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Dynamics of pore functions and gas transport parameters in artificially ameliorated soils due to static and cyclic loading

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ABSTRACT

Soil compaction is one of the main threats to sustain soil quality in modern agriculture. To improve our understanding concerning the interaction between soil physical properties and stress-strain on pore functions and soil aeration, measurements were performed with three different textures (sand, silt loam, clay loam), two matric potentials (-60 and -300 hPa), three compaction levels (50, 100 and 200 kPa) and two loading types (static and cyclic loading). Soil compaction led to a reduction in air-filled porosity ε_a, air permeability K_a, and relative gas diffusivity D_s/D_o. The differences in K_a and D_s/D_o among various treatments depend on the remaining air-filled porosity, pore continuity, and pore tortuosity. The water blockage effect on K_a and D_s/D_o with lower ε_a also should be considered sometimes after compaction. The question of how far the compacted and deformed soils can be ameliorated was tested in the same set of samples by artificially prepared five vertical holes. Due to this procedure of vertically arranged continuous and non-tortuous holes in the samples, the values of K_a even significantly increased up to more than one order of magnitude, and the values of D_s/D_o also increased obviously, even though the volume of air-filled pores only increased slightly. This situation was mainly attributable to the significant increase in pore continuity and a decrease in pore tortuosity compared to without vertical holes. We also found that there were minor differences on K_a but distinct differences on D_s/Do among all treatments after having drilled vertical holes.

1. Introduction

Globally, soil compaction is one of the most harmful processes to threaten soil quality. About 33 million ha of arable land in Europe and 68 million ha worldwide are seriously degraded by soil compaction (Peth et al., 2010). It can be caused naturally due to freezing-thawing (Defossez and Richard, 2002), swelling-shrinkage (Pagliai et al., 2003) and internal forces by clay migration or organic acids, or glacial processes (Hartge and Horn, 2016). Furthermore, soil deformation can be induced by external forces such as animal trampling (Hamza and Anderson, 2005; Krümmelbein et al., 2006), farm machinery traffic (Horn et al., 1995; Wiermann et al., 2000) and shear processes which even enhance the soil deformation processes. Among these factors, nonsite adjusted use of machinery has been recognized as the most common reason of soil compaction in agriculture especially if shearing and hydraulic processes are included (Saffih-Hdadi et al., 2009; Kuncoro et al., 2014). To meet the demands of modern agriculture, the weight of machinery has increased in recent decades (Berisso et al., 2012), which further enhances the unpredictability of crop yields, soil functions, environmental and climate change processes (Horn, 2015).

The sensitivity of soils for compaction depends on internal properties like texture and structure, amount and composition of organic matter, actual and former minimum matric potential, chemical properties, and biological processes. External factors like intensity, number of wheeling events and kind of loading (static/dynamic) alter the soil functions as well as the resilience of the soils mostly irreversibly if external stresses applied exceed the internal soil strength (Horn, 1981; Alakukku, 1996; Peng et al., 2004; Peth et al., 2010; Barik et al., 2014; Głąb, 2014; Horn et al., 1995).

Static loading leads to an increase in soil bulk density (Schäffer et al., 2008; Kim et al., 2010), primarily reducing large pores, and it also alters pore morphology and continuity (Servadio et al., 2001; Richard et al., 2001; Munkholm et al., 2002; Chen et al., 2014; Riggert et al., 2015). Consequently, soil aeration and gas fluxes are reduced or retarded which not only affects plant growth but it also alters the production and emission of greenhouse gases (Hamza and Anderson, 2005; Kim et al., 2010; Głąb, 2014; Glinski et al., 2011). In contrast to static loading, dynamic processes can create both a shear-induced deterioration of the pore arrangement and continuity as well as it will if puddling is included under wet soil conditions also completely

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Table 1
Basic physical and chemical properties of studied arable soils.

Sampling site	Depth (cm)	Particle size distribution (%)			Soil texture	pH ($CaCl_2$)	$CaCO_3$ (%)	OM (%)
		Sand	Silt	Clay				
		63–2000 µm	2–63 µm	< 2 µm				
Schuby	5–20	85.82	10.18	4.00	Sand	5.00	0.07	6.34
Bonn	5–20	10.68	73.10	16.21	Silt loam	7.39	0.21	2.04
Fehmarn	35–55	38.33	25.32	36.35	Clay loam	7.59	13.92	0.72

homogenize the formerly existing soil structure up to the complete loss of all strength. Dynamic i.e. repeated loading also results in cumulative effects which can be defined as time dependent strain effects (Wiermann et al., 2000; Alakukku et al., 2003). The first loading event causes the most probably soil deformation by a significant volume loss and a change in soil functions which can be detected down to deeper depth (Hamza and Anderson, 2005; Berisso et al., 2012; Horn, 1981; Horn et al., 1995; Hartge and Horn, 2016).

