Mechanical Properties and Air and Water Permeability of Three Subtropical Soils under Different Soil Uses

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Abstract: The effect of intensive arable land use for crop production on soil deformation and irreversible degradation is defined as a world wide problem which gets even more important due to increased mass of the machines and increased frequency of wheeling during wet or dry soil conditions. This study was conducted to evaluate mechanical properties, and air and water permeability of three subtropical soils under different uses. The two loading times tested (600 and 7200s), in four soil layers (0.00-0.07, 0.10-0.15, 0.25-0.30 and 0.40-0.45 m) did not affect significantly the pre-consolidation stress (σ_p) of the three soils (Oxisols, Alfisols, and Entisols). The σp for the Oxisols and Alfisols was increased under no-till soil compared either with native forest or grassland, in the layers of 0.00-0.07, 0.10-0.15 m, and even 0.25-0.30 m, due to farm machinery traffic. Thus, deeper soil layers were also affected under no-tillage. Traffic effected soil properties in deeper layers on clayey Oxisols, than for the sandier Alfisols, since in soils with higher clay content the applied pressure is transmitted deeper in the soil, thus increasing the layer of soil compaction. Air permeability (K_a) was greatest for the Oxisols under native forest, with highest macroporosity, particularly in the uppermost soil layer, where soil drying did not increase K_a. In contrast, no-till soil had low K_a and increased when decreasing matric potential. The highest saturated hydraulic conductivity was observed for Oxisols under native forest (754 mm h^{-1}) compared to less than 3 mm h^{-1} for no-till soil, in the uppermost soil layer. These data demonstrate that no-till soil might be significantly affected by soil compaction, and that proper soil managements systems must be used to allow proper soil functioning and maintain ecological properties related to water and air flow in the soil.

INTRODUCTION

Soil degradation is a severe problem in tropical and subtropical environments as a result of deforestation and improper soil use and management *(Lal, 1997)*.

Farm operations involving machinery traffic cause reduction in soil quality, where soil compaction is a good indicator *(Reichert et al., 2009)*. Soil compaction is more intense in clayey soils *(Reichert et al., 2009)*, whereas sandy soils are less affected *(Abu-Hamdeh & Reeder, 2003)*.

The mass and traffic frequency of farm machinery or trampling by animals determine the pressure accumulation and the rate of change of soil physics properties. These changes are higher in soil with greater soil moisture *(Dias Júnior & Pierce, 1996; Silva et al.,* 2002). The relation between soil compaction and increased weight of farm machines was shown by *Bedard et al. (1997), Abu-hamdeh et al. (1995)* and *Wood et al. (1990)*.

The sustainable use of the soil has been pursued and, in this context, soil compaction represents a threat to agriculture and should this be avoided *(Horn et al., 2000; Pagliai & Jones 2002)*. Soil compaction affects the relations between soil air, water and temperature, which affect directly plant growth *(Letey, 1985; Silva et al., 1994)*.

The pre-consolidative pressure (σp) has been as an indicator of soil compaction and of soil load support capacity *(Dias Júnior & Pierce, 1996; Imhoff et al., 2001)*. Thus, a compacted soil supports a higher load which is desirable, up to a limit, since farm machinery operational performance is optimized. However, the higher state of compaction may restrict important processes in the soils such as air and water fluxes *(Reichert et al., 2009)*. In clayey soils the surface applied loads is transmitted to deeper layers, increasing the depth of compacted soils *(Horn & Lebert, 1994)*, resulting an increased damage to soil ecological functioning.

Soil air (K_a) and water ($K_{\theta s}$) permeability are basic proprieties which inform about soil's capacity to function in the environment to fulfill its ecological functions. The K_a is a good indicator to verify changes in the soil porous system caused by different soil use and management *(Ball & Smith, 1991)*. Air flows predominantly in large porous soils *(Blanco-Canqui et al., 2007)*. Water and air are present simultaneously in the soil and their fluxes are favored by large, continuous pores *(Iversen et al., 2003)*.

This study was conducted to evaluate mechanical properties, as well as air and water permeability of three subtropical soils under native forest, native grassland or crop fields.

