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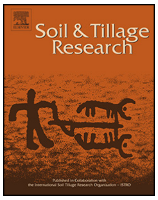

Post-tillage evolution of structural pore space and saturated and near-saturated hydraulic conductivity in a clay loam soil

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ABSTRACT

Soil structure varies considerably with time in agricultural soils, as a result of complex interactions between soil management (i.e. tillage and traffic) and site-specific environmental factors. The resulting temporal variations in soil hydraulic properties significantly affect the soil water balance (e.g. partitioning between infiltration and runoff), but are still poorly understood. Thus, post-tillage decreases in saturated and near-saturated hydraulic conductivities have been frequently observed, although the underlying changes in the properties of the structural pore-space have not been studied. We used X-ray tomography to quantify the temporal changes in the volume, size distribution and connectivity of structural pores in the harrowed layer of a conventionally-tilled agricultural field over one growing season. We also determined the extent to which these properties could explain temporal variations in saturated hydraulic conductivity measured on the same samples and near-saturated hydraulic conductivities measured in the field with tension disc infiltrometers. Early-season rainfall events caused significant decreases in the imaged porosity in the uppermost 5 mm of soil within one month of harrowing and also at 2.5–5 cm depth but only for pores >0.5 mm in diameter. Measurements of critical pore diameter showed that the sample-scale connectivity of these pores was very limited at all times. Temporal changes in the pore network characteristics were reflected in the field measurements of near-saturated hydraulic conductivity, but not in saturated hydraulic conductivity measured in the laboratory. Saturated hydraulic conductivity was, however, correlated (Spearman $\rho = 0.50$) with the connectivity probability which is a measure of global pore space connectivity. Large spatial variation combined with a small sample size limited our ability to quantify temporal variations in the soil structural pore-space. Increased automation of image processing would enable greater replication and therefore enhance the utility of X-ray tomography as a technique for investigating the properties of the structural pore space.

1. Introduction

The soil structural pore space at and close to the soil surface largely determines infiltration capacity, and thereby exerts an important control on hydrological processes such as the partitioning of precipitation between surface and subsurface runoff. Soil structure also varies considerably with time in agricultural soils, as a result of the dynamic nature of a diverse range of interacting soil structure-forming and degrading processes. Among such are tillage and traffic events, faunal and plant root activity, swelling and shrinking arising from wetting and drying cycles as well as freezing and thawing in cold climates (Fiener et al., 2011). Tillage usually causes the most pronounced alterations of soil structural and hydraulic properties. Mechanical loosening of the soil generally increases macro- and mesoporosities but may also interrupt vertically well connected biopores and shrinkage cracks (Jarvis, 2007; Strudley et al., 2008). The porosity generated by tillage is influenced by external stresses and usually decreases with subsequent rainfall events due to soil settling (consolidation) and pore clogging (Messing and Jarvis, 1993; Cameira et al., 2003; Alletto and Coquet, 2009; Dörner et al., 2012). Sealing and crusting of the soil surface resulting from the disruptive forces of raindrop impact may occur and substantially decrease the infiltration capacity on susceptible soils (Assouline, 2004). Other studies have documented increases in macroporosity and near-saturated hydraulic conductivity occurring after these initial decreases caused by rainfall or irrigation events, and attributed them to biological activity, root growth and wetting and drying cycles (Mubarak et al., 2009; Schwen et al., 2011b). The complex and poorly understood interactions between management-induced

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changes and site-specific environmental influences makes prediction of the structural and hydraulic properties of a given soil at a given time challenging. This is reflected in the discrepancy between the large number of studies that have demonstrated temporal changes of these properties (among many others Mapa et al., 1986; Moret and Arrue, 2007; Schwen et al., 2011b; Bodner et al., 2013) and the very limited number of modeling studies where such changes have been considered (Or and Ghezzehei, 2002; Schwen et al., 2011a; Alletto et al., 2015).

Temporal variations of saturated and near-saturated hydraulic conductivity have been frequently studied in the field, especially by tension disc infiltrometer measurements (e.g. Messing and Jarvis, 1993; Somaratne and Smettem, 1993; Alletto and Coquet, 2009). However, these measurements only indirectly reflect the underlying changes in the characteristics of the structural pore space. Computed X-ray tomography has in recent years become an increasingly accessible technique which allows direct and non-destructive quantification of soil structural properties on intact core samples (Wildenschild and Sheppard, 2013; Helliwell et al., 2013). In this study we used X-ray tomography to investigate the temporal changes in structural pore network characteristics occurring in the harrowed layer of a conventionally-tilled agricultural field over one growing season. We also investigated the extent to which these properties could explain temporal variations in saturated hydraulic conductivity measured on the same samples and near-saturated hydraulic conductivities measured in the field with tension disc infiltrometers. Our main hypotheses were that macroporosity would decrease following tillage as a result of rainfall impact, especially following the first rainfall events after harrowing, with the most pronounced changes occurring at the soil surface. We also expected decreases in the connectivity of the macropore network and in hydraulic conductivity at and near saturation. Wheel traffic was expected to reduce porosity and hydraulic conductivities compared to non-trafficked soil.

