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Physical properties of a Brazilian sandy loam soil after the traffic of a military vehicle *M113 BR*

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ABSTRACT: Soil physical properties can be changed after vehicle traffic, especially by heavy military tracked vehicles. The Santa Maria military Instruction Field, where the experiment was carried out, is currently the most used area for armored tracked vehicles training in Brazil, with the *M113 BR* being the main equipment. The aim of this study was to determine the effect of the straight line and pivoted traffic intensity of the *M113 BR* on the physical properties and advancement of the compaction state of an Abruptic Alisol (*Argissolo Vermelho-Amarelo Ta Distrófico abrúptico*) with military vehicle traffic history. The study was conducted in a completely randomized design, independently evaluating the effect of straight and pivoting traffic in three soil layers (0.00-0.04, 0.10-0.14, and 0.20-0.24 m). For the straight-line traffic, traffic intensities (TI) with one (TI_1), two (TI_2), and five (TI_5) passes on the same trail were evaluated. For the pivoting traffic, TI with one (TI_{1P}) and two (TI_{2P}) pivots was evaluated. Both studies had two non-traffic treatments (NT). The soil bulk density, total porosity, macroporosity, microporosity, saturated soil hydraulic conductivity, soil penetration resistance, soil bearing capacity, preconsolidation pressure, and gravimetric water content were analyzed in this study. In the straight-line traffic, cases with no significant differences in TP, Ma, Mi, and Ks prevailed. The highest TP, smallest Bd and largest Mi were observed in the 0.10-0.14 m layer. In the pivoting traffic, one pass was sufficient to increase Bd and decrease TP, Ma, Mi, and Ks in the 0.00-0.04 m layer and the increase from one to two pivotings had a significant difference only in Mi in this same layer. Both types of traffic intensity did not affect the PR in any layer. The Abruptic Alisol, pre-compacted from long-term military training, supported the loads applied by the M113 BR when additional traffic occurred in straight line mode, but not when in pivoting mode. The preconsolidation pressure parameter was not appropriate to assess the ability of the soil to support loads applied by pivoting traffic.

Keywords: soil compaction, off-road, trafficability, army land, bulk density.

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INTRODUCTION

Vehicle traffic has a potentially negative impact on soil quality as it produces surface and depth stresses, promoting changes in the soil physical properties. If the stress exceeds the internal resistance of the soil, compaction may occur as a consequence of physical changes (Dias Junior, 2000; Reichert et al., 2007). The persistence and intensity of soil changes promoted by vehicle traffic are mainly dependent on factors such as texture, moisture, organic matter content, and its stress history (Althoff and Thien, 2005; Nawaz et al., 2013).

Changes that may occur in the physical properties of the soil after vehicle traffic, especially in high humidity conditions include: increase of bulk density, decrease of total porosity (Solgi et al., 2014; Keller et al., 2019), decrease of infiltration capacity, and increase of soil penetration resistance (Keller et al., 2019). Other common features are the removal of vegetation cover (Althoff and Thien, 2005), soil rutting in vehicle tracks (Vennik et al., 2019), and erosion processes (Solgi et al., 2014).

Studies on the impacts of military armored vehicles on ecosystems are still limited when compared to agricultural vehicles. Worldwide, these impacts began to be considered in the late 70s and early 80s, in studies that included the effects of vehicle traffic on soil, vegetation, and edaphic fauna of military installations (Anderson et al., 2005). Some areas such as the Southwest United States are intensively studied. In the Brazilian context, no research on the impact of these vehicles was conducted, analyzing their climatic, pedological, geological, and dynamics of the use of military instruction fields. A more complete spatial coverage of studies on environmental impacts caused by armored vehicle traffic is needed to effectively evaluate mission relocation alternatives (Anderson et al., 2005) or conservation management practices of the used areas (Prosser et al., 2000).

The Santa Maria Instruction Field (CISM) belongs to the Brazilian Army and has an area of 5,867 hectares. It is currently the instruction field for armored tracked vehicles in Brazil with the highest use intensity, receiving military personnel from all over the country and even from foreign countries. Among the armored vehicles in CISM, the M113 BR stands out, used for the transportation of troops and cargo in the field (Fernandes, 2015).

For decades, heavy armored vehicle traffic, ranging from 10 to 60 Mg, has conditioned soil compaction over practically the entire CISM area. Currently, damage to roads, vegetation, soils, and waterways can be seen due to vegetation cover suppression, compaction, and soil erosion (Pittelkow, 2013; Fernandes, 2015). Considering the current intense use of CISM, we hypothesize that excessive military tracked vehicle traffic can promote additional compaction in previously compacted areas. Therefore, the aim of this study was to determine the effect of the straight and pivoted traffic intensity of the M113 BR vehicle on the physical properties and advancement of the compaction state of a sandy loam with military vehicle traffic history.

MATERIALS AND METHODS

The experiment was carried out at the Santa Maria Instruction Field (CISM), a military area of Brazilian Army, between the coordinates 53° 48' 12" and 53° 53' 23" W and 29° 42’ 31” and 29° 47’ 39” S, located in the municipality of Santa Maria, state of Rio Grande do Sul, Brazil. The relief of the site varies from plane to undulating (0 to 12 % of slope), with elevations ranging from 60 to 140 m, formed by sedimentary hills and established by Triassic sedimentary geological material, belonging to the Rosário do Sul Group and Santa Maria Formation. Massive clay siltstones corresponding to lake and floodplain deposits predominate in CISM (Sartori, 2009).

The climate of the region, according to the Köppen climate classification, is subtropical humid, with no defined dry season (Cfa) (Alvares et al., 2013), with an average annual temperature of 19.3 °C and annual rainfall of 1796 mm (Inmet, 2019a).

The CISM field and experimental area are characterized by the history of heavy traffic of armored combat vehicles and troop transport. The experimental area has been intensively used for military training in the last 15 years, especially in 2009, 2013, 2014, and 2018.