MATERIALS AND METHODS

Three soils from southern Brazilian were used: Hapludox, Hapludalfs and Quartzipsamments. The mechanical properties were determined on soil under 14 years of continuous no-tillage (NT) and compared to a reference area, which was native forest (NF), for the Oxisols, and native grassland (NG) grazed by beef cattle, for the Alfisols and the Entisols. No-till area was trafficked by farm machines applying 124 kPa (tractor) and 169 kPa (harvester) in the Oxisols, and 90 kPa (tractor) and 121 kPa (harvester) in the Alfisols and Entisols.

The soil samples were collected in Nov. 2005, in the middle of the soil layers 0.00-0.07, 0.10-0.15, 0.25-0.30 and 0.40-0.45 m. Replicates for each soil layer type were constituted by a set of collected samples. Five soil samples were collected with metallic cylinder (0.058 m of internal diameter by 0.04 m of height) for the determination of soil bulk density (Bd), macroporosity (Ma), microporosity (Mi), total porosity (Tp), saturated hydraulic conductivity ($K_{\theta s}$) and air conductivity (K_a). Except for $K_{\theta s}$, all determinations were done on the same soil samples. Particle density (Pd) (data not shown) and size distribution, down to 0.45 m of the soil profile were also determined for each soil (Table 1).

For the unaxial compressibility test, three samples were collected with metallic cylinders of 0.10 m internal diameter and 0.03 m depth.

The soil samples were sent to the Soil Science and Plant Nutrition Institute at the University of Kiel in Germany, for determination of the mechanical properties.

Soil Ma was determined on a sand column at -6kPa matric potential. Tp was estimated from the relationship: 1-Bd/Pd, soil Mi as the difference between Tp and Ma, and Bd as a mass/volume ratio. Water retention was measured at -3 and -6 kPa in sand column, and at -15, -30 and -50 kPa in nylon and ceramic porous plates. The $K_{\theta s}$ was determined with a falling-head permeameter *(Hartge & Horn, 1989).* The K_a was measured by the method described by *Peth (2004).* Soil compressibility was quantified with multi-step type odometers *(Rostek et al. 2006)* using two loading times (600 and 7200 s), and the consolidation pressure (σ_p) was calculated using the Casagrande method *(Holtz & Kovacs, 1981)*.

Table 1. Particle size distribution for the studied soils.

Layer	Sand	Silt	Clay
-- m --	-----------------	g kg^{-1}	-----------------
		Hapludox	
0.00-0.07	348	201	451
0.10-0.15	267	185	548
0.25-0.30	300	133	567
0.40-0.45	301	185	514
		Hapludalfs	
0.00-0.07	632	276	92
0.10-0.15	627	294	79
0.25-0.30	618	289	93
0.40-0.45	586	321	93
		Quartzipsamments	
0.00-0.07	838	68	94
0.10-0.15	832	61	107
0.25-0.30	782	72	146
0.40-0.45	753	93	154

The statistical analysis such as analysis of variance (ANOVA) and the LSD α=0.05 was carried out.

RESULTS

For the Oxisols, the uses NT and NF in layers 0.00-0.07, 0.10-0.15, 0.25-0.30 m affected Bd, Tp, Ma, Mi and $K_{\theta s}$, whereas at 0.40-0.45 m depth the use affected only Ma, Mi and $K_{\theta s}$ (Table 2). There was an inverse relationship between Ma, Tp and $K_{\theta s}$ with Bd, indicating that soil compaction might restrict water fluxes in the soil. For the Alfisols, the uses NT and NF differed in soil properties Bd, Mi and Tp in the layers 0.10-0.15 m and 0.25-0.30 m. For the Entisols, NT and NF affected Ma and Mi only in the 0.00-0.07 m soil layer.

Table 2 - Bulk density (Bd), macroporosity (Ma), microporosity (Mi), total porosity (Tp) and saturated hydraulic conductivity ($K_{\theta s}$) for three soils, four layers and two uses.

