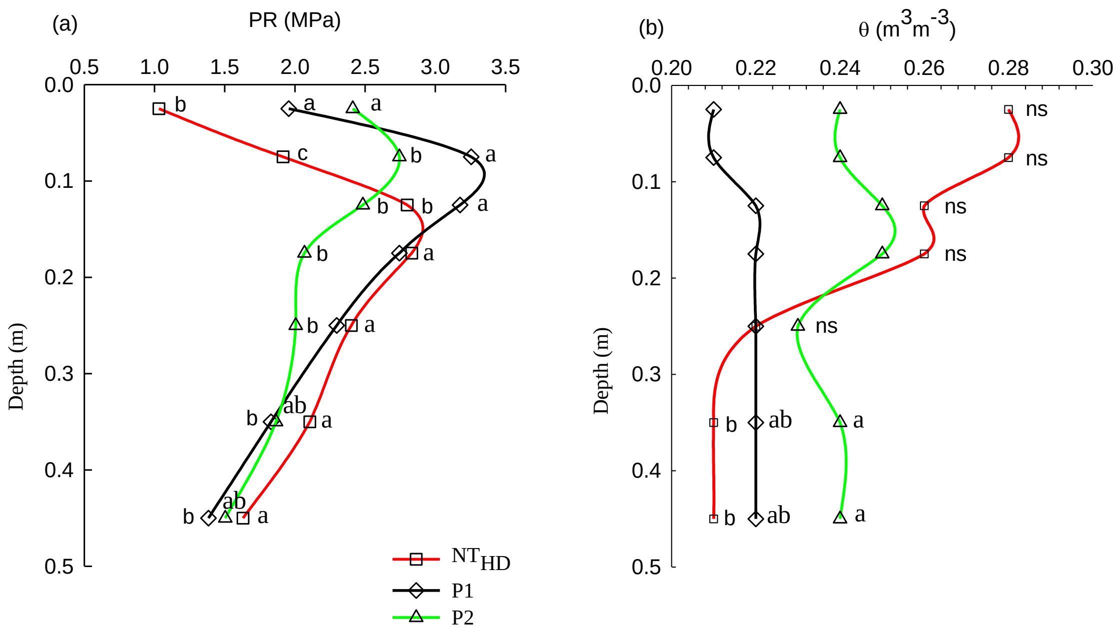
Figure 9: Soil penetration resistance (PR) (a) and volumetric water content (θ) (b) in treatments with no traffic (NTHD) and after 1 and 2 pivoting maneuver (P1 and P2) of Leopard 1A5BR in straight line. ns = not significant by Tukey test (5%)



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4 DISCUSSION

4.1 Leopard 1A5BR straight traffic

The combat vehicle traffic promoted the soil compaction in the surface layer, evidenced by the increase of Bd and reduction of TP and Ma, especially for straight traffic with three passes. The increase in soil density corroborates the effects observed by the traffic of military vehicles over a silt clay loam and a silt clay soil studied by Althof and Thien (2005) in military areas.

Despite the high soil moisture, which enhances the soil alteration through a deeper layer (Lamande and Schjønning 2011), the negative effects on traffic intensities (TI1 and TI3) were mostly in the surface layer (0.00-0.04 m) and the deepest layer (0.20-0.24 m). The 0.10-0.14 m layer was not compacted with increasing traffic (Figure 6), which demonstrates a pre-compacted soil state, also evidenced by the laminar/massive structure observed in the morphological description of the soil profile representative of the experimental area.

The absence of significant differences for most properties in the non-traffic areas compared to the vehicle traffic area (TI1) indicates that there is a pre-compaction state due to previous traffic, which corroborates with the historical use of the area. However, for the TI3, there was an increase of compaction in relation to the non-traffic treatments, with the increase of Bd, reduction of TP and Ma in the surface layer, indicating that passing three times over the soil promotes its additional compression.

However, trafficking once or three times over the soil did not increase its compaction, so that with only one traffic, the altered physical properties of the soil (Figure 6) were negatively affected when the vehicle trafficked over the low density soil. The higher degree of the soil deformation after the first traffic corroborates the studies by Ayers (1994); Prosser et al. (2000).

