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Pore size distribution and stability of ortstein and overlying horizons in podzolic soils under forest

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ABSTRACT

Podzolic soils with ortsteins are used for forestry worldwide. Pore size distribution (PSD) and strength of cemented ortstein horizons affect soil transport properties and plant growth but they are scarcely understood. The aim of this study was to quantify the PSD and tensile strength of ortstein and overlying horizons in two podzolic soils under forest. The PSD in the range of pore size from 0.0016 to 178 μm in radius was determined in undisturbed aggregates (6–8 mm in diameter) using a mercury porosimeter. The results were presented in the form of both a cumulative pore volume curve and a logarithmic differential pore curve as a function of the pore radius. The tensile strength (kPa) of the soil horizons was assessed by crushing an aggregate and measuring the breaking force. The results showed that the total mercury intrusion volume, median pore radius (volume and area), and average pore radius were lower and that the total pore area was higher in the ortstein than in the overlying horizons in all soils. The lower volume of larger pores (58–32 μm) in the ortstein horizons of the forest soils was accompanied by a greater volume of smaller pores. The differential PSD curves were unimodal in all horizons and soils. The representative peaks in the ortsteins, compared to those in respective overlying horizons, were of lower magnitude (0.31 to 0.41 $cm^3\,g^{-1}$ vs. 0.49 to 0.60 $cm^3\,g^{-1}$). Irrespective of the soil, the peaks in the ortstein, compared to overlying horizons, occurred at lower equivalent pore radii. The tensile strength of the ortstein horizons (112.5–123.9 kPa) was many times greater than in the overlying horizons (7.1–14.0 kPa). Both the greater contribution of smaller pores and the tensile strength in the ortsteins than in the overlying horizons were ascribed to an increased concentration of carbon, iron, aluminum, and silica. The study provides new insights into understanding the structural and strength discontinuity in soils with ortsteins.

1. Introduction

Ortstein forms primarily in podzolic soils by translocation of Al-humus complexes from A and E horizons and immobilization thereof in ortstein horizons where they bridge and cement sand grains (Bockheim, 2011). Cementation of ortstein horizons can be favored by a soil pH gradient that allows hydrolysis and precipitation of Al compounds (Bockheim, 2011; Catoni et al., 2014), presence of silicate clays in coatings of fine materials bridging soil particles (Rabenhorst and Hill, 1994), occurrence of coarse fragments that increase Al and Fe concentrations in a restricted soil volume as well as limited growth of plant roots and low activity of microflora and fauna (Bronick et al., 2004; Chodorowski, 2009). In soil taxonomy, ortstein is defined as a layer ≥ 25 mm thick and ≥ 50% cemented (Soil Survey Staff, 2014; IUSS Working Group WRB, 2015). Formation of ortstein by cementing of soil grains is a gradual process and lasts at least a few thousand years (Bronick et al., 2004).

Ortsteins occur worldwide in various site conditions, including North America (Schaffhauser et al., 2016; Bronick et al., 2004), Central Europe (Chodorowski, 2009; Kaczorek et al., 2004; Catoni et al., 2014), Russia (Dmitriev and Zheveleva, 1987), and temperate and tropical areas of Australia (Bockheim, 2011). Soils with ortstein horizons in the USA cover 2.2 million ha and are more common than soils with placic horizons (Bockheim, 2011). In Poland, the area occupied by ortstein soils is approximately one hundred thousand ha (Chodorowski, 2009). Most of the ortstein soils are used for forestry and less for pastures and cultivated crops (Chodorowski, 2009).

The presence of cemented subsurface layers leads to an uneven distribution of the density and associated pore size distribution and connectivity in the soil profile. The alterations influence the fluxes of water, heat and gas and C cycling in soil (e.g. Catoni et al., 2014; Haas et al., 2016; Mossadeghi-Björklund et al., 2016). Additionally,

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increasing volume of smaller pores at the expense of larger pores in cemented layers results in a greater both number of contact points between soil particles and soil strength (Lipiec et al., 2012; Arthur et al., 2013). The interrelation of the pore size ranges along with strength of variously cemented layers in soil profile is important to growth and distribution of plant roots and the evolution of soil (Richard et al., 2001) and mathematical modelling of soil transport processes (e.g. Menon et al., 2015).

Despite the wide global occurrence of ortstein soils, their pore structure and mechanical strength are poorly understood. Therefore, the aim of this study was to describe quantitatively the pore size distribution in a wide range of pore sizes and tensile strength of ortstein and overlying horizons in two podzolic soils under forest. We hypothesized that increased content of illuvial organic matter, iron, aluminum, and silica influence differently the pore size distribution and strength of ortstein in forest soils.

2. Materials and methods

2.1. Study sites and soil sampling

The study was performed on two podzolic soils under forest, i.e. suboceanic Middle-European pine forest *Leucobryo-Pinetum* in Karolówka (FK) (50°25′52.36″ N, 21°38′07.51″ E) and under a community with fir in the habitat of continental mesotrophic oak-pine mixed forest *Querco roboris-Pinetum* in Hadykówka (FH) (50°20′06.07″ N, 21°44′54.92″ E). According to the IUSS Working Group WRB (2015), the studied soils were classified as Albic Ortsteinic Podzol (Arenic) in FK and Gleyic Albic Ortsteinic Podzol (Arenic) in FH. Symbol representing the overlying horizons in FK and FH is E (5–15 and 6–26 cm respectively) and this corresponding to the ortstein horizons is Bhsm (15–17.5 and 26–32 cm). Both soils are located in the Sandomierz Basin, south-eastern Poland, in the same temperate climate with continental influences. The long-term mean annual temperature and precipitations in the study area are 7.4 °C and 572 mm, respectively.

