Soil & Tillage Research 184 (2018) 78–92

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Soil functions and in situ stress distribution in subtropical soils as affected by land use, vehicle type, tire inflation pressure and plant residue removal

Dörthe Holthusen[a,*], André Anibal Brandt[b], José Miguel Reichert[a], Rainer Horn[c], Heiner Fleige[c], Alexander Zink[d]

[a] Soils Department, Universidade Federal de Santa Maria (UFSM), Brazil
[b] Agronomy Department, Universidade do Estado de Santa Catarina (UDESC), Lages, Brazil
[c] Institute of Plant Nutrition and Soil Science, Christian-Albrechts-University, Kiel, Germany
[d] GZP, center of innovation and technology (KITZ), Kiel, Germany

ARTICLE INFO

Keywords:
Soil bearing capacity
Agricultural machinery
Contact pressure
Soil functionality
Stress state transducer

ABSTRACT

Soil deformation due to compaction and shearing with heavy machinery is still one of the largest threats to soil functionality and thus to crop performance on arable soil. By determining the in-situ stress input and propagation due to tractor and harvester wheeling on two south Brazilian soils, a Typic Hapludox and a Typic Hapludalf, we aimed to investigate the consequences of different wheeling conditions on soil composition and functions. Stress state transducer (SST) sensors were installed in three to four soil depths to measure stress impact and propagation and to quantify the effect of different contact pressures by different agricultural machines, tire inflation pressures, and absence or presence of plant residues on soil under no-tillage (NT, each Hapludox and Hapludalf) and natural grassland (NG, only Hapludalf). Field measurements of principal stress σ_1 were amended by laboratory analyses to quantify changes of soil precompression stress σ_p, air permeability, and water retention before and after the passage of a harvester.

Wheeling with heavy load in the Hapludox under NT even ruptured the "no-till pan", resulting in lower σ_p, while the Hapludalf under NT was compressed more and became more stable. The biologically stabilized Hapludalf under NG suffered strongly from wheeling by reduced σ_p, water retention, and air permeability. Reasons for this behavior are clayey (Hapludox) vs. sandy loam soil texture (Hapludalf) as well as higher bulk density in the Hapludalfs than in the Hapludox. By comparing the evaluated factors, the most pronounced impact was found for tire inflation pressure. Lower pressure strongly diminished contact pressure and σ_1 in the soil. Straw had a similar, but less striking effect. The harvester, being heavier than the tractor, caused higher stress input and altered soil physical properties profoundly in all sites. Subsequent passes lead to further compaction, though of decreasing intensity with each additional pass. The effect was the stronger, the closer to the surface, but the surface layer itself showed a quite irregular result due to lug/interlug interactions.

A low contact pressure, e.g. by low tire inflation pressure, is an efficient measure to avoid harmful soil compaction. Keeping plant residues also helps in preserving soil structure, but is less efficient in the short-term.

1. Introduction

The knowledge of bearing capacity of soils at a given water content or matric potential is crucial for sustainable soil management, to avoid compaction especially in the subsoil. A certain state of compaction seems acceptable to guarantee trafficability and workability of the soil within a broad range of water contents (Smucker and Erickson, 1989) and extended water availability in dry periods (Camargo and Alleoni, 1997; Raghavan and McKyes, 1983). But overconsolidated soil mostly exhibits negative properties like a lack of pores and/or pore connectivity (Schjønning et al., 2013; Reichert et al., 2007; Streck et al., 2004) and requires more fuel and mechanical power to be worked (Bicki and Siemens, 1991; Soane, 1990) due to increased density (Kim et al., 2010; Krebstein et al., 2014).

Compacted soil directly influences plant growth as it reduces both radicular and vertical plant root development and impedes germination (Suzuki et al., 2007; Foloni et al., 2003; Glab, 2013; Whalley et al., 1995). Furthermore, it negatively affects plant nutrition due to a lack of accessible pores both storing and conducting water and air together with a low available surface area and thus "entrapped" nutrients. As

---

* Corresponding author.
E-mail address: Doerthe.Holthusen@web.de (D. Holthusen).

https://doi.org/10.1016/j.still.2018.07.009
Received 28 March 2018; Received in revised form 11 July 2018; Accepted 18 July 2018

hence less soil volume is available and furthermore that small volume being difficult to explore, crop productivity is lowered pronouncedly (Collares et al., 2006, 2008; Czyz, 2004; de Marins et al., 2018; Ivonir Gubiani et al., 2014; Lipiec et al., 2003; Merotto and Mundstock, 1999).

The factors influencing the impact of soil loading and its resulting compaction are of either external or internal nature. Examples for the first are the load, the contact area, the duration of the loading, and kind of loading (e.g. single or multiple loading events and temporal distance between single loading events), while the latter unites intrinsic soil properties like initial water content or density (Horn et al., 2000). To achieve favorably low contact pressures (ratio of pressure per contact area) for least stress transmission into the soil, different approaches are in use (Hamza and Anderson, 2005). Especially in soil under conservational management (no-tillage, direct drilling), residues on the surface attenuate the stress propagation in a positive way. As they are of soft, elastic consistence, they are capable to adsorb part of the incoming stresses and thus help avoid soil compaction (Blanco-Canqui et al., 2006; Braida et al., 2006; Dao, 1996; Ess et al., 1998; Reichert et al., 2016a).