The mass of Leopard 1A5BR is approximately 42 Mg, but the static pressure it applies to the soil is only 87 kPa. When the traffic occurred, the soil was susceptible to compaction by loads of this magnitude only in the surface layer (Figure 5), the layer most susceptible to compaction, with low Bd (1.2 to 1.5 Mg m^{-3}) and high θ (0.33 m^3 m^{-3}). At the moment of traffic, the combinations of Bd with θ applied in equation (1) result in σp between 60 and 92 kPa, which indicates that, only in the 0.00-0.04 m layer, the soil would be further compacted if subjected to the load of 87 kPa.

In the other layers, the soil had more restrictive conditions for compaction due to higher Bd. Higher Bd in subsurface layers are common in agricultural (Lanzanova et al. 2010) and military (Prosser et al. 2000; Retta et al. 2013) trafficked areas because wetting and drying cycles and biological activity are less intense than it is in the surface, where they are most efficient in promoting unpacking (Webb 2002; Reinert et al. 2008).

Residues on the soil surface absorb the effect of vehicle pressures helping to prevent soil compaction (Palazzo et al. 2005; Braida et al. 2011). The vegetation present at the time of traffic, with dry mass between 7.8 and 10.6 Mg ha^{-1}, possibly absorbed part of the pressure applied to the soil surface by the combat vehicle when passing only once, but did not have the same effect when the traffic intensity was higher (TI3).

The increase in soil compaction provided by straight traffic was also evidenced by PR. The PR indicated that the traffic causes negative soil effects up to 0.50 m depth. The increase in PR with traffic in the surface layer (0.00-0.20 m depth) is associated to only one pass (TI1) in a straight traffic. In greater depth, the highest PR was after passing three times on the soil. However, the largest increase in PR occurred in the surface layer and was less pronounced in the deepest layers, possibly due to the lower surface density (Reinert et al. 2008), which was also observed by Valicheski et al. (2012).

4.2 Leopard 1A5BR pivoting maneuver

The greatest effect of pivoting maneuver occurred in the surface layer. The maneuver with only one pivot promoted effect on Bd, TP, Ma and Ks when compared to the no-traffic treatment (NT_{LD}). However, these effects did not occur when compared to the no-traffic with higher density (NT_{HD}) and to the area with two pivots, as also verified by Braunack (1986) and Prosser et al. (2000).

The lack of effect of pivoting maneuvers on the 0.10-0.14 m layer also indicates a pre-compaction condition in the study site. This condition of greater compaction is corroborated by the higher resistance to static loads (Figure 5), with σp of 60 and 92 kPa. Although the pivoting maneuver promoted a dynamic load greater than the predicted 87 kPa due to the effects of vibration, soil shear and increased frictional force during the vehicle rotation (Ayers 1994; Nie et al. 2001;

Liu et al. 2010; Alakukku 2012), it was not enough to promote the compaction of subsurface layers.

The Ks ranged from 15 to 80 mm h^{-1} and yet no statistical difference between traffic intensities in the 0.10-0.14 and 0.20-0.24 m layers, indicating a high variability of this property. The high Ks mean in these layers seems to be related to the variability associated with the use history of the field. It is also noteworthy that soils with higher Ma do not always have high Ks. This behavior is possibly associated to changes in the structure, continuity and connectivity of soil pores due to the degradation of the area by the military vehicle traffic (Rizzardi et al. 2014).

Pivoting maneuvers (P1) increased PR only up to 0.15 m. Only in the surface layer (0.00-0.05 m), 2 pivots resulted in superior PR effects. Only one pivoting maneuver on the ground already increases PR to levels critical to root growth (> 2 MPa), as observed by Silva et al. (2000) and Reinert et al. (2008).

4.3 Environmental implications of military vehicle traffic in the CISM

The morphology of the Abrupt Alisol of the study area, conditioned by the sandy loam texture in the A and E horizons, with abrupt transition to a loam clay Bt horizon (Table 1, Figure 2), favors the occurrence of surface and subsurface erosive processes (Pedron et al. 2012). The presence of a compacted layer in the 0.10-0.15 m layer, evidenced by the laminar/massive structure, higher Bd and lower porosity caused by the combat vehicle traffic over time, reduces water infiltration rates, also affecting the Ks (Figure 6 and 8), which increases the runoff and soil erosion (Solgi et al. 2014).