Soil	Layers m	Use (1)	Bd Mg m³	Ma	Mi	Tp	$K_{\theta s}$ mm h^{-1}
				---------------- m^3 m^{-3} ----------------			
Hapludox	0.00-0.07	NF	0.84 b	0.28 a	0.41 a	0.68 a	754.82 a
		NT	1.41 a	0.12 b	0.35 b	0.47 b	2.56 b
	0.10-0.15	NF	1.06 b	0.16 a	0.44 a	0.60 a	40.33 a
		NT	1.43 a	0.12 b	0.34 b	0.46 b	1.78 b
	0.25-0.30	NF	1.10 b	0.14 a	0.45 a	0.58 a	119.36 a
		NT	1.40 a	0.10 b	0.37 b	0.47 b	2.51 b
	0.40-0.45	NF	1.23 a	0.09 b	0.44 a	0.54 a	70.59 a
		NT	1.27 a	0.13 a	0.39 b	0.52 a	1.91 b
Hapludalfs	0.00-0.07	NG	1.57 a	0.20 a	0.21 a	0.41 a	58.93 a
		NT	1.57 a	0.18 a	0.22 a	0.41 a	22.79 a
	0.10-0.15	NG	1.55 b	0.20 a	0.22 a	0.42 a	63.31 a
		NT	1.65 a	0.19 a	0.19 b	0.38 b	22.95 a
	0.25-0.30	NG	1.51 b	0.21 a	0.22 a	0.43 a	62.59 a
		NT	1.57 a	0.21 a	0.19 b	0.41 b	38.80 a
	0.40-0.45	NG	1.51 a	0.22 a	0.21 a	0.43 a	45.39 a
		NT	1.48 a	0.23 a	0.20 b	0.44 a	53.98 a
Quartzipsamments	0.00-0.07	NG	1.56 a	0.24 b	0.18 a	0.41 a	251.92 a
		NT	1.44 a	0.33 a	0.13 b	0.46 a	79.58 b
	0.10-0.15	NG	1.62 a	0.25 a	0.15 a	0.40 a	182.35 a
		NT	1.64 a	0.22 a	0.16 a	0.39 a	63.21 b
	0.25-0.30	NG	1.58 a	0.22 a	0.18 a	0.40 a	178.99 a
		NT	1.62 a	0.21 a	0.18 a	0.39 a	82.31 b
	0.40-0.45	NG	1.53 a	0.23 a	0.19 a	0.42 a	210.21 a
		NT	1.54 a	0.22 a	0.20 a	0.42 a	109.42 b

(1) NF = native forest; NT = no-tillage; NG = native grassland.

Means followed by the same letter do not differ significantly (LSD α = 0.05).

The σ_p increased with depth in all three soils (Figure 1), except for NT in the Alfisols. In soils under no traffic (NF and NG), the σ_p was lower compared to soil with farm machinery traffic, particularly in the uppermost soil layer (0.00-0.07 m and 0.10-0.15 m).