The soil is an *Argissolo Vermelho-Amarelo Ta Distrófico abrúptico*, according to the Brazilian Soil Classification System (Santos et al., 2018), which corresponds to an Abruptic Alisol (Densic, Differentic, Loamic, Profondic) according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) or an Arenic Hapludult, according to the Soil Taxonomy (Soil Survey Staff, 2014) (Figure 1a).

The morphological description of the soil was performed according to the Manual of Soil Description and Collection in the Field (Santos et al., 2015). Environmental/landscape information, moist color, structure, porosity, texture, consistency, depth of horizons, type of transition between horizons, and presence of special morphological features were evaluated in the field. Soil samples with non-preserved structure were collected at each profile horizon for chemical and particle size analyses according to Teixeira et al. (2017).

The botanical composition and dry mass of the above-ground vegetation present in the experimental area were characterized. Sampling was performed in three 1 × 1 m plots, randomly allocated to positions of the area with low (0.30 m), medium (0.60 m) (predominant on the day of the experiment) and high (1.10 m) vegetation (Figure 1b). The collected plant material (above-ground biomass) was oven-dried at 65 °C until it reached a constant weight and subsequently weighed (Haydock and Shaw, 1975).

The experiment to evaluate the effect of the military armored tracked vehicle of troops transport *M113 BR* traffic on soil physical and mechanical properties was conducted on September 27, 2018, two days after an 89.8 mm cumulative rainfall over three days (Inmet, 2019b). In addition to the fact that high humidity favors the detection of the traffic effect, it was decided to study under these conditions to simulate the military training in the rainy period.

The *M113 BR* is 2.53 m high, 2.67 m wide, and 4.86 m long. It moves on two 0.38 m wide and 3.05 m long tracks, fitted with a 0.15 × 0.10 m rubber pad (Figure 2). At the time of traffic, the *M113 BR* carried only two crew members, resulting in a total mass of 10,15 Mg and a static ground pressure of 44 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. The traffic occurred at an average speed of 15 km h^{-1}.

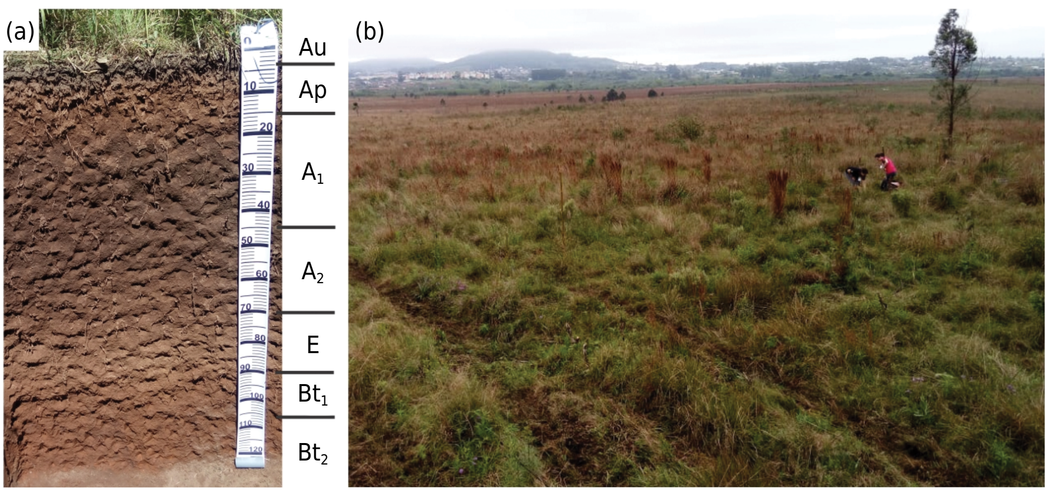

Figure 1. Soil profile (a) and landscape of experimental site (b) (Au: anthropogenic A horizon; Ap: agricultural A horizon; A: natural A horizon; E: eluvial horizon; Bt: textural B horizon).

The study was conducted in a completely randomized experimental design, independently evaluating the effect of straight and pivoting traffic (turning in the same place with the inside track braked). For the straight traffic study (Figure 3), traffic intensities (TI) were

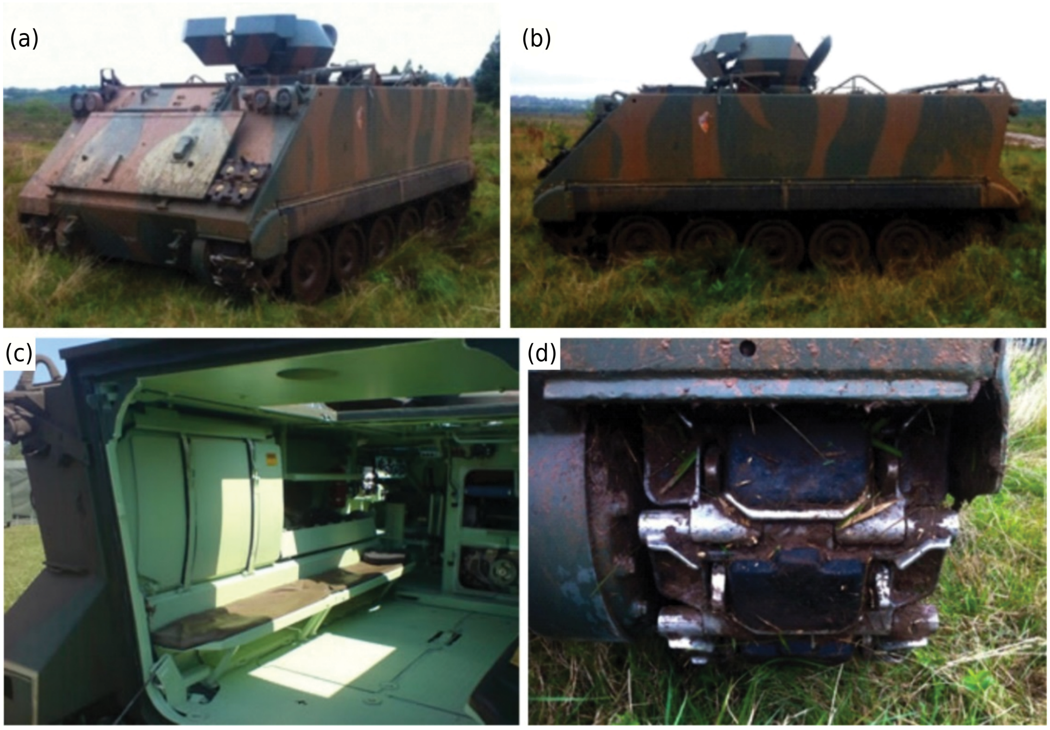

Figure 2. The military armored tracked vehicle of troops transport "M113 BR" used in the experiment: front view (a), side view (b), load compartment (c), and wheeled track (d).

