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Analysing the impact of compaction of soil aggregates using X-ray microtomography and water flow simulations

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ABSTRACT

Soil aggregates are structural units of soil, which create complex pore systems controlling gas and water storage and fluxes in soil. Aggregates can be destroyed during swelling and shrinking or by external forces like mechanical compaction and yet, the knowledge of how physical impact alters aggregate structure remains limited. The aim of the study was to quantify the impact of compaction on macroaggregates, mainly on the pore size distribution and water flow. In this study, aggregates (2–5 mm) were collected by dry sieving in grassland of the Fuchsenbigl–Marchfeld Critical Zone Observatory (Austria). The structural alterations of these soil aggregates under controlled compaction were investigated with a non-invasive 3D X-ray microtomography (XMT). The detailed changes in pore size distribution between aggregates (interpores, diameter >90 μm) and within the aggregates (intrapores, diameter $\leq$90 μm) in pre- and post-compacted soils were revealed at two soil moisture (9.3% and 18.3% w/w) and two bulk density increments (0.28 and 0.71 g cm^{-3} from the initial values). The soil permeability was simulated using lattice Boltzmann method (LBM) based on 3D images. Soil compaction significantly reduced total pores volume and the proportion of interpores volume and surface area, while total pore surface area and the proportion of intrapores volume and surface area increased. The increases in soil moisture tended to reduce the effects of compaction on interpores and intrapores, while the high compaction increment drastically changed the pore size distribution. The aggregate compaction decreased water penetration potential due to the increase of small intra-aggregate pores and cavities as demonstrated by LBM. Notably, the LBM results showed a significant linear correlation between the water flow rate and bulk density of soil aggregates and predicted that the water flow could be reduced by up to 97–99% at bulk density of $\geq$1.6 g cm^{-3} with soil water content of 18.3% w/w. Thus, a combination of imaging and modelling provided new insights on the compaction effects on aggregates, underpinning the importance of protecting soil structure from mechanical compaction to minimise environmental impacts of soil compaction and maintain water infiltration and percolation in arable soils.

1. Introduction

Aggregates are the structural units of soils with different size and shape, and are formed by the agglomeration of mineral particles (i.e. clay, silt and sand) and a variety of binding agents such as roots, fungal hyphae and microbial polysaccharides, calcium bridges and different (hydr) oxides (Six et al., 2004; Tisdall and Oades, 1982). The structure and stability of aggregates is crucial for water infiltration and movement, gas exchange, soil erosion, biological activity and rooting influencing the growth of crops (Hillel, 1998; Amézketa, 1999; Bronick and Lal, 2005).

Soil compaction is the densification of soil by application of mechanical energy (Holtz et al., 2010), which can occur naturally or driven by anthropogenic activities. The result is an increase of bulk density and a reduction of pore space, affecting the percolation of soil water as well as gas exchange or production. Soil compaction has been strongly linked to the loss of nitrogen by the accelerated production of greenhouse gases (e.g. N_2O) through denitrification in anaerobic conditions (Keller et al., 2013).

Due to above ecological impacts, soil compaction has been widely recognized as a soil threat by many regional, national and international organisations (Hartemink, 2008; Banwart, 2011). It

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has been described as an 'unnecessary form of land degradation' by Food and Agricultural Organization (FAO, n.d). In Europe, compaction is widespread and it accounts for about 17% of the total area of degraded soil (EEA, 2012). The EU Soil Thematic Strategy identified compaction as one of the major soil threats in Europe (COM, 2006).

Most of the studies investigating soil compaction were conducted using bulk soils under lab or field conditions. However, the compaction of soil aggregates was rarely investigated despite the fact that the size distribution of aggregates has been often used as an indicator of soil fertility. For example, an empirical rule suggests that a soil structure consisting of more than 60% of macro-aggregates (0.25–10 mm) can be classified as "agronomically valuable" (Shein, 2005). The size and stability of soil aggregates regulate gas and liquid diffusion in soil (Sexstone et al., 1985; Horn and Smucker, 2005), enhance the accumulation of soil organic matter by physical protection (Bossuyt et al., 2002), provide specific microbial habitats and directly influence microbial composition and activity (Blaud et al., 2012). However, soil aggregates turnover (i.e. cycles of formation and natural disruption of aggregates) (Stamati et al., 2013) is easily disturbed in presence of external factors such as tillage or compaction. In particular, macroaggregates (diameter >0.25 mm) are disrupted the most. However, there is a limited mechanistic understanding how breakdown of macroaggregates occur and how this can affect the movement of air and water in soils.

Dexter (1988) proposed three main changes in soil aggregate structure during compaction depending on soil moisture content. Firstly, when soil aggregates are dry and hard, the soil particles will be rearranged under compaction. Secondly, when aggregates are weak or brittle, fracture will occur and broken aggregates fragments may fill up the spaces between existing soil aggregates and particles. Thirdly, aggregates are plastic (depends on moisture content) and when compacted, the compression creates plastic flow with flat areas of contact between the aggregates. However, the dynamics of pore space in these scenarios are to be studied in order to produce meaningful predictions on water or air flow; i.e. further insights are needed on how compaction affect the internal (intra-aggregate pores or intrapores) along with changes in porosity between them (inter-aggregate pores or interpores) as well as overall pore size distribution.