2. Materials and methods

2.1. Study site and soil sampling

Soil samples were collected from an experimental field 0.42 ha in size located approximately 15 km south of Uppsala, in eastern Sweden (59°43′60″N; 17°41′21″E). The soil is a clay loam (32% clay, 33% silt, 35% sand) with 13 g kg^{-1} of organic carbon. Average annual temperature and precipitation recorded at a nearby climate station (Ultuna, 59°81′67″N; 17°66′67″E) are 5.5 °C and 572 mm respectively. Fig. 1 shows daily and accumulated rainfall during the studied growing season of May to August 2013, as well as the dates of management operations and soil sampling. The field was mouldboard plowed to ca. 20 cm depth in November 2012. Harrowing to approximately 6 cm depth and sowing of spring barley (*Hordeum vulgare* L.) was carried out on 17th May 2013. Undisturbed soil core samples were then collected on each of five dates: 23rd May, 18th and 28th June, 11th July and 15th August. Only 4 mm of rain fell in the 6-day period between harrowing on 17th May and the first sampling occasion six days later. On five sampling occasions, cores were taken at four locations (20 samples in total) representing a transect across the field at a spacing of ca. 20 m. PVC cylinders (68 mm inner diameter, approximately 100 mm height), internally lubricated with liquid paraffin, were used to retrieve the soil cores. The soil surface was kept intact and approximately the uppermost 8–10 cm of soil was sampled. Tension disc infiltrometer measurements were carried out on these same dates, close to where the soil samples were collected. These measurements are further described in Section 2.3.2. Pesticides were applied on 20th June (between the second and third sampling occasions) which left wheel tracks that remained visible until the soil was plowed in the autumn. From the third sampling date (28th June), one additional core was collected from within these wheel tracks at each of the four locations to compare the temporal development of the properties of the structural pore space and near-saturated hydraulic conductivities in trafficked and non-trafficked soil. After sampling, the soil cores were sealed with plastic caps at both ends and carefully transported back to the laboratory. The samples were stored at 3 °C until all analyses were completed.

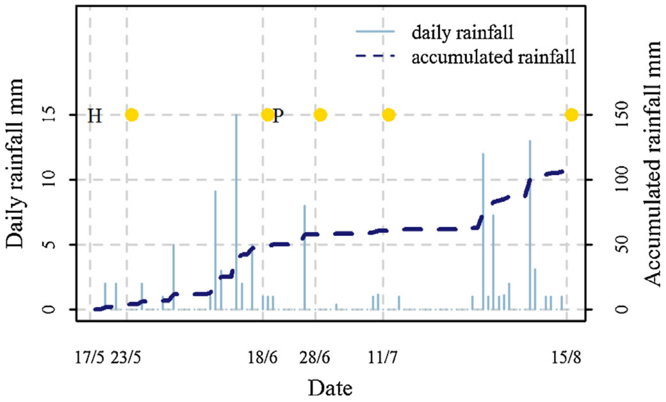

Fig. 1. Daily and accumulated rainfall during the studied growing season (2013), together with dates of harrowing (H), pesticide spraying (P) and collection of soil samples (yellow dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. 3D imaging of macropore networks

2.2.1. X-ray tomography

All samples were scanned within a month of sampling using a GE Phoenix v|tome|x m industrial X-ray scanner. For all scans, 2000 radiographs per sample were collected with the voltage set at 170 kV and the current at 220 μA. The exposure time of each radiograph was 250 μs. The image resolution was 60 μm in both directions. The GE software datos|x was used to reconstruct 3D images from the radiographs. The 3D images were then exported as 16-bit grayscale TIFF-stacks.

2.2.2. Image processing

Image pre-processing was carried out using the FIJI distribution (Schindelin et al., 2012) of the open access software ImageJ (Abramoff et al., 2004). Unless otherwise stated, ImageJ default parameter settings were used for all processing steps. Illumination differences between and within scans were corrected using two plastic rods with different densities attached to the cylinders as references. Images were then cropped to only include the soil sample. These images were re-scaled by a factor 0.5 in all directions (final voxel size 120 μm) to reduce the time needed for the following image processing and analyses. A 3D median filter with a 2-voxel radius was applied to reduce noise and an unsharp mask filter with a standard deviation of one voxel and a filter weight of 0.6 was applied to enhance the sharpness of object edges. A two-step segmentation procedure was adopted. Images were first segmented using Otsu's method (Otsu, 1979), which roughly separated gray values corresponding to dense soil aggregates from values corresponding to less dense mineral soil, organic matter and larger pores. A second segmentation with Otsu's method performed on images that only contained voxels within the latter range of gray-scale values gave a satisfactory separation of values corresponding to pore-space from those of solid material.