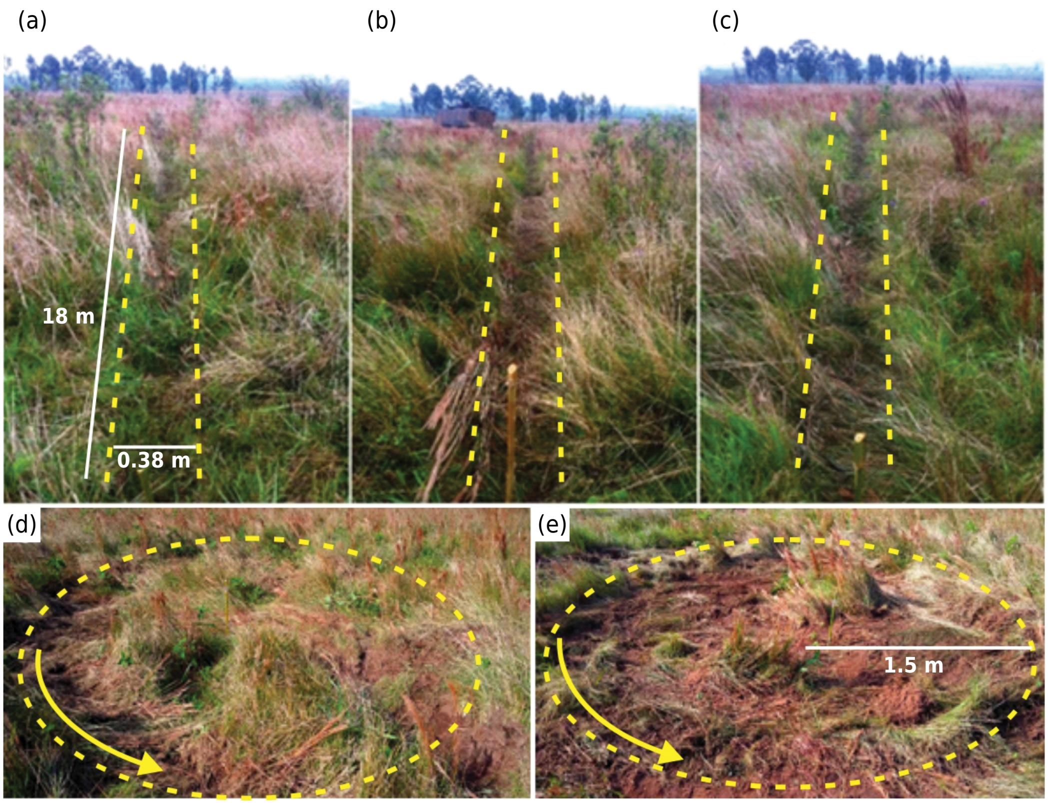

Figure 3. Study area after 1 pass (a), 2 passes (b), and 5 passes (c) of M113 BR in a straight line and 1 pivoting (d) and 2 pivoting maneuvers (e). Yellow dashes indicate the track path.

evaluated with one (TI_1), two (TI_2), and five (TI_5) passes on the same lane (trail), adding two more non-traffic treatments (NT). 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.

Treatments TI_1, TI_2, and TI_5 were applied in lanes of 18 m in length and approximately 0.40 m in width. Each lane was divided into 18 plots of one meter, of which five were randomly selected to compose the sample units of each traffic intensity. In the two non-traffic lanes, located on both sides of the traffic lanes, five plots were also selected to compose their experimental units. In total, 25 sample units were used in this study.

For the pivoting experiment (Figure 3), traffic intensities were evaluated with one (TI_{1P}) and two (TI_{2P}) pivots, each applied to a single point in the area. At each point, five plots were marked by a completely random draw on the vehicle trail to compose the sample units. Two treatments without traffic were also considered in the pivoting experiment. In total, 20 sample units were used in this study.

Undisturbed soil samples were taken with metal rings (0.039 m high and 0.057 m diameter), in the 0.00-0.04, 0.10-0.14, and 0.20-0.24 m layers. These samples were used to determine soil 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}). Considering the textural homogeneity of the local soil surface horizons, disturbed samples were taken only in the 0.00-0.10 and 0.20-0.30 m layers for particle size and total organic carbon analysis.

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

Undisturbed soil samples were saturated for 48 h for the determination of Ks with a constant head permeameter (Teixeira et al., 2017). Subsequently, the samples were again saturated for 48 h, weighed for determination of TP, and subjected to a suction of 6 kPa on a sand column (Reinert and Reichert, 2006) for the determination of Mi. After that, the samples were heated at 105 °C. Total porosity was considered the volumetric water content at saturation; Mi was considered the volumetric content of water retained at a suction of 6 kPa; and Ma was calculated by the TP-Mi difference (Danielson and Sutherland, 1986).

The soil penetration resistance (PR, MPa) was measured in the field with a digital penetrograph, equipped with an automatic data collector and 1 cm diameter cone rod with 60° angle. The penetration rate was approximately 2 cm s^{-1} and data acquisition every 0.01 m, up to 0.40 m deep. Five measurements were registered in each experimental unit. Those measurements were not done on the same day of the traffic, but two weeks later with a slight dryer soil condition.

Disturbed soil samples were taken simultaneously to the evaluation of the soil penetration resistance to determine the gravimetric soil moisture at the moment of traffic and during the PR evaluation. The gravimetric water content was multiplied by the bulk density of the corresponding layer to yield the volumetric water content (θ, m^3 m^{-3}).