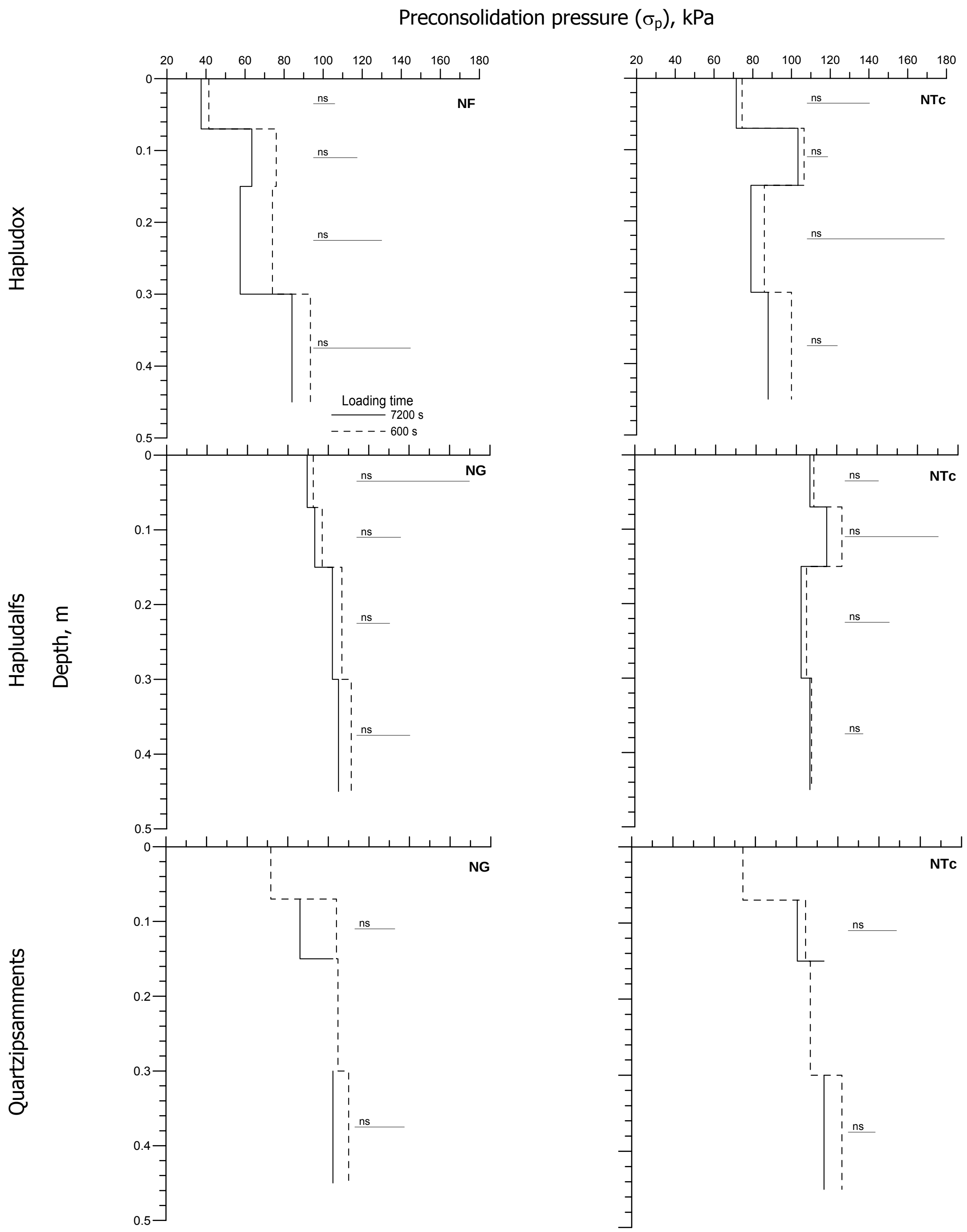

Figure 1 – Preconsolidation pressure with depth for two loading times (600 e 7200 s), for three soils and two uses. NF = native forest NT = no-tillage; NG = native grassland.

In the Oxisols and Alfisols, the highest σ_p was observed for the 0.10-0.15 m layer, an observation which shows the effect of the history of pressure application by farm machines. Such effect was not so clear for the Entisols.

Independently of soil type, use or layer, the lowest σ_p were observed for greater loading time (7200 s), although not statistically different. This shows a tendency for greater soil deformation with larger loading, with a consequent reduction in soil porosity.

The K_a was associated with increased water tension in all soils, with a steeper relation for the Oxisols (Figure 2). Soil use affected K_a only in the surface layer (0.00-0.07 m) of the Oxisols and Alfisols.

For a given water retention, particularly at low tension, the K_a was always lowest in the Oxisols, except for the surface layer in the NF. In this layer, the higher Ma allowed drainage of a higher volume of water, thus favoring air flux. For soils under NT, only at 30 kPa tension the Oxisols reached K_a values similar to the Alfisols and Entisols at 6 kPa tension, for all soil layers.

DISCUSSION

The soil layer 0.10-0.15 m reflected the effect of soil use on the physical and mechanical properties of the three soils, where $K_{\theta s}$ was the soil property more sensitive to structural changes caused by soil use. This result is similar to the observations by *Veiga et al. (2007)* and *Reichert et al. (2009),* who observed that soil compaction caused by farm machinery traffic in no-tillage soils was most evident in the layer of 0.07 to 0.15 m. Reichert el al. (2009) named this layer as no-till part, as an analogy to the "plow pan" observed under conventional tillage.

When taking $K_{\theta s}$ for NF and NG as reference, the $K_{\theta s}$ for NT is 0.36 for the Alfisols, 0.35 for the Entisols and only 0.04 for the Oxisols (Table 3). Thus, there was a reduction of 0.65 for the sandier soil (the first two soils) and of 0.96 for the clayey soil (latest soil). Even though the reference use (NF) in the Oxisols was different than for the other two soils (NG), causing greater changes in Bd and Tp due agricultural use (no-till cropping), there were clear evidences that $K_{\theta s}$ is more dependent on pore geometry and size distribution on than total pore volume. For instance, for Tp of 0.38 and 0.39 m^3 m^{-3} the $K_{\theta s}$ was respectively 22.9 and 63.2 mm h^{-1} (for the Alfisols and Entisols), whereas for Tp of 0.46 m^3 m^{-3} the $K_{\theta s}$ was de 1.8 mm h^{-1} (for the Oxisols). Contrarily to Tp, an increase in Ma (0.12, 0.20 and 0.22 m^3 m^{-3}, respectively for the Oxisols, Alfisols and Entisols) augmented $K_{\theta s}$. A direct relationship between Ma and $K_{\theta s}$ was also observed by *Tuli et al. (2005)*. In terms of soil hydrological processes, the $K_{\theta s}$ data show that it is more difficult to maintain the functional quality of clayey soils, and thus require more attention when managing these soils for agricultural use.

