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Soil porosity, permeability and static and dynamic strength parameters under native forest/grassland compared to no-tillage cropping

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ABSTRACT

Improper soil management, increasing farm machinery mass and traffic frequency threaten the ecological functionality of soils under intensive agricultural use. Especially in Brazil, no-tillage (NT) cropping was adopted as a type of soil management that possibly preserves soil functions. Hence, the objective of the present study is to evaluate the effect and intensity of long-term NT compared to soil under natural forest (NF) or grassland (NG) based on parameters of composition (density, porosity, water retention) and functionality by means of mechanical strength (precompression stress σ_p, cyclic compressibility c_n), air permeability K_a, and saturated hydraulic conductivity k_s. The studied Hapludox, Hapludalf and Quartzipsamment from southern Brazil under subtropical climate mostly reacted based upon their grain size distribution, namely clay, loamy sand and loamy fine sand. The largest impact appeared in the Hapludox, where compaction occurred (higher σ_p, lower c_n and smaller porosity, especially macroporosity). k_s and K_a were highest at the surface of the Hapludox under NF, but were reduced strongly under NT. In both the Hapludox and the Hapludalf deeper soil layers were also affected by NT, but in the clayey Hapludox the applied pressure resulted in the largest compacted layer. The Hapludalf of loamy sand texture showed, supposedly due to shallow soil operations, a weak, but permeable surface layer under NT above a dense layer, while the other layers were only slightly affected by cropping. In the Quartzipsamment, there was no increase in σ_p and little in c_n, whereas density in deeper layers slightly decreased. While k_s was increased strongly under NT compared to NG, the opposite was found for K_a which could not be explained by the investigated parameters. The results demonstrate that soil under NT might be significantly affected by soil compaction with regard to soil functions if not adequately managed by adjusted machinery. This is of even greater importance in fine-textured soils like the investigated Hapludox, compared to coarse-textured soils of poor aggregation like the investigated Quartzipsamment.

1. Introduction

Soil degradation is a severe problem in tropical and subtropical environments because of deforestation and improper soil use and management (Lal, 1997). Soil compaction due to heavy machinery or improper soil management threatens soil functionality and should thus be avoided (Horn et al., 2000; Pagliai and Jones, 2002; Reichert et al., 2014). Various studies proved that compaction negatively affects the relations between soil air, water and temperature (Awe et al., 2015a,b; Mentges et al., 2016; Reichert et al., 2016c; Reichert et al., 2015a,b), which directly alter plant growth (Da Silva et al., 1994; Letey, 1958).

Farm operations involving machinery may cause soil compaction, even more intensely in clayey soils (Reichert et al., 2009) than in sandy soils (Abu-Hamdeh and Reeder, 2003), although depending on soil structure, i.e. aggregation type and intensity, clayey soils also may exhibit a high bearing capacity. Traffic frequency of farm machinery or trampling by animals in dependence of their contact pressure (mass per contact area) accumulates stresses and therewith increases the rate of change of soil physical properties (Duttmann et al., 2013). In this regard, the relation between soil compaction and increased weight of farm machines was shown by Bédard et al. (1997), Abu-Hamdeh et al. (1995) and Wood et al. (1991), and proven to be of even greater extent the wetter the soil (Dias Júnior and Pierce, 1996; Duttmann et al., 2014; Silva et al., 2002).

As regular agricultural traffic not only results in volume loss (compaction), but also deforms the soil due to shearing (Horn and Peth, 2011a), density alone is not a sufficiently sensitive parameter to describe the consequences of soil loading because it only defines the mass

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per volume, but not where or how this mass is located or aggregated. Consequently, soils of comparatively low density might have a high bearing capacity, while overcompacted soil due to homogenization may exhibit low strength (Fazekas and Horn, 2005; Holthusen et al., 2012a; Horn et al., 1991). The precompression stress σ_p is a measure for the bearing capacity of a soil, i.e., the load it is capable to withstand without deforming plastically. It is both a measure of the load history of a soil (due to mechanical, hydraulic or physicochemical processes) as well as an index for sustainable loads, i.e., stresses smaller than the precompression stress (Horn and Fleige, 2003; Zink et al., 2010). Furthermore, it is useful in differentiating elastic and plastic deformation as well as complete homogenization (Riggert et al., 2016). Hence, precompression stress (σ_p) is a better indicator of soil compaction by means of a soiĺs capacity to support load (Horn, 2003; Horn and Peth, 2011b).

On the one hand, a compacted soil supports higher loads without further alterations of soil functions like hydraulic conductivity due to stress attenuation, and allows for optimizing the operational performance of farm machinery. However, a higher degree of compaction may restrict important processes in the soils such as air and water fluxes (Reichert et al., 2009; Schjønning et al., 2013) and negatively affect plant growth (Houlbrooke et al., 1997; Krebstein et al., 2014). Especially in deformable, e.g., loamy to clayey or poorly aggregated soils, loads are transmitted to deeper layers of the soil profile, increasing the extent of compacted layers (Peth et al., 2006). This subsoil compaction results in an increased damage of soil ecological functionality as these layers are less resilient due to less intense swelling and shrinkage, thawing and freezing as well as lower content of organic matter, less biological activity and other aggregating agents (Horn et al., 2000).