Another set of 36 undisturbed soil samples was taken with metal rings (0.03 m high and 0.057 m diameter) in the 0.00-0.04, 0.10-0.14, and 0.20-0.24 m layers of a non-traffic area for the determination of the soil precompression stress. Samples were saturated and divided into four groups containing nine samples each. To have the Bd variation in each group they were composed with three samples of each soil layer. The drainage in each group was different so that they had different water contents. 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); 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.

At the end of each step, the samples were weighed to determine the volumetric water content (θ, $m^3 m^{-3}$) and subjected to static sequential loads of 0, 12.5, 25, 50, 100, 200, 400, 800, and 1600 kPa for 5 min each load (Silva et al., 2000) in a uniaxial compression press. At the end of the load application, the samples were dried at 105 °C for Bd calculation. The soil bearing capacity was estimated by the preconsolidation pressure (σp), which was determined in each sample by the method of Casagrande (Casagrande, 1936) using the SCC supplement (Gubiani et al., 2017). A nonlinear model (Busscher, 1990) was fitted to the dataset of σp, Bd and θ:

$$\sigma p = aBd^{b}\,\theta^{c} \quad \text{Eq. 1}$$

in which a, b, and c are fitting parameters.

The normality of the variables was assessed by the Shapiro-Wilk test and the homogeneity of variances was assessed by the Welch test. Logarithmic transformation was applied to variables without adherence to normal distribution. In each soil layer, the effect of traffic on Bd, TP, Ma, Mi, Ks, PR, and θ was evaluated by analysis of variance ($p \leq 0.05$). In cases with traffic effect, the means were compared by the Tukey test ($p \leq 0.05$).

RESULTS

The evaluation of two treatments without traffic (NT) was performed due to soil variability provided by the use and history of traffic in the experimental area. The NT_{LD} (non-traffic, low density) treatment represents an area without traffic in the experiment but with traffic in previous years and a lower current density when compared to NT_{HD} (non-traffic, high density).

Soil morphological description and vegetation cover characterization

The texture of the soil profile is sandy loam down to 1.05 m. The average clay content in the A horizons is 101 g kg^{-1}, decreasing to 66 g kg^{-1} in the E horizon (Table 1). The transitions between A horizons are clear, becoming abrupt between horizon E and Bt_1 (Figure 1a). In the Au horizon, the structure is granular with the presence of coal from recurrent burning of the vegetation. In the Ap horizon, the structure is laminar/massive in the 0.08 to 0.15 m layer, while in the rest of the profile, the block structure predominated.

The variability of particle size in the experimental area is small in both layers, from 0.00-0.10 and 0.20-0.30 m, and between them (Table 2). The most striking difference in the area was the decrease from 13.74 to 6.29 g kg^{-1} in the Corg of the 0.00-0.10 m layer to the 0.20-0.30 m layer. The dry mass of the above-ground biomass was 7.8, 9.7, and 10.6 Mg ha^{-1} in the locations with low, medium, and high vegetation, respectively.

Preconsolidation pressure

The data for preconsolidation pressure (σp) can be found in figure 4. In the adjusted model $\sigma p = 13.22 \times Bd^{1.85} \times \theta^{-1.23}$, all coefficients were significant ($p \leq 0.05$) and the coefficient of determination was $R^2 = 0.75$. By setting in the equation a 44 kPa σp, which is the static load of *M113 BR*, the combinations of Bd and θ that result in 44 kPa σp generate a curve in the orthogonal plane θ-Bd (Figure 4). Above the line are combinations (θ; Bd) for which *M113 BR* traffic would compact the soil; below the line are combinations (θ; Bd) for which *M113 BR* traffic would not compact the soil. Although traffic occurred at θ close to field capacity, the combinations of θ and Bd determined in NT_{LD} and NT_{HD} plots at the time of application of traffic in the other plots (points in Figure 4) indicate that the traffic occurs in an unfavorable soil condition to compaction by the *M113 BR*.

Table 1. Characterization of the Abruptic Alisol of the experimental site

Horizon	Layer	Moist Color	Structure(1)	Granulometry			Textural class
				Sand	Silt	Clay	
	m			g kg^{-1}			
Au	0.00-0.03	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 3/4	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

(1) gr.: granular; lam.: laminar; ma.: massive; ang.: angular; sang.: subangular; mod.: moderate; wk.: weak. Granulometry determined according to Gee and Bauder (1986) and Suzuki et al. (2015).

Table 2. Statistics of particle size and organic carbon content in the 0.00-0.10 and 0.20-0.30 m layers of the 25 plots analyzed in the straight line study

Descriptive statistics	Sand	Silt	Clay	Corg
	g kg^{-1}			
	0.00-0.10 m			
Mean	671.7	222.9	105.4	13.74
Standard deviation	29.4	27.8	18.2	2.53
CV (%)	4.38	12.48	17.30	18.41
Minimum	628.7	172.3	70.9	11.05
Maximum	733.8	279.8	132.9	18.28
	0.20-0.30 m			
Mean	649.0	223.7	127.3	6.29
Standard deviation	25.7	23.0	26.3	0.64
CV (%)	3.96	10.30	20.66	10.17
Minimum	588.5	180.0	97.0	5.32
Maximum	693.4	270.1	191.9	7.59

Granulometry determined according to Gee and Bauder (1986) and Suzuki et al. (2015). Organic carbon (Corg) was quantified by the wet combustion method (Nelson and Sommers, 1982) and by the Mebius procedure in the digester block (adapted by Teixeira et al., 2017).