Soil air permeability was less affected by soil use, when compared to the effect on $K_{\theta s}$. The relative K_a was close to 1 for the Alfisols and Entisols, and even greater than 1 (3.01) for the Oxisols. Thus, the relationship between K_a and soil structural quality, as observed by *Ball & Smith (1991)* and *Moldrup et al. (2003),* was less informative on the damage of the soil ecological system caused by soil use and poor management. Therefore, when considering only K_a, a better quality attribute of these soils could be predicted than that given using $K_{\theta s}$ as indicator of soil quality.

Table 3. Relative values (NT/(NF or NG).100) of soil bulk density (Bd), total porosity (Tp), saturated hydraulic conductivity ($K_{\theta s}$), preconsolidation pressure (σ_p) and air conductivity (K_a), in the 0.10-0.15 m soil layer.

Soil	Bd	Tp	$K_{\theta s}$	σ_p	K_a (1)
Hapludox	1.35	0.77	0.04	1.50	3.01
Hapludalfs	1.06	0.90	0.36	1.25	0.74
Quartzipsamments	1.01	0.98	0.35	1.28	0.87

(1) Here K_{ar} values were for soils at field capacity and was assumed the soil moisture values at -15 kPa matric potential.

Although the relative K_a was highest for the Oxisols, the absolute values measured at 15 kPa water tension, for instance, were much lower in these soils (0.10 and 0.30 μm^2 for the NF and NT, respectively). However, K_a values were 1.26 and 2.40 μm^2 for the NF and NT, respectively in the Alfisols; and 1.71 and 1.49 μm^2 for the NG and NT, respectively for the Entisols.

