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Impact of long-term fertilization practice on soil structure evolution

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ABSTRACT

The study characterized soil structure development and evolution in six plots that were amended with varying amounts of animal manure (AM) and NPK fertilizer over a period of 106 years in a long-term fertilization experiment in Bad Lauchstädt, Germany. Two intact soil cores (10-cm diameter and 8-cm tall) and bulk soil samples were extracted from a depth between 5 and 15-cm from each plot. Soil properties including texture, organic carbon, soil–water characteristic, air permeability and diffusivity were measured and analyzed along with X-ray computed tomography (CT) data. Long-term applications of AM and NPK had a major impact on soil organic carbon content which increased from 0.015 kg kg^{-1} (unfertilized plot) to 0.024 kg kg^{-1} (well fertilized plot, 30 T ha^{-1} $2y^{-1}$ AM with NPK). Total porosity linearly followed the organic carbon gradient, increasing from 0.36 to 0.43 m^3 m^{-3}. The water holding capacity of the soil was considerably increased with the increase of AM and NPK applications. Gas diffusivity and air permeability measurements clearly indicated that the level of soil aeration improved with increasing AM and NPK fertilizer amount. The three-dimensional X-ray CT visualizations revealed higher macroporosity and biological (earthworm) activity in the well fertilized areas when compared to plots without or only a small amount of fertilizer applied. A combined evaluation of the soil water characteristic, gas transport and X-ray CT results suggested that pore size distributions widened, and pore connectivity was significantly improved with increasing fertilizer amount. Furthermore, the soils fertilized with both AM and NPK showed a more aggregated structure than soils amended with AM only.

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1. Introduction

Soil structure is important for all aspects of soil use and management. A healthy soil structure is a key for crop production because it controls depth-penetration of roots, the extent of soil water storage, and the movement of water, air and soil fauna (Pardo et al., 2000). A healthy soil commonly consists of a combination of a well-aggregated soil matrix and a well-developed soil pore system enabling sufficient aeration for plants and other organisms, high water retention capacity, and various other important soil functions (Eden et al., 2012). For a distinct region (climate, relief), the soil type (e.g. particle size distribution, mineralogy and pH) influences the structure of the entire soil profile over long time periods (>100 yr), while land use (e.g. cropping system and management) has a short-term impact (<1 yr), mainly affecting the top 30 to 40 cm of the soil profile (Lamandé et al., 2011). However, the dynamic evolution of agricultural soil structure in a given climate is expected to be profoundly dependent on the cycling of organic matter. Addition of animal manure (AM) and NPK fertilizer are considered as a source of relative enrichment of the surface soil with organic matter which in turn results in an increase in biological activity and a concomitant increase in soil porosity and overall width of the pore size distributions (Pagliai and Vignozzi, 1998; Yang et al., 2011; Zhengchao et al., 2013). The physical and chemical effects of mineral fertilizers on soil structure further depend on fertilizer type. Phosphate fertilizers promote soil aggregation by lowering soil pH and facilitating precipitation of aluminum phosphate as a cementing agent to form stable aggregates (Haynes and Naidu, 1998). Ammonium fertilizers (large amount) on the other hand can disperse clays, adversely affecting soil aggregation. However, in most situations, NH_4^+ is rapidly nitrified to NO_3^- within a period of a few weeks so that its dispersing effect is likely to be temporary (Haynes and Naidu, 1998).

To evaluate the impact of AM and mineral fertilizer (NPK) applications on the soil environment it is necessary to quantify the modifications to the soil structure. The main challenge in addressing this question is to find suitable measures to characterize soil structure from micro- to macro-scales. We combined soil physical measurements with analysis of X-ray Computed Tomography (CT) data for intact soil cores to provide a comprehensive characterization of soil structure

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and to evaluate its sensitivity to fertilization. Soil physical measurements including the soil–water characteristic, gas diffusivity, and air permeability have been used separately or in combination in the past to characterize soil structure under different treatments indirectly (Blackwell et al., 1990; Schjønning et al., 2002). The soil water characteristic is traditionally used to estimate the water holding capacity and the pore size distribution of soils. The latter is obtained based on the well-known capillary rise equation (Jury and Horton, 2004). Gas diffusivity (D_P/D_0) is a concentration-driven gas transport parameter and is controlled by total air-filled pore space and the connectivity and tortuosity of pores (Moldrup et al., 2000a, b). Air permeability (k_a) on the other hand is a pressure driven gas transport parameter that is mainly governed by air-filled macropores and their connectivity (Kawamoto et al., 2006, Moldrup et al., 1998). Both gas transport parameters further provide a reasonable estimate for the level of soil aeration and its sufficiency for plant growth and biological activity (Stepniewski, 1980, 1981). X-ray CT is an emerging nondestructive tool to characterize the soil structure (Vaz et al., 2011; Wildenschild et al., 2002). Recently, various properties of the soil pore system have been estimated with X-ray CT: e.g. porosity (Dowuona et al., 2009; Naveed et al., 2013), pore size distribution (Naveed et al., 2013; Vogel et al., 2010), tortuosity (Luo et al., 2010) and topology (Schlüter et al., 2011; Vogel et al., 2010). However, X-ray CT suffers from a tradeoff between achievable resolution and observable sample size. Therefore, our understanding of micro-scale soil processes is somewhat limited with most research focusing on soil macroporosity (Luo et al., 2010; Nunan et al., 2006; Perret et al., 1999). Zhou et al. (2013) studied organic and inorganic fertilization effects on aggregate soil structure using X-ray CT and found significantly higher macroporosity for soils fertilized with both pig manure and NPK when compared to a control plot without fertilization. Deurer et al. (2009) studied the effects of organic fertilizers on macropore structure and showed that organic matter influenced both pore connectivity and tortuosity.

