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Long-term effects of conventional and reduced tillage on soil structure, soil ecological and soil hydraulic properties

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ABSTRACT

There is a long-lasting debate about the effects of tillage practices on soil structure and structure-mediated ecosystem properties like hydraulic conductivity and crop productivity. This is investigated in a long-term field experiment on tillage practices at the Westerfeld trial in Bernburg, Germany (25 years of different management). Here we combine soil structure information obtained by X-ray microtomography with bulk properties like bulk density, air capacity and saturated hydraulic conductivity, as well as integrative, ecological properties like earthworm abundance and crop yield. This study goes beyond previous studies in that the soil microstructure is investigated in two different depths, within (13–23 cm) and underneath (28–38 cm) the plow horizon. Furthermore the microstructure is investigated at two different resolutions (60 µm and 20 µm) by employing a nested sampling design.

The plowed horizon in the conventional tillage plots differs from the undisturbed soil underneath the cultivator depth (13–23 cm) in the reduced tillage plot by lower bulk density, higher air capacity, higher saturated hydraulic conductivity, higher macroporosity and pore connectivity. After 25 years of reduced tillage saturated hydraulic conductivity only marginally recovered in the abandoned plow pan (28–38 cm). Macropore density and connectivity did not change significantly as compared to the current plow pan under conventional tillage. The topsoil underneath the cultivator depth in the reduced tillage plot developed a “no-till pan”, as porosity and pore connectivity where smaller than in greater soil depths. Image-based macroporosity and laboratory-based air capacity showed good agreement.

Overall, the combination of hydraulic measurements and X-ray CT imaging of soil microstructure at different resolutions provides a comprehensive view on soil structure modification by tillage practices. The change from conventional to reduced tillage led to a compaction of soil that was not compensated by higher bioturbation as reported for other sites. This is explained by unfavorable conditions for anecic earthworms (frequent dry periods with severely impaired penetrability of the loess substrate) as well as the absence of very deep rooting, perennial crops in crop rotation.

1. Introduction

Conservation agriculture has a profound impact on soil structure and consequently on structure-mediated ecosystem functions like carbon sequestration, greenhouse gas emissions and soil water storage. The benefits of reduced tillage practices as compared to conventional plowing may be lower costs, higher carbon storage, higher energy input/output ratio, reduced erosion, more stability against compaction and lower herbicide loss (Palm et al., 2014; Tebrügge and Düring, 1999). Drawbacks associated with reduced tillage can be a risk of topsoil compaction, reduced aeration and lower soil temperature (Soane et al., 2012). With reduced tillage the absence of plowing typically leads to a loss in air capacity and an increase in bulk density and penetration resistance in the topsoil beneath the tillage depth of disc harrows or other cultivators (Abdollahi et al., 2017; Abdollahi and Munkholm, 2017; Deubel et al., 2011; Pagliai et al., 2004; Rasmussen,

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1999; Rücknagel et al., 2017). Saturated hydraulic conductivity (K_s) and infiltration capacity are typically lower under reduced tillage (Abdollahi et al., 2014; Lipiec et al., 2006; Pagliai et al., 2004) but can also exceed values for conventional tillage (Kahlon et al., 2013; Vogeler et al., 2009) depending on whether intact, elongated macropores resulting from root growth and earthworm burrowing activity can compensate for the overall reduction in macroporosity. Rücknagel et al. (2017) compared K_s values under conventional and reduced tillage in seven field trials in Germany and found comparable (five) or significantly lower (two) K_s values under reduced tillage. A comprehensive literature review about tillage effects on hydraulic properties (Strudley et al., 2008) indicated inconsistent results across soil textures, climate and specific managements with respect to trends in saturated hydraulic conductivity and infiltration capacity. Often temporal and spatial variability mask these long-term treatment effects.

The inconsistent trends between tillage practices and hydraulic properties can be better understood by investigating tillage effects on soil microstructure. In recent years traditional approaches to measuring tillage-induced changes in soil physical properties have been increasingly complemented by the characterization of undisturbed soil structure via non-invasive imaging techniques like X-ray computed tomography (X-ray CT). Attributes of the macropore network measured with X-ray CT and image analysis have been used to explain a range of bulk soil properties like water and solute transport (Larsbo et al., 2014; Paradelo et al., 2016), soil friability (Munkholm et al., 2012) and soil structure turnover (Schlüter and Vogel, 2016). Studies on management induced changes in pore space attributes mainly comprise fertilization effects (Dal Ferro et al., 2013; Naveed et al., 2014; Schlüter et al., 2011) and tillage effects (Dal Ferro et al., 2014; Garbout et al., 2013; Kravchenko et al., 2011; Pöhlitz et al., 2018). A typical outcome of these studies is that visible porosity above the image resolution is highly correlated with bulk density, since unresolved micro- and mesoporosity is less affected by management practices. Plow horizons with loose soil structure typically have an isotropic, well connected pore network, whereas macropores in unplowed soil tend to be less connected and more vertical and anisotropic, since they mainly evolve from bioturbation and are less susceptible to concomitant compaction (Hartge and Bohne, 1983).

