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Effects of subsoil compaction on hydraulic properties and preferential flow in a Swedish clay soil

M. Mossadeghi-Björklund[a,*], J. Arvidsson[a], T. Keller[a,b], J. Koestel[a], M. Lamandé[c], M. Larsbo[a], N. Jarvis[a]

[a] Swedish University of Agricultural Sciences, Department of Soil and Environment, P.O. Box 7014, SE-750 07 Uppsala, Sweden
[b] Agroscope, Department of Natural Resources and Agriculture, Reckenholzstrasse 191, CH-8046 Zürich, Switzerland
[c] Aarhus University, Department of Agroecology, Research Centre Foulum, Box 50, DK-8830 Tjele, Denmark

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ABSTRACT

Soil compaction by vehicular traffic modifies the pore structure and soil hydraulic properties. These changes potentially influence the occurrence of preferential flow, which so far has been little studied. Our aim was to study the effect of compaction on soil hydraulic and transport properties in subsoil. A randomized block design trial at two sites on a well-structured clay soil in central Sweden was established. Plots with two levels of compaction were created at both sites, in the following referred to as trafficked and control. The trafficked treatment was created by 4 passes track-by-track with a three-axle dumper with a maximum wheel load of 5.8 Mg. After one year, undisturbed soil columns (20 cm height × 20 cm diameter) from both trafficked and control plots at a depth of 30–50 cm were sampled. The columns were analyzed using X-ray CT imaging, together with measures of the degree of preferential transport derived from non-reactive tracer breakthrough curves and measurements of saturated hydraulic conductivity (K_s) and air permeability at the field moisture content (K_a).

Although the traffic treatment did not cause any compaction effects at one of the two sites, it did result in significant reductions in saturated hydraulic conductivity, air permeability and number of macropores at the second site. At this site, the traffic also significantly reduced the strength of preferential flow, presumably due to compaction-induced disruption of macropore continuity. In apparent contrast, some previous studies have shown increases in the strength of preferential flow as a result of compaction. We propose a conceptual model to explain these apparently contradictory results, which suggests that preferential flow should be strongest at some intermediate level of compaction.

1. Introduction

Compaction is the process by which soil bulk density increases and porosity decreases, for example due to vehicular traffic. Compaction not only reduces total pore volume but also modifies the pore size distribution, geometry, morphology and connectivity of soil pores (e.g., Servadio et al., 2001). Compaction reduces the saturated and near-saturated hydraulic conductivity of soil (Arvidsson, 1997; Schwen et al., 2011) and also leads to poorer aeration and crop growth and an increased risk of surface runoff (Lipiec and Hatano, 2003). Whereas the effects of topsoil compaction may be partly alleviated when the soil is mouldboard ploughed (Arvidsson and Håkansson, 1996), effects of subsoil compaction persist much longer, and may even be more or less permanent (Etana and Håkansson, 1994). Due to its persistence, subsoil compaction is a major concern in agriculture. Although compaction decreases hydraulic conductivity at and close to saturation, it may cause an increase in conductivity at larger water tensions (i.e., water contents below field capacity), due to an improved connectivity between these smaller pores, which may also increase in volume (Lipiec and Hatano, 2003; Lipiec et al., 2009; Richard et al., 2001).

Changes in the characteristics and geometry of structural pore networks following compaction may also significantly influence solute transport in soil, especially the risk of rapid preferential solute transport under near-saturated and saturated conditions in soil macropores (Hendrickx and Flury, 2001; Jarvis, 2007). However, these effects are still poorly understood and the results of the few studies so far that have investigated this question seem contradictory. As compaction mainly disrupts or destroys macropores in soil, it might be expected to reduce the extent of preferential flow. Heitman et al. (2007) found that trafficked areas

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[*] Corresponding author.
E-mail address: mona.mossadeghi@slu.se (M. Mossadeghi-Björklund).

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of the field showed a slower breakthrough of non-reactive solute. On the other hand, Koestel et al. (2013), Katuwal et al. (2015a) and Soares et al. (2015) found for breakthrough curve experiments on undisturbed soil columns that the strength of preferential transport was positively correlated with bulk density. However, none of these studies investigated the impact of discrete compaction events. Mooney and Nipattasuk (2003) found for sieved and repacked samples that compaction increased preferential flow in a sandy loam, whereas preferential flow was detected at all compaction levels in a clay loam. Dye tracing studies have demonstrated that strong preferential flow may be induced in any macropores remaining after the compaction event or those that are subsequently re-generated due to physical (i.e., swell/shrink) or biological processes (e.g., root growth, faunal activity) (Alaoui and Goetz, 2008; Etana et al., 2013; Janssen and Lennartz, 2008; Kulli et al., 2003). Annual tillage also creates large voids which allow preferential flow and solute fluxes to by-pass denser traffic-compacted zones or clods in the plow layer (Coquet et al., 2005; Janssen and Lennartz, 2008).