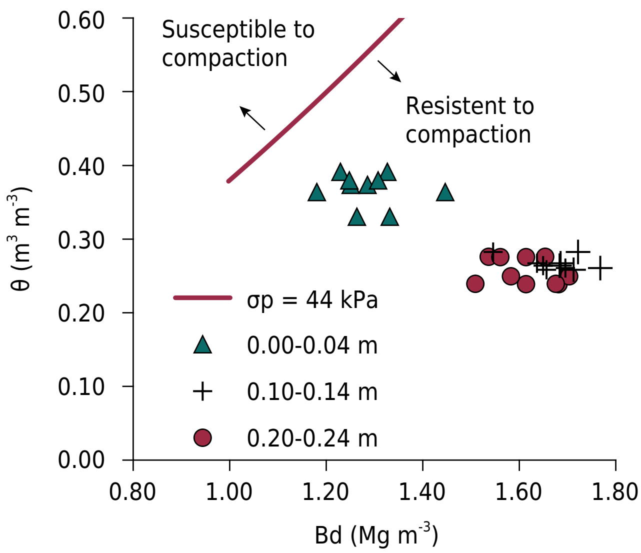

Figure 4. Combinations of bulk density (Bd) and volumetric water content (θ) that result in the preconsolidation pressure (σp) of 44 kPa (M113 BR's static load) using the parameterized equation 1.

M113 BR straight traffic

At the time of straight traffic, the average soil water content was 0.26 $m^3 m^{-3}$ - close to the A horizon field capacity water content of this soil (0.32 $m^3 m^{-3}$). There were fewer cases with significant differences associated with traffic than cases with no difference in TP, Ma, Mi, and Ks (Figure 5). In the surface layer (0.00-0.04 m) there was a difference only in Ma, which was higher in NT_{LD}. In the 0.10-0.14 m layer, the highest TP, smallest Bd, and largest Mi were observed in the NT_{LD}. Only Ks differed in the 0.20-0.30 m layer, being larger in NT_{LD}. There was no significant difference in PR and θ associated with traffic at any depth (Figure 6).

M113 BR pivoting traffic

The effect of pivoting on soil properties was clear in the 0.00-0.04 m layer, but barely noticeable in the other layers (Figure 7). One pivoting was sufficient to increase Bd and decrease TP, Ma, Mi, and Ks in the first layer (Figure 7). In this same layer, the increase from one to two pivotings did not affect Bd or TP, Ma, and Ks, but there was a significant difference in Mi. In the other layers, the few differences are not always clearly associated with traffic. The PR was not affected by the pivoting intensity in any layer (Figure 8a) and θ differed only in the 0.25 and 0.35 m layers (Figure 8b).

DISCUSSION

M113 BR straight traffic

Evidence indicates that there was no compaction or the compaction caused by an *M113 BR* moving in a straight line was poorly expressed and can only be detected in the surface layer Ma (Figure 5). The Bd and TP curves with traffic are nearly parallel to non-traffic Bd and TP curves, suggesting that the pattern of Bd and TP in the profile was not modified by traffic. The combined analysis of the magnitude of the applied load, the compressive strength of the soil, and the vegetation damping lead us to believe that the differences in the properties evaluated should be more associated with the variability of the area than the traffic effect.

Although the mass of *M113 BR* is approximately 10 Mg and the static pressure applied to the soil is 44 kPa, the stress distribution at the track-soil interface, also called “dynamic pressure”, is not uniform, and the maximum stress should be much higher than the static value. For example, the rubber pads’ surface applies much more pressure to the soil than the rest of the track. However, when traffic occurred, the stress was not enough to overcome the σp between 63 and 92 kPa estimated by the BD and the θ (Equation 1) in the surface layer. The soil was not susceptible to compaction by loads of this magnitude in either layer (Figure 4).

In the layers below the surface, soil condition was even more restrictive to the occurrence of compaction, especially due to the higher Bd (Figure 4). The occurrence of subsurface layers with higher Bd is common in trafficked areas (Tolón-Becerra et al., 2012; Keller et al., 2019) because the wet and drying cycles and the biological activity are less intense than on the surface, where they are most efficient for promoting the soil unpacking (Beylich et al., 2010; Schjønning et al., 2016).

The properties measured in the experimental area indicate the presence of a more compact subsurface layer, which is in agreement with the history of the traffic of the area. The PR profiles (Figure 6) are more informative than Bd, TP, and Ma profiles (Figure 5) to indicate that the most compacted portion of the profile is about 0.15 m deep. However, in the two deepest layers, Bd was higher and θ lower than in the superficial layer (Figure 4). Therefore, the calculated σp with equation 1 ranged from 100 to 133 kPa in these layers. Because they are the most resistant layers to compaction and because they received less traffic stress than the surface layer, it is unlikely that *M113 BR* surface traffic would cause compaction on these two subsurface layers.