Another common method to reduce vertical stress propagation and thus, soil compaction and soil deformation, is to lower the air pressure of the tires to create larger areas of contact (Arvidsson and Keller, 2007; Keller and Arvidsson, 2004). However, as vertical and horizontal stress distribution can differ remarkably and carcass stiffness impedes the effect, until now there is no general statement available about stress propagation or attenuation strategies in combination with the varying rigidity of structured unsaturated soils. Hence, quite a number of laboratory studies with the help of precompression stress measurements was executed to investigate the effects of external factors on different soil types at various water contents and initial densities (e.g. Arthur et al., 2013; Berli et al., 2015; Chaplain et al., 2011; Destain et al., 2016; Horn, 2003; Räty et al., 2010; Silva et al., 2002). However, it became obvious that the stress propagation in the field is more complex and deserves its own observation (Wiermann, 1998; Wiermann et al., 2000; Arvidsson and Keller, 2004; Keller et al., 2004; Riggert et al., 2016, 2017), e.g. with the in-situ use of stress state transducers (SST) (Horn et al., 1992; Zink et al., 2010). The SST is a spherical sensor that records both the main stresses as well as transversal (shear) stresses and, when installed in various depths, allows for in-depth observation of loading effects on the soil. When using SST in the field for comparing a Luvisol from Loess under conventional and reduced tillage Luvisol, Wiermann et al. (2000) found a more stable soil structure and less stress propagation in conservation tillage plots, assuming a higher ability to recover even from large wheel loads and repeated passes. These results were later confirmed by Pytka (2001) in an in-situ laboratory study.

As the in-situ measurement of stress propagation and distribution due to agricultural traffic with the help of SST is quite labor-intensive and the equipment is restricted to few laboratories, there are very limited data sets. Especially for Brazil, the application of SST should contribute profoundly to the understanding of the compaction process in Hapludox and Hapludalf under different land uses, as affected by different external factors. The objective of our study was to detect the effect of wheeling on these two representative soils in South Brazil under natural conditions and/or no-tillage agricultural use, with and without residue removal and with different vehicles/loads, tire inflation pressures and amount of passes. We hypothesized a stronger effect of wheeling on soils under natural grassland than under already traffic-intensive no-tillage land use. Furthermore, we expected higher susceptibility and larger stress propagation in soils of more clayey texture, without residues and wheeled with higher loads/higher tire inflation pressure. The effects are supposed to increase with increasing number of passes. To verify our hypotheses, SST measurements were applied to detect stress propagation in-situ, while laboratory analyses of air permeability and water retention complemented the field data of the wheeling trials.

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

Soil	Depth (m)	Sand ($g\,kg^{-1}$)	Silt	Clay	Texture (-)
Hapludox, NT	0.00 - 0.07	348	201	**451**	Clay
	0.10 - 0.15	325	198	**477**	
	0.25 - 0.30	352	81	**567**	
	0.40 - 0.45	280	164	**556**	
Hapludalf, NG	0.00 - 0.07	**635**	282	83	Sandy Loam
	0.10 - 0.15	**631**	297	72	
	0.25 - 0.30	**626**	288	86	
	0.40 - 0.45	**597**	326	78	
Hapludalf, NT	0.00 - 0.07	**629**	270	101	Sandy Loam
	0.10 - 0.15	**621**	293	86	
	0.25 - 0.30	**610**	291	99	
	0.40 - 0.45	**574**	319	107	

2. Material and methods

2.1. Experimental sites

The experiments were conducted on two different subtropical soils in South Brazil of distinctively different texture that were classified according to USDA (2014) as a Typic Hapludox (Oxisol) on the experimental area of the Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuaria – Embrapa Trigo) in Passo Fundo, and a Typic Hapludalf (Alfisol) on the experimental area of the Federal University in Santa Maria, both described in more detail by Holthusen et al. (2018) and Reichert et al. (2018). At the time of the wheeling experiment, in 2006, both the Hapludox and the Hapludalf had experienced conservational tillage (no tillage) for 14 years. The Hapludox had been usually cultivated with wheat (during summer), soybean, and corn (during winter). The Hapludalf was investigated under both natural grassland (NG) and no-tillage conditions (NT), the latter being characterized by oat and lolium grass cultivation, while the first was occasionally subjected to animal trampling and exhibited a generally low soil fertility with sparse grassland vegetation.

The grain size distribution of the corresponding soils is given in Table 1. While the Hapludox is dominated by clay, the two Hapludalfs are sandy soils. The organic matter content in the first 20 cm of the given soils is 3.0, 1.8 and 1.4% ($kg\ kg^{-1}$) for the Hapludox (NT), Hapludalf (NG) and Hapludalf (NT), respectively (Awe et al., 2015; dos Santos et al., 2015; Vogelmann et al., 2013).

As the initial conditions during wheeling have a pronounced impact on stress propagation in the soil, they were evaluated by means of gravimetric water content Θ_{grav} and bulk density ρ_B (Table 2). From the later-on determined water retention curve, it was possible to estimate the matric potential of the field soil without having to install

Table 2
Initial soil conditions before wheeling: gravimetric water content Θ_{grav}, bulk density ρ_B and calculated corresponding matric potential Ψ_m (n = 1–3).

Soil	Depth (m)	Θ_{grav} ($g\,g^{-1}$)	ρ_B ($Mg\,m^{-3}$)	Ψ_m (kPa)
Hapludox, NT	0.00 - 0.07	0.308	1.41	−210
	0.10 - 0.15	0.285	1.43	−193
	0.25 - 0.30	0.312	1.40	−73
	0.40 - 0.45	0.339	1.27	−78
Hapludalf, NG	0.00 - 0.07	0.106	1.57	−872
	0.10 - 0.15	0.127	1.55	−232
	0.25 - 0.30	0.111	1.51	−534
	0.40 - 0.45	0.117	1.51	−231
Hapludalf, NT	0.00 - 0.07	0.101	1.57	−324
	0.10 - 0.15	0.123	1.65	−173
	0.25 - 0.30	0.128	1.57	−147
	0.40 - 0.45	0.122	1.48	−179