Knowledge of the 3-D macropore network structure is essential for a quantitative understanding of the impact of soil compaction on soil susceptibility to rapid preferential flow. There are many methods available to quantify macropore networks in soil, each with their own advantages and disadvantages (Allaire et al., 2009). In this study, we used X-ray tomography to visualize and quantify soil pore structures (Kim et al., 2010; Lamandé et al., 2013; Pires, 2011; Schjønning et al., 2013; Larsbo et al., 2014) in 20 cm diameter soil columns taken from the upper subsoil (i.e., below the depth of tillage at 30–50 cm) of control and trafficked plots at two nearby field sites on a clay soil in Sweden. The imaged soil macroporosity was related to saturated hydraulic conductivity, air permeability and non-reactive tracer breakthrough measured on the same samples.

2. Materials and methods

2.1. Site description and sampling

Two wheeling experiments were carried out at two field sites on a well-structured clay soil (hereafter denoted as the Upper site and the Lower site) close to Uppsala (59°48′N, 17°39′E), in central Sweden. The two sites were situated approximately 300 m apart. The climate at the site is cold-temperate and semi-humid with an average annual temperature of 5.5 °C and an average annual precipitation of 527 mm (1961–1990). The coldest month is January (mean −4.9 °C) and the warmest is July (mean +16.4 °C). The soil is classified as a Eutric Cambisol in the WRB system and has a strong prismatic structure in the subsoil. The field is cultivated in a rotation dominated by cereals, with barley (*Hordeum vulgare* L.), winter wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.) and spring oilseed rape (*Brassica napus* L.) as the main crops. Some basic soil properties are presented in Table 1. Soil texture was measured by the pipette method and organic matter content was estimated using the loss on ignition method (Schulte and Hopkins, 1996) for both soils.

The experiment was designed as a randomized block trial with 2 treatments (trafficked and control), with 4 blocks at each site, and a plot size of 9 × 20 m. In November 2010, the trafficked treatment was created by four passes track-by-track with a three-axle dumper truck (Bell B25D 6 × 6) with 5.8, 5.4 and 4.6 Mg wheel load on the first, second and third axle and 420 kPa tyre inflation pressure (tyre size: 23.5R25) when the soil was at field capacity. The Upper site was under grass ley at this time, while the surface of the Lower site was covered with cereal stubble following the harvest of the previous crop. After wheeling, both sites were mouldboard ploughed to a depth of approximately 20 cm. In 2011, spring oats was grown on both sites and harvested at the end of August. On 20 September, 32 undisturbed soil columns, 2 from each plot (20 cm height and 20 cm diameter) were sampled from both trafficked and control plots at a depth of 0.3–0.5 m using a tractor-mounted hydraulic press. After sampling, the soil columns were stored at 1 °C until analysis in order to prevent earthworm activity inside the columns. During storage, the soil columns were tightly closed at both ends to restrict evaporation. Before starting the laboratory measurements, the tops and bottoms of the soil columns were carefully trimmed with the point of a sharp-edged knife to reveal undisturbed soil.

2.2. Computer tomography imaging

A medical CT-scanner (SIEMENS Biograph Truepoint 64 combined CT/PET) at the Aarhus Hospital in Denmark was used to visualize the macropore system in the large soil columns. A voltage of 120 kV with a flux of 600 mAs and exposure time of 1 s were used to X-ray scan the soil columns. The soil columns were first prepared by removing loose particles on the surface with a vaccum cleaner. The soil columns were scanned at the field moisture content at the time of sampling which was drier than field capacity. The resolution of each horizontal slice was 512 × 512 pixels and each scan contained 300 slices. The voxel size was 0.43 × 0.43 × 0.6 mm. This means that pores less than 1.2 mm in diameter (2 voxels in width) cannot be reliably detected with this CT-scanner.

Images were then analyzed using the Avizo software® (Visualization Sciences Group, Burlington, MA). The PVC cylinders as well as 1 cm of the soil at both ends were cropped from the images. As a result, the region of interest (ROI) was a cylinder 19 cm in diameter and 18 cm in height (volume of 5103.5 cm^3) for each column.

Thresholding based on the intensity histogram of the entire sample (at field water content) was used to segment air-filled pore space: the threshold value between air-filled pore space and water-filled pore space or soil matrix was defined as the minimum value of a parabola fitted to the intensity histogram between the peak for air and the peak for water. More details about the method can be found in Lamandé et al. (2013). All segmented objects less than 2 voxels in diameter might be partial voxels (i.e., noise) and therefore were removed from the analysis. Macroporosity was

Table 1
Soil texture and organic matter content of the soils from Upper site and Lower site.

Soil-texture	Layers	Particle size distribution (%)			
		Clay (<0.002 mm)	Silt (0.002–0.06 mm)	Sand (0.06–2 mm)	Organic matter (%)
Upper site-clay	15 cm	47.3	31.5	21.2	3.5
	30 cm	46.5	32.0	21.5	1.3
	50 cm	46.5	35.3	18.2	0.3
Lower site-clay	15 cm	50.0	30.0	20.0	3.0
	30 cm	50.5	32.5	17.0	0.3
	50 cm	53.8	32.5	13.7	0.0