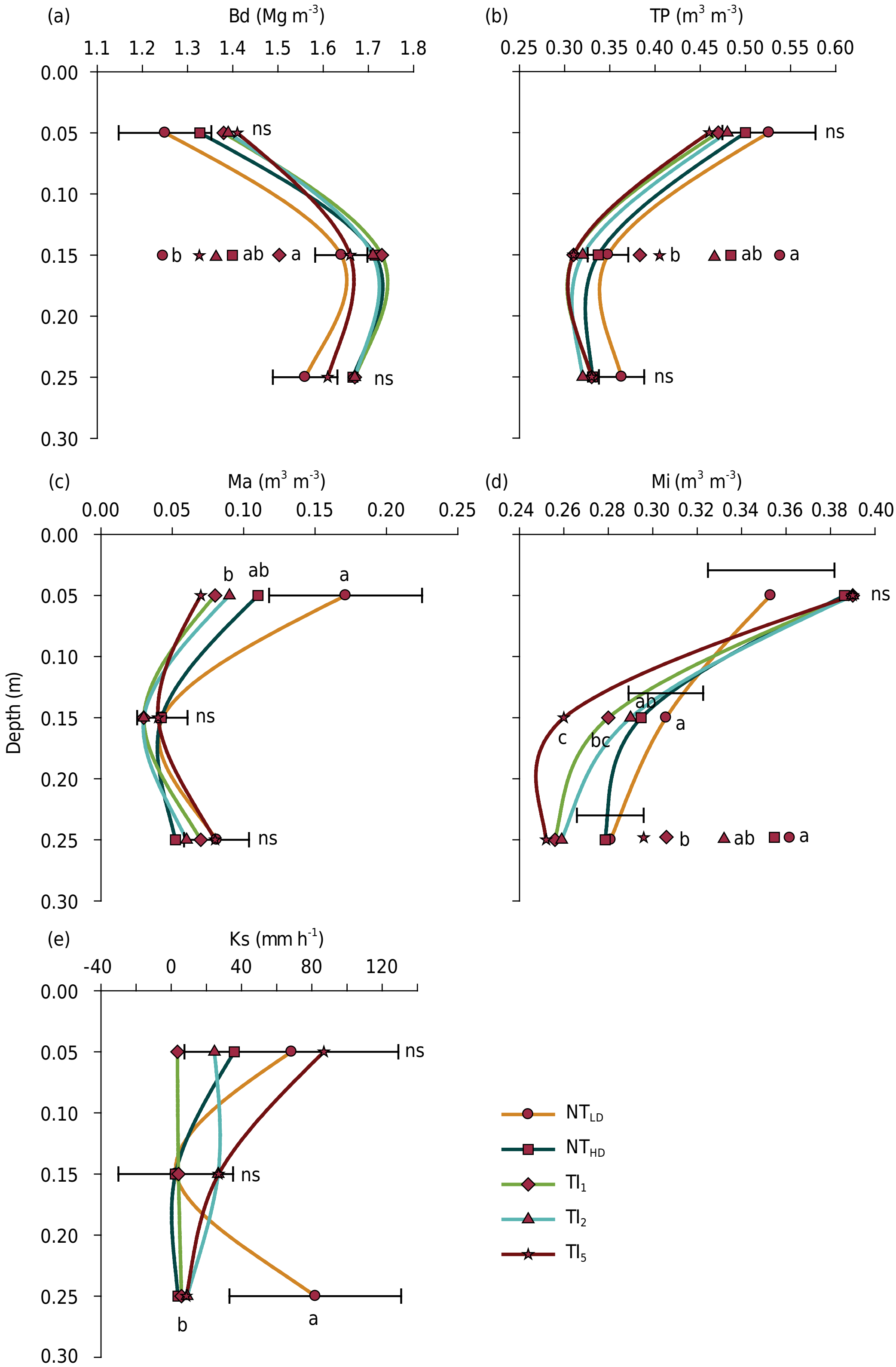

Figure 5. Soil bulk density (Bd) (a), total porosity (TP) (b), macroporosity (Ma) (c), microporosity (Mi) (d), and saturated hydraulic conductivity (Ks) (e) in treatments with no traffic (NT_{LD} and NT_{HD}) and after 1, 2, and 5 passes (TI_1, TI_2, and TI_5) of *M113 BR* in a straight line. Averages followed by the same letter do not differ from each other by Tukey's test (5 %). ns: not significant by Tukey test (5 %). The horizontal error bars represent the standard deviation of all samples.

The absence of significant traffic effects on Bd, TP, Mi, Ks (Figure 5), and PR (Figure 6) must also have been conditioned by the vegetation cover (Figures 3a, 3b, and 3c). Soil surface residues (biomass) have reduced the effect of pressure applied by the vehicle

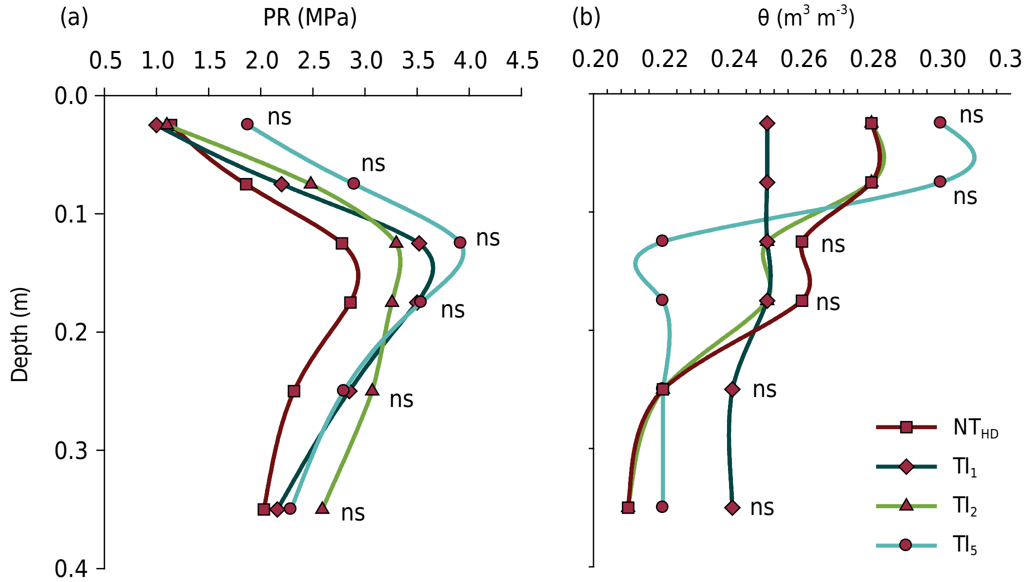

Figure 6. Soil penetration resistance (PR) (a) and volumetric water content (θ) (b) in treatments with no traffic (NT_{HD}) and after 1, 2, and 5 traffic (TI_1, TI_2, and TI_5) of *M113 BR* in a straight line. ns: not significant by Tukey test (5 %).

(Balesdent et al., 2000; Palazzo et al., 2005; Braida et al., 2011; Reichert et al., 2016; Holthusen et al., 2018), probably helping to distribute the stress and reducing some stress peaks in the contact (track/soil) area. The existent vegetation at the moment of traffic, with dry above-ground biomass between 7.8 and 10.6 Mg ha^{-1} and predominantly perennial graminoid species, must have dissipated a significant portion of the applied surface pressure by the *M113 BR*. As assessed visually, vegetation biomass helped avoid the common shear deformation on the soil surface in the straight traffic. In addition, the soil elasticity on the surface may be higher because of the Corg content (Balesdent et al., 2000; Braida et al., 2011), which in the 0.00-0.10 m layer is approximately double of the Corg content than in the 0.20-0.30 m layer.