The soil's capacity to fulfill ecological functions in agroecosystems can be derived from its permeability for air and water, usually described with the help of air permeability K_a, unsaturated hydraulic conductivity k_s and unsaturated hydraulic conductivity as a function of soil water pressure head, $k_u(h)$. Especially K_a is a suitable indicator of changes in the soil pore system caused by soil use and management because it is more sensitive to changes in the porous system then density or air capacity itself (Ball and Smith, 1991; Schjønning et al., 2013). Both water and air fluxes favor large and continuous pores (Iversen et al., 2003), making the one a possible predictor of the other (Blanco-Canqui et al., 2007). Especially biopores of predominantly vertical orientation give raise to increased soil strength and, furthermore, even if compaction occurs, these pores are less susceptible to destruction, allowing for still high pore functionality despite compaction (Schäffer et al., 2008a,b).

The relationship between soil pore functionality and soil bearing capacity was already investigated in several soil types in many regions; however, there is a gap of knowledge regarding tropical and subtropical soils. Especially in Brazil, the common conservation soil management (no tillage) might help maintain the soil functionality as possible compaction remains limited to shallow depths. Hence, the objective of our study was to evaluate comprehensively the reaction of three differently textured subtropical soils under no-tillage cropping in comparison with natural conditions (forest, grassland) to static and dynamic loading by means of density and pore capacities as well as air permeability and water conductivity.

2. Material and methods

2.1. Studied soils

Three soils from southern Brazil were investigated, namely a Typic Hapludox (Passo Fundo), a Typic Hapludalf (Santa Maria), and a Typic Quartzipsamment (São Francisco de Assis) (according to USDA, 2014b). Hapludoxes are Oxisols with an udic moisture regime and low fertility, characterized by low base saturation and acid soil reaction, and they exhibit little difference in clay content from surface to subsoil layers (USDA, 2014a). Hapludalfs are Alfisols with udic moisture regime and a clay-enriched subsoil horizon below an eluvial horizon, while the Quartzipsamments are sandy Entisols (Psamments), dominated by quartz and other minerals highly resistant to weathering, causing low water-holding capacity and a generally high need of supplemental water and nutrients if cultivated (USDA, 2014b). The Hapludox in about 650 m altitude is characterized by a minimum monthly rainfall of 60 mm and is situated in the climatic zone “Cfa” to “Cfb” according to the Köppen-Geiger classification (Peel et al., 2007). Both the Hapludalf and the Quartzipsamment are located in a subtropical humid climate zone without drought (“Cfa”) in about 95 m altitude.

At each site, soil under 14 years of continuous no-tillage (NT) was compared to a reference area under natural conditions, which was native forest (NF) for the Hapludox and native grassland (NG) for the Hapludalf and the Quartzipsamment. For each pair of sites, care was taken to choose most similar areas, i.e., of similar slope and in closest distance possible (less than 50 m). The Hapludox under NT was cultivated with wheat during winter, and soybeans and corn during summer. The other soils were cultivated also with soybeans in summer, while during winter the soil was covered by oat and lolium grass, which are desiccated for the drilling of the following crop. The cropped soil was trafficked by farm machines with contact pressures/contact areas of 124 kPa/0.140 m^2 (tractor) and 169 kPa/0.183 m^2 (harvester) in the Hapludox, and 90 kPa/0.189 (tractor) and 121 m^2/0.263 kPa (harvester) in the Hapludalf, while for the Quartzipsamment the load history could not be evaluated due to comprehensive recent changes in machinery. The Hapludox under natural forest did not experience any animal trampling or machinery, while beef cattle periodically grazed the Hapludalf and the Quartzipsamment.

Grain size distribution by sieving and sedimentation in three repetitions according to Smith and Mullins (2001) resulted in the textural classes shown in Table 1. The Hapludox and the Hapludalf are a clay and a sandy loam, respectively, while the Quartzipsamment was classified as loamy fine sand in the first two layers and as sandy loam in the last two layers. The organic matter contents in the studied soils in the upper 20 cm of the soils were on average 3.1 and 3.0% in the Hapludox (dos Santos et al., 2015), 1.8 and 1.3% in the Hapludalf (Awe et al., 2015a; Vogelmann et al., 2013) and 0.6 and 0.2 in the Quartzipsamment (Reichert et al., 2016a). The differences are more pronounced at the surface (4.0 vs. 3.6%, 2.7 vs. 1.4 and 0.7 vs. 0.3 in the Hapludox, Hapludalf and Quartzipsamment, respectively).

2.2. Sampling and measurements

Soil samples were collected in depths of 0.00–0.07, 0.10–0.15, 0.25–0.30 and 0.40–0.45 m. For the determination of precompression stress and cyclic compressibility, undisturbed soil was collected in steel cylinders of 0.10 m diameter and 0.03 m height with three replicates;

Table 1
Mean particle size distribution of the studied soils; bold the dominant fraction, texture according to USDA (2014a,b).

Soil	Depth (m)	Sand (g kg^{-1})	Silt	Clay	Texture (−)
Hapludox	0.00–0.07	349	201	**450**	Clay
	0.10–0.15	268	184	**548**	
	0.25–0.30	300	133	**567**	
	0.40–0.45	301	185	**514**	
Hapludalf	0.00–0.07	**632**	276	92	Sandy Loam
	0.10–0.15	**626**	295	79	
	0.25–0.30	**618**	290	92	
	0.40–0.45	**586**	322	92	
Quartzipsamment	0.00–0.07	**838**	67	95	Loamy fine sand
	0.10–0.15	**831**	61	108	
	0.25–0.30	**781**	72	147	Sandy loam
	0.40–0.45	**753**	91	156	