Compaction is a multidisciplinary problem and several methods can be used to study structural alterations in soils. Thus, a selection of method for studying compaction will depend on the research context and resources available (see review from Keller et al., 2013). Total porosity can be calculated by measuring bulk density and the soil density in laboratory. Odometer is also used widely to study compaction. However, these methods do not provide information about pore size distribution in the sample and for this, the soil water retention curve has to be measured using the pressure plate apparatus. Imaging tools can yield high resolution 2D or 3D images of pore space. For 2D imaging, thin sections are made from resin impregnated soil samples and images are processed for different pore characteristics (Murphy, 1986). This method suffers from the problem of destructive sampling, and cross sections do not provide information on the real 3D geometry of the pores in samples. In contrast, using the advanced 3D imaging tools such as XMT (X-ray microtomography, also known as micro-CT) and image analysis software, it is now possible to study the pore size characteristics with very high spatial resolution (up to a few microns, depending on the sample size) non-destructively (Mooney et al., 2012). In addition, the data from XMT can be directly used for modelling to quantify processes such as diffusion of fluids. However, imaging methods suffers from the fact that the resolution depends on the sample diameter. Despite its several advantages, it has not been used widely to study soil compaction. Few studies have already demonstrated the water flow through aggregates using 2D images (Aravena et al., 2014; Berli et al., 2008; Carminati et al., 2007). Notably, Aravena et al. (2014) showed that root-induced compaction led to deformation of aggregates and subsequent reduction in inter-aggregate porosity (or increased inter-aggregate contact areas), which increased the unsaturated flow of water towards the root by 27%. However, above studies used 2D image slices and the dynamic of intra-aggregate pore space was not evaluated. An alternative modelling method is available, that uses 3D image data is Lattice Boltzmann Method (LBM), which is simpler and faster and do not require finite element meshing of images as demonstrated earlier by Menon et al. (2011).

The aim of this laboratory study was to investigate the impact of compaction on a pack of soil aggregates on its pore structure and water flow with the following specific objectives: (1) visualize and quantify inter- and intra-aggregate pores in compacted soils, (2) compare the effect of soil moisture content and different compaction strengths on the pore size characteristics (inter and intra aggregate porosities and pore volume distribution) of soil aggregates, (3) predict the effect of compaction on water flow using LBM. We hypothesise that the deformation of aggregates due to soil compaction increases with soil moisture content and compaction level, leading to a decrease in water flow and pore space which is directly related to the dynamics of inter- and intra-aggregate pores.

2. Materials and methods

2.1. Soil sampling and preparations

Dry sieved soil aggregates were collected from bulk soil below the main rooting zone (5–10 cm soil depth) at an agriculturally used grassland site located in Fuchsenbigl–Marchfeld Critical Zone Observatory in September 2011. The field site is located east of Vienna, Austria, in the National Park "Donau-Auen" and developed on approx. 350 year old alluvial Danube River sediments (48°11′N, 16°44′E; Lair et al., 2009). The soil aggregates distribution of bulk soil (5–10 cm soil depth) obtained by wet sieving (Haynes and Swift, 1990) revealed the following aggregate size distribution: <0.25 mm (6.1%), 0.25–0.5 mm (6.9%), 0.5–1 mm (5.2%), 1.0–2.0 mm (14.5%), 2.0–5.0 mm (37.8%) and 5–10 mm (21.5%). More than 90% of the aggregates were water stable. Therefore, the predominant aggregate size class of 2–5 mm was selected for this study. Particle size distribution in this aggregate size class was 78 g kg^{-1} sand, 644 g kg^{-1} silt and 278 g kg^{-1} clay. The organic C concentration was 49.0 g kg^{-1} and total N 33.8 g kg^{-1} in the studied aggregates.

To study the effect of soil compaction, samples were prepared with two different moisture levels: (1) aggregates with gravimetric water content of 9.3% (W1), representing the field moisture content at the time of sampling, and (2) an elevated moisture content of 18.3% (W2), at which aggregates were only slightly plastic and thus easier to handle in imaging experiments. For the latter, the aggregates were saturated with water first and air-dried until the desired soil moisture was attained. Soil aggregates were weighed and filled into a specially designed plastic cylinder (14.9 mm inner Ø and 60 mm height) with a piston. The size of the plastic cylinder was particularly selected in order to fit (sample size limits for the imaging device: 60 mm length and 50 mm diameter) the imaging device as well as to achieve a resolution of 10 μm. The bottom of the container was sealed with a flat metal sheet. Three replicated samples were used for the two moisture and compaction levels, respectively, using the same weight (4.14 g for W1 and 4.84 for W2) of aggregates. Soil aggregates were filled and gently tapped to settle the aggregates in the cylinder and the initial bulk