M113 BR pivoting traffic

The pivoting maneuver with the *M113 BR* degraded the soil even though its bearing capacity was greater than the static load applied by the *M113 BR*. The loads supported by the soil structure without undergoing compaction in the different layers where there was pivoting are the same already mentioned for straight traffic because the reference plots were the same for both studies. The σp in the surface layer indicated that the soil structure would be able to withstand loads between 63 and 92 kPa without further compaction. However, the load of the *M113 BR* in pivoting compacted the topsoil with only one maneuver (Figure 7). The second pivot did not increase the effect of the first, since the first traffic usually deforms the soil structure extensively (Prosser et al., 2000; Kane et al., 2013).

Several factors contributed to the *M113 BR* compacting the topsoil. The layer would resist loads similar to 63 and 92 kPa. In pivoting there are load transfer and soil shear deformation. During movement, part of the track applies load greater than the estimated static one and ground shear, resulting from vibration combined with increased frictional force during rotation of the *M113 BR* on the ground, reducing its load-bearing capacity (Li et al., 2007; Retta et al., 2013).

The consequences of the particularities of pivoting traffic, which simultaneously apply shear and compressive force to the soil, cannot be predicted from the analysis of σp, because the σp indicates soil resistance to static and compressive loads. Comparison

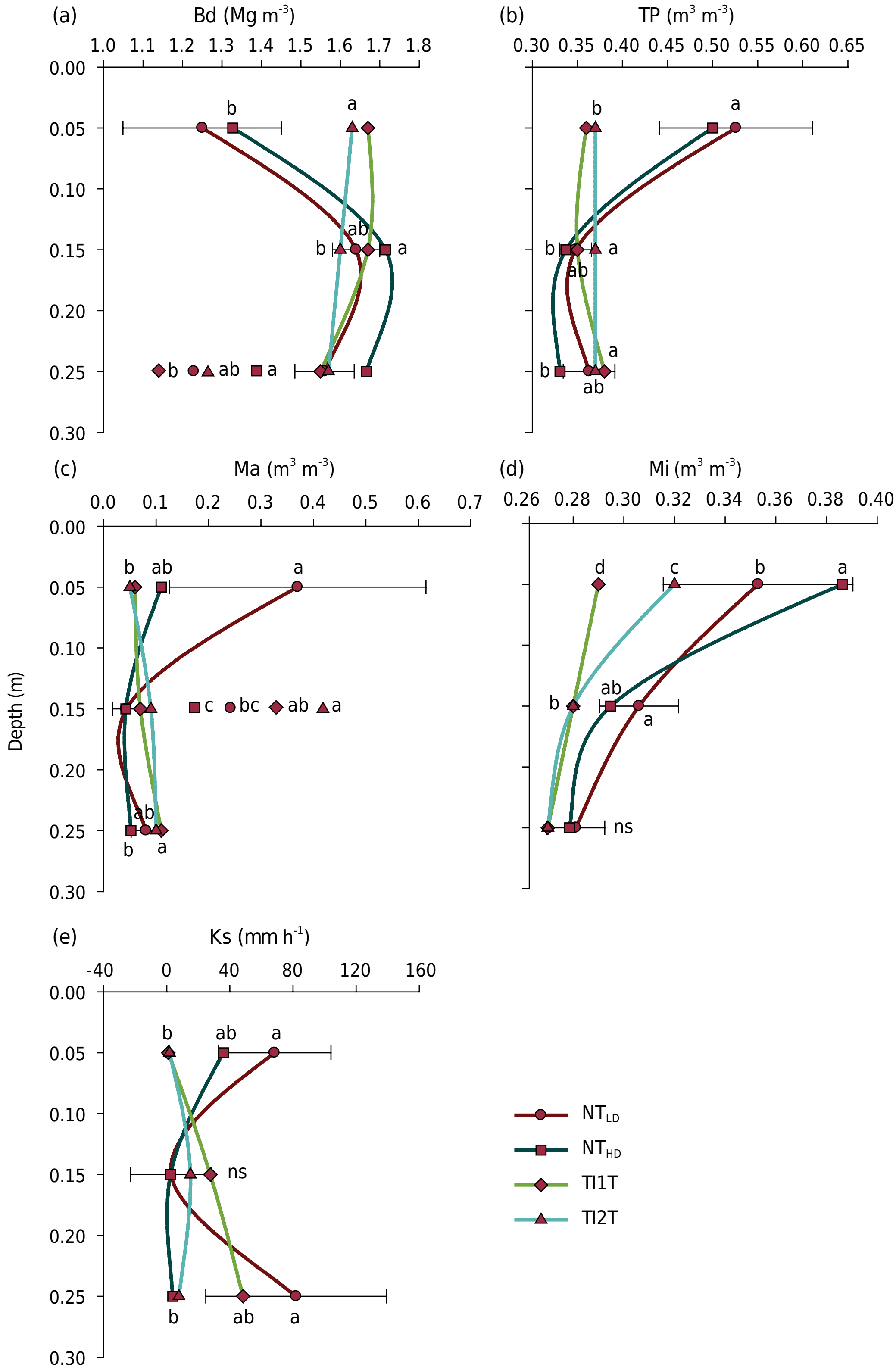

Figure 7. Soil bulk density (Bd) (a), total porosity (TP) (b), macroporosity (Ma) (c), microporosity (Mi) (d), and saturated hydraulic conductivity (Ks) (e) in treatments with no traffic (NT_{LD} and NT_{HD}) and after 1 and 2 pivoting maneuvers (TI1T and TI2T) of M113 BR. Averages followed by the same letter do not differ from each other by Tukey test (5 %). ns: not significant by Tukey test (5 %). The horizontal error bars represent the standard deviation of all samples.

of the visual appearance of the soil surface after traffic (Figure 3) and the properties measured in the first layer (Figures 5 and 7) illustrates that the load of the *M113 BR* was much more damaging to the soil in a pivoting maneuver. Soil resistance and load