Long-term fertilization experiments provide excellent means to study soil physical properties and structure as a function of AM and mineral fertilizer applications under controlled conditions. For this study, the “Static Fertilization Experiment” in Bad Lauchstädt, Germany, was selected to evaluate how different amounts of AM and NPK fertilizer inputs over a period of more than 100 years have affected the soil environment. The specific objective was to characterize and compare soil physical properties and soil structure evolution in plots without fertilizer application (control), in plots amended with varying amounts of AM and in plots where both AM and NPK fertilizers were applied in varying amounts.

2. Materials and methods

2.1. Fertilization experiment, sampling and texture analysis

The static fertilization experiment located in Bad Lauchstädt, Germany (51° 24′N, 11° 53′E) was initiated in 1902. Mean annual temperature and precipitation for the period from 1896 to 2004 were recorded as 8.7 °C and 484 mm (Eden et al., 2012). The soil at the field site was classified as Haplic Chernozem, which is known for its fertility and as a favorable ecological regime (Körschens, 2006). The field was cultivated with a 4-year rotation of sugar beet, potato, winter wheat and spring barley (Schlüter et al., 2011). Barley and wheat straw were baled and removed from the plots after harvest. An offset disk plough (30 cm depth) was used for autumn tillage, while spring tillage consisted of a rotary harrow followed by a heavy harrow and then a light harrow. The main field was divided into three blocks receiving different amounts of animal (cattle) manure (AM). One block did not receive any AM amendment, while the remaining 2 blocks were fertilized every other year with 20 and 30 tons AM per hectare, respectively. This is equivalent to 1.8 and 2.7 tons of carbon per hectare, respectively. Each block was further divided into two plots with different mineral fertilizer applications. A schematic of the fertilization practice adopted since 1902 for all six studied plots is presented in Fig. 1 (+/− indicates whether NPK fertilizer was applied or not).

From each plot, two intact soil cores (10-cm diameter and 8-cm tall) were extracted from 5 to 15 cm depth. Two replicates were selected as uniform soil conditions exist in all studied plots regarding texture and bulk densities (Arthur et al., 2013; Schlüter et al., 2011) and also because of the costs and work involved with X-ray CT scanning and analysis. All soil cores were extracted by stepwise pushing a customized core sampler containing the aluminum sampling cylinders into the soil and step by step removing the surrounding material. Extracted cores were immediately covered with tight plastic lids, placed in plastic bags, and carefully transported from field to the laboratory to avoid smearing and compaction effects. In the laboratory the soil cores were preserved at −2 °C until measurements started. In addition, small bulk soil samples were collected from each plot for texture and organic carbon analysis. Soil texture was determined on pre-sieved (≤2 mm) samples by means of wet sieving and the hydrometer method (Gee and Or, 2002). Soil organic carbon was determined with a LECO carbon analyzer (St. Joseph, MI, USA) coupled with an infrared CO_2 detector.

2.2. Soil physical measurements

The soil–water characteristic (SWC) measurements were carried out in the laboratory at constant temperature (20 °C). The cores were placed in a sand box and saturated with water from below. After saturation, suction was successively applied to establish matric potentials (ψ) of −10, −30, and −100 hPa. A ceramic plate was subsequently used to apply the higher suction level of −300 hPa (Tuller and Or, 2005). The dry part of the soil–water characteristic (at −1.5, and −80 MPa matric potentials) was measured on small bulk soil samples with a WP4-T Dewpoint Potentiameter (Decagon Devices Inc., Pullman, WA, USA). The well-known van Genuchten (1980) model was then parameterized based on the SWC measurements:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\frac{1}{[1+(a\psi)^n]^m} \quad (1)$$

where θ_s and θ_r are the saturated and residual volumetric water contents, respectively, n and a are shape parameters $m = 1 - 1/n$, and ψ is the matric potential in hPa. The free model parameters a, n, and θ_r were determined with nonlinear regression analysis with the Excel solver tool.

Air permeability (k_a) was measured with the steady-state method described in Iversen et al. (2001) first under in-situ conditions that prevailed during sampling and then at matric potentials established at −30, −100, and −300 hPa. The pressure gradient was established at 5 hPa to ensure laminar flow during the measurements. The k_a was calculated from Darcy's equation based on the pressure difference across the core. Gas diffusivity was also measured under the same moisture and matric potential conditions by means of a non-steady state method employing a two gas/dual chamber gas diffusion measurement device (Schjønning et al., 2013). This device consists of two chambers purged with different tracer gases, oxygen and argon. The method involves frequent measurements of both change of oxygen concentration in the argon chamber previously flushed with argon and change of argon concentration in the oxygen chamber. Before measuring the diffusivity and permeability, the soil was gently pushed to the edge of the soil core to minimize the risk of air diffusing or leaking along the sample/container boundary.

2.3. X-ray computed tomography (CT) analysis

An industrial X-ray CT scanner (X-Tek HMX225) at the Helmholtz Center for Environmental Research in Halle, Germany was used to

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