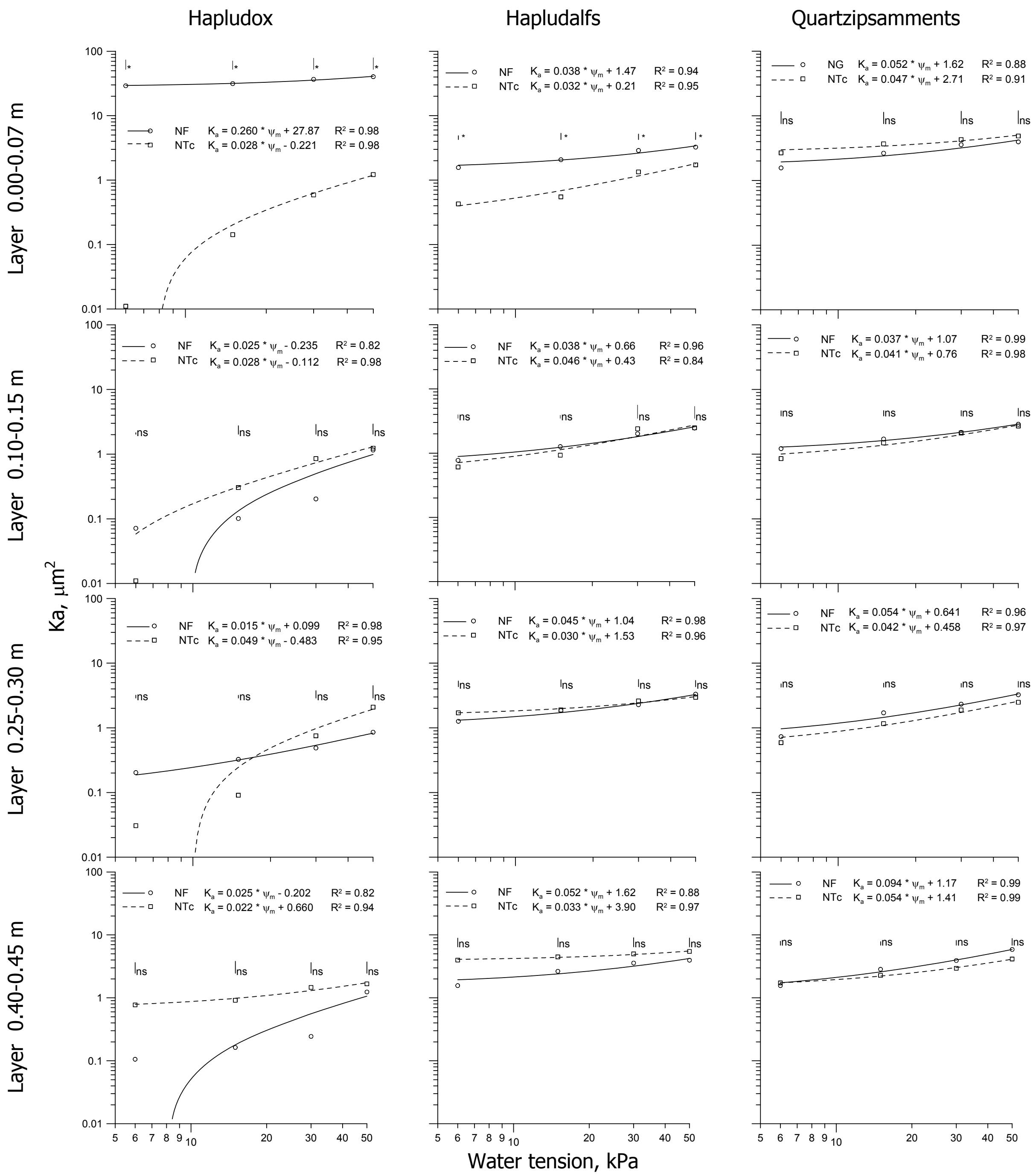

Figure 2 – Air permeability (K_a) as a function of tension, for three soils and four layers. NF = forest native; NT = no-tillage; NG = native grassland.

These differences are associated to pore size distribution and continuity, which in turn controls the proportion of pore space occupied by air or water at a given tension. Even though Tp was highest for the Oxisols, the lesser Ma (Table 1) lowered the pore space for air flow at low water tensions (i.e. moist soil). This behavior was also observed for the other soil layers in the Oxisols.

The level to which soil property changes with soil use was predominantly highest in the Oxisols (Table 2). The mean increases in σ_p were 17 kPa in 0.00-07 m layer and 24 kPa in 0.10-0.15 m layer for NT

Alfisols, whereas for the Oxisols, the increases in σ_p were 32 kPa in 0.00-0.07 m layer, 35 kPa in 0.10-0.15 m layer and 17 kPa in 0.25-0.30 m layer (Figure 1). These results are in agreement with those observed by *Horn & Lebert (1994)* who reported that mechanized no-till cropping compacts clayey soils deeper into the soil profile. Thus, soil aeration and soil redistribution processes are negatively affected to a greater extent as previously discussed for $K_{\theta s}$.

The highest compaction in the Oxisols is a result of heavy farm machinery traffic and the smaller soil particles (Table 1). With a reduction in larger pores, water retention is increased and drainage and permeability is decreased (Reichert et al., 2009), which favors the occurrence of traffic on soils with moisture conditions favorable to soil compaction.

In the Alfisols, farm machinery traffic caused more soil compaction in crop land than animal trampling on natural grassland, but compaction was restricted to surface soil layers. In the Entisols, there was almost no effect of soil use on σ_p, possibly due to greater resistance of sandy soils to compaction. The results also show that sandy soils are less susceptible to compaction. Thus, for a given level of soil mechanization, soil compaction and pore ecological functionality related to air and water fluxes are less affected when continuous no-tillage is practiced on soils with low clay content. Alternatively, improved soil management systems should be used to reduce deleterious effects of soil compactions, particularly on clayey soil.

CONCLUSIONS

Clayey Oxisols is more susceptible to soil compaction and changes in soil structural properties occur beyond the soil surface layer.

Saturated hydraulic conductivity was most affected by soil structure depletion through compaction, whereas air permeability, porosity and density were not significantly affected.

In soils with higher sand content, the structural condition of soils under long-term continuous no-tillage for annual crops was similar to soil under natural grassland with grazing and trampling by beef cattle, although saturated hydraulic conductivity was adversely affected.

REFERENCES

Abu-Hamdeh, N. H. Reeder, R. C., 2003. Measuring and predicting stress distribution under tractive devices in undisturbed soils. Biosystems Engineering 85, 493-502.