One major shortcoming of soil structure analysis with X-ray CT is the trade-off between image resolution and sample size, with a fixed factor of 1000–2000 depending on the X-ray detector hardware (Rabot et al., 2018). Information on mesopores ($< 10\,\mu$m or $< 50\,\mu$m depending on definition) can only be achieved with small soil cores or individual aggregates (Crawford et al., 2012; Kravchenko et al., 2011; Schlüter and Vogel, 2016), whereas representative samples for preferential flow in large macropores require big samples up to 20 cm in diameter with image resolutions of 100 µm and larger (Luo et al., 2008; Paradelo et al., 2016). Nested sampling strategies are a viable strategy to extend the scale window towards mesopores (Dal Ferro et al., 2013; Schlüter et al., 2011; Vogel et al., 2010). First a soil column is scanned at coarse resolution and then subsamples are extracted and scanned at a higher resolution, so that eventually the pore size distribution from both scales can be merged. A second shortcoming of X-ray tomography is the time and labor for taking undisturbed soil columns at large soil depths as well as the time-consuming image analysis of large datasets. While soil physical properties like penetration resistance, air capacity or bulk density are easily measured at high spatial resolution for entire soil profiles (Abdollahi et al., 2017; Deubel et al., 2011), X-ray CT studies on tillage practices are often restricted to soil samples from one depth within the first 30 cm.

This paper addresses both shortcomings by employing a nested sampling design in two soil depths, the plow horizon and the deeper soil partially covering the plow pan. The objective of the paper is (1) study changes in pore space attributes after 25 years of reduced tillage in a long-term field trial on tillage effects and (2) to relate these changes in pore morphology to soil physical properties like bulk density, air capacity and saturated hydraulic conductivity as well as ecological properties like earthworm abundance and crop yield.

2. Materials and methods

2.1. Field site

The long-term tillage trial at the Westerfeld site in Bernburg, Germany, was established in 1992 (Deubel et al., 2011). The Chernozem soil (WRB) is developed on loess over limestone and has a texture of 8% sand, 79% silt and 13% clay (0–30 cm). The average annual temperature is 9.7 °C with a rather low average annual precipitation of 511 mm (1981–2010). The crop rotation on five experimental blocks (1.2 ha each) is grain maize (*Zea mays*), winter wheat (*Triticum aestivum*), winter barley (*Hordeum vulgare*), winter rape (*Brassica napus* ssp. *napus*) and again winter wheat. N-fertilization is site-specific and pest management as required. An experimental block consists of four non-randomized plots, each split into two subplots with different tillage practices, resulting in a total of 40 subplots. Reduced tillage (RT), is carried out as stubble processing and soil loosening with a cultivator (down to 12–15 cm), whereas conventional tillage (CT) comprises stubble control and soil turning with a moldboard plow (down to 20–30 cm, varying depth to reduce plow pan). All residues remain on the field after harvest.

Yields [dt ha^{-1}] were measured every year as triplicates per subplot (total of twelve harvest plots per crop and tillage treatment, each 18 m^2, threshed with a parcel harvester). Grain yields are reported here as averages for the period 2012–2016 with 14% and 9% moisture for cereals and oilseed rape, respectively. Earthworm abundance was determined with hand sampling of the topsoil down to a depth of 30 cm in combination with subsoil extraction by 0.2% formaldehyde solution on eight replicated areas (0.125 m^2), i.e. two per sub-plot (DIN ISO 23611-1, 2007). Sampling was carried out in 2016 on the maize block, which was also used for undisturbed soil sampling in the following year (see Section 2.2. below). Values are reported as numbers of individuals [m^{-2}] and biomass [g m^{-2}] and aggregated into anecic and endogeic species as well as adults and juveniles, whereas epigeic species where absent. Older time series (2010–2013/14) for rape and wheat on rotating blocks are also reported here.

2.2. Sampling

Soil sampling took place in April 2017 on the winter wheat block (after maize in 2016), 6 months after last tillage. Undisturbed soil cores for X-ray tomography analysis were taken by pushing down polycarbonate cylinders (94 mm inner diameter, 100 m height, 694 cm^3) with a rotating sampling device (sample ring extraction device, UGT GmbH, Germany) (Kuka et al., 2013) in two different depths. The first depth (13–23 cm) corresponds to the plow horizon in the conventional tillage plots (CT) or the lower topsoil beneath the tillage depth of the cultivator in the conservation tillage plots (RT). Previous studies at this site demonstrated large differences in penetration resistance (CT: 0.6 MPa, RT: 1.4 MPa), bulk density (CT: 1.25 g/cm^3, RT:1.52 g/cm^3) and air capacity (CT: 17%, RT: 6%) in that depth (Deubel et al., 2011). The second depth (28–38 cm) corresponds to deeper soil within and underneath the compacted plow pan in CT plots and the former plow pan in the RT treatment. Reported soil physical properties (Deubel et al., 2011) in that depth indicate higher compaction in the conventional tillage plots (penetration resistance – CT: 1.4 MPa, RT: 1 MPa, bulk density - CT: 1.42 g/cm^3, RT:1.35 g/cm^3, air capacity - CT: 9%, RT: 11%). Two samples per tillage sub-plot and depth were taken from each of the four plots in the winter wheat block, constituting a total of 32 undisturbed samples. For soil physical laboratory analysis 32 smaller, undisturbed soil samples (250 cm^3) were taken in the same pits. All results will be presented as averages out of two samples per sub-plot, i.e. $n = 4$ for each tillage practice and depth. Samples were stored at