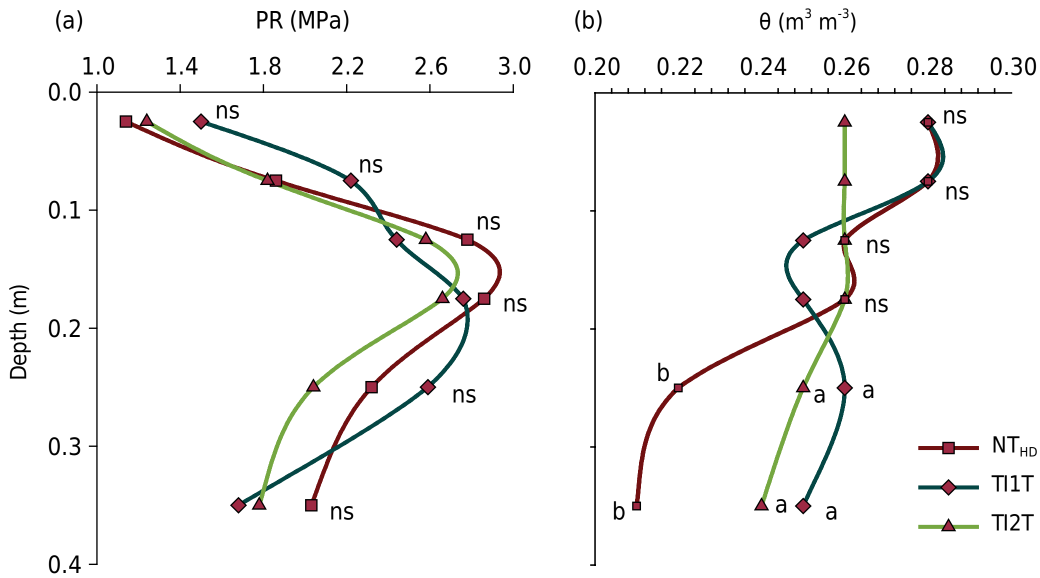

Figure 8. Soil penetration resistance (PR) (a) and volumetric water content (θ) (b) in treatments with no traffic (NT_{HD}) and after 1 and 2 pivoting maneuvers (TI1T and TI2T) of M113 BR in a straight line. ns: not significant by Tukey test (5 %).

damping by vegetation compensate the effects of charge transfer and vibration when traffic was in a straight line. However, these factors did not prevent soil compaction with pivoting traffic, corroborating the result of Ayers (1994).

The soil response difference to the *M113 BR* traffic mode is an important warning about the risk of predicting soil consequences when comparing σp with the static load of equipment. The progressive increase in the axle mass of the equipment in the last decades (Keller et al., 2019) causes the static load of the equipment to approach or even exceed the soil σp if there is no compensation in the soil contact area. This increases the risk of predicting soil resistance in situations where compaction is caused by traffic. Furthermore, recent studies highlighted that σp frequently fails to access soil bearing capacity (Keller et al., 2011; Dastjerdi and Hemmat, 2015; Somavilla et al., 2017; Gubiani et al., 2018). Thus, it is urgent either (i) to access the capability of σp to indicate the bearing capacity for the upper layer, in which the soil structure resistance is highly dynamic, due to changes in water content, biological activity, and soil aggregation state, and (ii) to alert on a misinterpretation of σp when dynamic loads applied by traffic is disregarded.

Similar to the locations where straight traffic occurred, the PR profiles (Figure 8) were more efficient than the Bd, TP, and Ma profiles (Figure 7) in showing that the most compacted portion of the profile is about 0.15 m deep. As discussed earlier, in the two deepest layers, the calculated σp with equation 1 ranged from 100 to 133 kPa. These layers were more resistant to compaction, received lower stresses and vibrations, and did not suffer the shear that occurred on the surface. It is therefore likely that some differences associated with traffic (Figure 7), especially those of the deepest layer, were due to the variability of the area and not to *M113 BR* traffic.

Potential environmental consequences of military vehicle traffic

The horizon sequence A-E-Bt of the soil profile of the experimental area (Figure 1a), with an abrupt textural change from sandy loam to clay loam, favors the occurrence of surface and subsurface erosion (Pedron et al., 2012). In addition, the presence of a compacted layer around 0.15 m deep (Figures 5, 6, 7, and 8) and low Ma reduces water infiltration capacity on the A horizon, favoring the occurrence of runoff (Solgi et al., 2014).

The native and spontaneous grass species that occupy the CISM fields seem to be resilient to traffic damage. According to Yorks et al. (1997) and Dickson et al. (2008), the perennial graminoids, as found in the study area, are the most resistant and resilient species. From visual observations made four months after the *M113 BR* traffic, the vegetation has recovered, indicating its possible adaptation to the new soil physical conditions. Therefore, although the soil density, where pivoting occurred, was 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 is not a good indicator of growth restriction of plant species occupying the area. For the same reason, Ma less than 0.1 m^3 m^{-3}, which is considered a critical value (Reichert et al., 2003), in the surface layer after traffic (Figures 5c and 7c) is also not a good indicator. However, even if the native vegetation of the site is resilient, the resilience of soil functions in the environment may be compromised by military vehicle traffic.

The traffic of heavy military vehicles can cause damage to the soils, limiting, or even disabling some important environmental soil functions (Cambi et al., 2015; Keller et al., 2019). Water infiltration, water retention capacity (Keller et al., 2019), plant development, and biodiversity (Yorks et al., 1997; Dickson et al., 2008), biomass (Althoff and Thien, 2005), organism habitats (Beylich et al., 2010), carbon stock, and gas emission (Cambi et al., 2015) are examples of the functions that may be affected by the pores and structure deformation, increase of bulk density and soil erosion (Solgi et al., 2014). Research in those subjects can contribute to enhanced and sustainable military land use planning.

CONCLUSION

The Abruptic Alisol, pre-compacted from long-term military training, supported the loads applied by the *M113 BR* military vehicle of troops transport when traffic occurred in a straight line.

Only pivoting traffic from the *M113 BR* degrades the soil, while straight traffic did not significantly modify soil structure properties.

Preconsolidation pressure was not an appropriate parameter to assess the ability of the soil to support loads applied by pivoting traffic.

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