Ball, B. C. Smith, K. A., 1991. Gas movement. In: Smith, K. A., Mullins, C.E. (ed.). Soil analysis physical methods. 3rd ed., Madison: Marcel Dekke, pp. 511-549.

Bedard, Y. Tessier, S. Lague, C. Chen, Y., 1997. Soil compaction by manure spreaders equipped with standard and oversized tires and multiple axles. Transactions of the ASAE 40, 37-43.

Blanco-Canqui, H. Lal, R. Post, W. M. Izaurralde, R. C., Shipitalo, M. J., 2007. Soil hydraulic properties influenced by corn stover removal from no-till corn in Ohio. Soil & Tillage Research 92, 144-155.

Dias Júnior, M. S. Pierce, F. J., 1996. The soil compaction process and its modelling. Brazilian Journal of Soil Science 20, 175-182.

Hartge, K. H. Horn, R., 1989. Die physikalische Untersuchung von Böden. Ferdinand Enke Verlag, 3. Auflage, Stuttgart, p. 177.

Horn, R. Lebert, M. 1994. Soil compactability and compressibility. In: Soane, B. D. van Ouwerberk, C. (Eds.) Soil compaction in crop production. Amsterdan: Elsevier. p.45-69

Horn, R., van Der Akker, J. J. H. Arvidson, J., 2000. Subsoil compaction - distribution, processes and consequences. Advances. Geoecology 32, 462p. Catena Verlag, Reiskirche, Germany.

Holtz, R. D. Kovacs, W. D., 1981. An introduction to geotechnical engineering. New Jersey: Prentice-Hall, 733p.

Imhoff, S. Silva, A. P. Dias Junior, M. S. Tormena, C. A., 2001. Quantifying critical pressures for plant growth. Brazilian Journal of Soil Science 25, 11-18.

Iversen, B. V. Per Moldrup, P. Schjønning, P. Jacobsen, O. H., 2003. Field application of a portable air permeameter to characterize spatial variability in air and water permeability. Vadose Zone Journal 2, 618-626.

Lal, R., 1997. Degradation and resilience of soils. Philosophical Transactions of the Royal Society B: Biological Sciences 352, 997-1010.

Letey, J., 1985. Relationship between soil physical properties and crop productions. Advances in Soil Science 1, 277-294.

Moldrup, P. Yoshikawa, S. Olesen, T. Komatsu, T. Rolston, D. E., 2003. Air permeability in undisturbed volcanic ash soils: predictive model test and soil structure fingerprint. Soil Science Society of American Journal 67, 32-40.

Peth, S., 2004. Bodenphysikalische Untersuchungen zur Trittbelastung von Böden bei der Rentierweidewirtschaft an borealen Wald- und subarktischalpinen Tundrenstandorten – Auswirkungen auf thermische, hydraulische und mechanische Bodeneigenschaften. Dissertation, Kiel, p.160.

Reichert, J. M. Suzuki, l. E. A. S. Reinert, D. J. Horn, R. Hakansson, I., 2009. Reference bulk density and critical degree-of-compactness for no-till crop. production in subtropical highly weathered soils. Soil & Tillage Research 102, 242-254.

Rostek, J. Peth, S. Horn, R. Development of a multistep oedometer to analyse the soil behaviour due to cyclic loading. International Soil Tillage Research Organisation 17th Triennial Conference - Kiel, Germany, 2006.

Silva, A. P. Kai, B. D. Perfect, E., 1994. Characterization of the least limiting water range. Soil Science Society of American Journal 58, 1775-1781.

Tuli, A., Hopmans, J. W., Rolston, D. E. Moldrup, P., 2005. Comparison of air and water permeability between disturbed and undisturbed soils. Soil Science Society of American Journal 69, 1361-1371.

Veiga, M. Horn, R. Reinert, D. J. Reichert, J. M., 2007. Soil compressibility and penetrability of an Oxisol from southern Brazil, as affected by long-term tillage systems. Soil & Tillage Research 92, 104-113.

Wood, R. L. Morgan, M. T. Holmes, R. G. Brodbeck, K. N. Carpenter, T. G. Reeder, R. C., 1990. Soil physical properties as affected by traffic: Single, dual and flotation tires. Transactions of the ASAE. 90-1550, St, Joseph, MI: ASAE.