In recent studies, some contradictory conclusions related to the effect of compaction on gas transport parameters have been reported. Naveed et al. (2016) observed that air permeability was reduced by 55–80% for topsoils (5–25 cm depth) and by 10–20% for subsoils (25–35 cm depth) under 620 kPa stress and this reduction was associated with lower total porosity and macroporosity and Chen et al. (2014) found that air permeability in 0–12 cm soil depth was decreased with the level of compaction and this reduction was related to the increase of pore tortuosity and the decrease of pore continuity. In the work of Ball and Ritchie (1999), relative gas diffusivity on undisturbed soil with the texture between loam and sandy loam from 0 to 25 cm decreased after heavy compaction using a laden tractor (up to 4.2 Mg). On the contrary, Kuncoro et al. (2014) observed that air permeability in soil mixed with rice straw was lower than in the control soil at compaction levels of 150 and 225 kPa, even though its air content was a bit higher. They proposed that the presence of soil organic matter was likely to block soil pores and might also facilitate the formation of bottle-necks by water menisci, which results in lower air permeability in soils mixed with organic matter than in the control soil for a given air content. Fujikawa and Miyazaki (2005) reported that soil compaction led to an increase in D_s/D_o at the same air-filled porosity, probably due to lower volumetric water content. Lower water blockage effects resulted in the increase in active air-filled pore space for gas diffusion.

To investigate whether differences in K_a are only attributed to differences in air-filled porosity or whether they should be attributed partly to geometrical aspects of the air-filled pore space, such as pore size distribution, tortuosity, and continuity. Groenevelt et al. (1984) introduced two pore continuity indexes (C_2 and C_3), which were further verified by Ball et al. (1988), Blackwell et al. (1990), and Dörner et al. (2012). They proposed that soils with similar values of C_2 have similar pore size distributions and pore continuities whereas soils with similar values of C_3, have similar pore size distributions only, so that differences between C_2 and C_3 can be related to differences in pore continuity independent of pore size distribution. For gas diffusion, Currie (1960) proposed that D_s/D_o was affected not only by porosity, but also by pore tortuosity. This info was also confirmed by Ball, 1981, Moldrup et al., 2001 and Hamamoto et al., 2009. Zhai and Horn (2018) determined soil aeration properties at the compaction level of 50 kPa as a function of texture (sand, silt loam, clay loam), matric potential (−60 hPa and − 300 hPa) and soil structure (vertical holes). However, the effects of compaction levels and kinds of stress applications on pore functions and gas transport are mostly unknown although it is obvious that the effect of vertical biopores on gas exchange in soils should improve the gas exchange more effective than at random pores due to the better stress attenuation of vertical systems (for more details also see Hartge and Horn, 2016). Therefore, the objective of the experiments was to investigate:

i. effects of static and cyclic loading with different compaction levels (50, 100 and 200 kPa) on pore properties like air-filled porosity, pore continuity, pore tortuosity and gas transport parameters (air permeability and relative gas diffusivity),
ii. effects of the quantity and quality of air-filled pores on the changes in K_a and D_s/D_o,
iii. the impact of vertical holes on the above mentioned functions.

2. Material and methods

2.1. Soil sampling and properties

Disturbed soil samples with different textures were collected from three sites in Germany: (i) the sandy material of a Podsol derived from glacial outwash was collected at the experimental agricultural site located in Schuby (54°52′N, 9°45′E) where the vegetation is annual ryegrass (*Lolium multiflorum*). (ii) The silt loam substrate of a Haplic Luvisol derived from loess was collected at the experimental station Klein Altendorf (50°37′N, 6°59′E) in Bonn with the land use of cropland. (iii) The clayey material of a Stagnosol derived from glacial till and is located in Fehmarn (54°27′N, 11°16′E) where the land use is cropland. The basic soil properties are shown in Table 1.

2.2. Sample preparation

The samples were air-dried, sieved through 2 mm and then repacked in 235 cm^3 soil cylinders (10 cm wide and 3 cm long) with an initial dry bulk density of 1.4 g/cm^3. The soil cylinders were saturated and then successively drained to matric potentials of −60 hPa on sandboxes and −300 hPa on ceramic plates. The cylinders of clay loam soil at the matric potential of −60 hPa were not prepared, due to the extremely low air-filled porosity which would result in very small values of air permeability and gas diffusivity (close to zero).

In both silty and clayey samples occur obviously shrinkage from saturation to the matric potential of −300 hPa, resulting in the change of initial bulk density and an enhanced preferential airflow through the cracks within the soil sample. Therefore, the cylinders of silt loam and clay loam soil at the matric potential of −300 hPa were prepared as follows: the corresponding water contents of silt loam and clay loam soil at the matric potential of −300 hPa were tested. The air-dried samples were wetted by spraying distilled water to achieve the desired water content and kept in plastic bags for 24 h, to achieve a homogeneous distribution of water in the samples. Thereafter, the prepared soil samples were repacked into the cylinders.

2.3. Compaction experiments

The prepared cylinders were compacted under static loads of 50, 100 and 200 kPa, respectively. The stress was applied for 4 h, followed by an unloading for 1 h. Prior to the loading and thereafter the air permeability and gas diffusivity were determined. Then, all cylinders were compacted under cyclic load (50 cycles) with an identical external