Native vegetation found in the study area is resistant to damage from Leopard 1A5BR traffic. Damaged vegetation cover during the experiment was fully recovered after 4 months, which demonstrates its resilience. Considering that Bd in the pivoting area were above restrictive limits for plant growth (1.75 Mg m^{-3}, suggested by USDA 1996; 1.65 Mg m^{-3}, suggested by Reichert et al. 2003), it was not an appropriate restriction indicator. Ma lower than 0.10 m^3 m^{-3}, considered the critical value (Reichert et al. 2003), in all evaluated layers after traffic (Figure 6 and 8) was also not a good indicator. However, although native vegetation has proved resilient, constant traffic from heavy military vehicles may be compromising the resilience of soil functions in the environment.

5 CONCLUSIONS

Traffic from the armored combat vehicle Leopard 1A5BR compacted the sandy loam Abrubtic Alisol of the Santa Maria Military Instruction Field when the traffic occurred in a straight line and pivoting maneuver.

Changes in physical properties were concentrated in the surface layer (0.00-0.04 m) and the highest expression was after the first straight traffic and pivoting. For the study with straight traffic there was the highest depth compaction, reaching up to 0.45 m, as observed by the penetration resistance, whereas the pivoting maneuver had its changes concentrated in the surface layer (0.00-0.15 m).

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

ACKNOWLEDGMENTS

To the Coordination for the Improvement of Higher Education Personnel (CAPES) for the masters scholarship; to the PROEX resources, through the Soil Science Graduate Program/UFSM; and to the National Council for Scientific and Technological Development (CNPq) for the masters, postdoctoral and researcher scholarships. To SESU/MEC, through the Tutorial Education Program, for the tutoring scholarship. To the Brazilian Army South Command through the General

Walter Pires Armored Instruction Center and the Santa Maria Instruction Field for their logistical assistance in carrying out the research.

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Authorship contributions

1 – Cândida Regina Müller
Mestre em Ciência do Solo, Doutoranda do Programa de Pós Graduação em Ciência do Solo, Universidade Federal de Santa Maria.
https://orcid.org/0000-0003-1891-4727 - candidarmuller@gmail.com
Contributions: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft.

2 – Fabrício de Araújo Pedron
Doutor em Ciência do Solo, Professor do Centro de Ciências Rurais, Departamento de Solos, Universidade Federal de Santa Maria.
https://orcid.org/0000-0002-5756-0688 - fapedron@ufsm.br
Contributions: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

3 – Beatriz Wardzinski Barbosa
Mestre em Ciência do Solo, Doutoranda do Programa de Pós Graduação em Ciência do Solo, Universidade Federal de Santa Maria.
https://orcid.org/0000-0002-2411-4913 - beatriz.wb@gmail.com
Contributions: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft.

4 - Miriam Fernanda Rodrigues
Doutora em Ciência do Solo, Pós Doutoranda do Programa de Pós Graduação em Ciência do Solo, Universidade Federal de Santa Maria.
https://orcid.org/0000-0001-5026-7887 - miriamf.solos@gmail.com
Contributions: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft.

5 - Paulo Ivonir Gubiani
Doutor em Ciência do Solo, Professor do Centro de Ciências Rurais, Departamento de Solos, Universidade Federal de Santa Maria.
https://orcid.org/0000-0002-8840-3976 - paulo.gubiani@ufsm.br
Contributions: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing.

6 - Ricardo Simão Diniz Dalmolin
Doutor em Ciência do Solo, Professor do Centro de Ciências Rurais, Departamento de Solos, Universidade Federal de Santa Maria.
https://orcid.org/0000-0002-8834-9869 - dalmolin@ufsm.br
Contributions: Writing – original draft.

7 - Ricardo Bergamo Schenato
Doutor em Ciência do Solo, Professor do Centro de Ciências Rurais, Departamento de Solos, Universidade Federal de Santa Maria.
https://orcid.org/0000-0003-4268-7691 - ribschenato@gmail.com
Contributions: Data curation, Formal Analysis, Writing – original draft.

How to quote this article

MÜLLER, C. R.; PEDRON, F. A.; BARBOSA, B. W.; RODRIGUES, M. F.; GUBIANI, P. I.; DALMOLIN, R. S. D.; SCHENATO, R. B. Soli degration after te traffic of a military combat vehicle leopard 1A5BR. **Ciência e Natura**, Santa Maria, v. 43, e87, p. 1-31, 2021. Available in: https://doi.org/10.5902/2179460X62685.