The moist soil samples (approximately 3 kg) with an undisturbed structure were taken from the middle of overlying and ortstein horizons in May 2015. Ortstein samples were broken manually into smaller fragments in the moist state when breakable. Then the samples were brought into the rigid containers and transported to the laboratory. Following drying of the soil to the air-dry state aggregates (6–8 mm in diameter) were selected for measurements of pore size distribution and tensile strength.

2.2. Particle size distribution and chemical properties

Particle size distribution was determined using the sieving and hydrometer method (Ostrowska et al., 1991). Soil pH and organic carbon content (SOC) were measured (3 replicates) respectively using a pH meter in a 1:2.5 soil/distilled water (v/v) suspension and the wet oxidation method with K2Cr2O7 using Tiurin's procedure (Ostrowska et al., 1991). In order to determine the amount of pedogenic forms of Fe-, Al- and Si-oxides, acid ammonium oxalate (Fe_o, Al_o, Si_o) and sodium pyrophosphate (Al_p) extracts were used according to the procedure given by McKeague (1978). The extracts were analyzed (2 replicates) using the atomic absorption spectrometry (AAS) method (ParkinElmer 3300 apparatus).

2.3. Determination of pore size distribution

An Autopore IV 9500 (Micromeritics Inc. USA) mercury porosimeter was used to determine the pore size distribution. The aggregates were vacuum degassed under pressure of 6.67 Pa at a temperature of 20 °C before intruding mercury in step-wise pressure increments in the range from 0.0035 to 400 MPa. This allowed determining the pore size distribution in the range of an equivalent pore radius from 0.0016 μm to 178 μm using the Washburn equation (Washburn, 1921):

$$P = \frac{2\gamma_{\mathrm{Hg}}\cos\theta}{r} \tag{1}$$

where P is the external pressure (Pa) applied in the vacuum chamber, γ_{Hg} is the surface tension of mercury (0.485 J m^{-2}), is the contact angle of mercury (130°), and r is the pore radius of a pore aperture (m) for a cylindrical pore. The measurements were done in three replicates.

Mercury intrusion porosimetry (MIP) provides complementary data on structure of pores of radius < 0.1 μm that cannot be derived from the more frequently used soil water retention curve. It has been accepted by the ASTM Committee as a standard method to characterize pores (ASTM, 1994) and was useful to quantify the pore structure as affected by soil management and tillage practices (Wairiu and Lal, 2006) and earthworm activity (Görres et al., 2001; Lipiec et al., 2015).

2.4. Determination of aggregate tensile strength

The tensile strength q (kPa) was determined (12 replicates) using a strength testing device (Zwick/Roell) for crushing an air-dry aggregate placed in its most stable position and then calculated as suggested by Dexter and Kroesbergen (1985) from the equation:

$$q = 0.576\ F{\cdot}d^{-2} \tag{2}$$

where: F- is the vertical breaking force (N); d- is the mean aggregate diameter (taken along the longest, intermediate, and smallest axis, mm), and 0.576 is the coefficient. The aggregate stability is considered as an indicator of soil structural quality and physical protection of soil organic carbon (Mataix-Solera et al., 2011).

2.5. Statistical analysis

Statistical analysis was performed using STATISTICA 12.0 (StatSoft, Inc., Tulsa, OK, USA). The standard Student's *t*-test ($P = 0.05$) was used to determine statistical significance between mean values.

3. Results

3.1. Soil characteristics

The data in Table 1 show that in both soils there was an accumulation of soil organic carbon (SOC), amorphous iron (Fe_o), amorphous aluminum (Al_o), aluminum complexed by organic matter (Al_p), silica (Si_o) in the ortstein horizons (Bhsm). This resulted in a greater index of accumulation of Fe and Al in the ortstein ($Al_o + 0.5Fe_o$). The Bhsm horizon from FH compared with FK had higher SOC level (22.6 vs. 13.6 g kg^{-1}) whereas Fe_o, Al_o, Al_p, and Si_o concentrations and particle size distribution were similar in both soils. Irrespective of the soil and horizon pH values were highly acidic (pH 4.1 to 4.5). The Munsell values (moist) in ortsteins (7.5-10YR 2-3/2-3) and overlying albic (10YR 4-5/1-2) horizons clearly indicate darker color in the former due to accumulation of SOC and Fe. Numerical values of the characteristics fulfil most of the diagnostic criteria of albic material and an ortstein as a spodic horizon (IUSS Working Group WRB, 2015). Similar differentiation of the soil characteristics between both horizons was observed in other Podzols with ortstein in the study area (Chodorowski, 2009).

The total mercury intrusion volume, median pore radius (volume and area), and average pore radius were lower and that of the total pore area was higher in the ortstein than in the overlying horizons (Table 1).

3.2. Cumulative pore size distribution

The cumulative PSD curves in Fig. 1A indicate that the lower volume of larger pores, i.e. > 58 μm in radius in FK and > 32 μm in radius in FH in the ortstein, compared to the overlying horizons, was accompanied by a greater volume of smaller pores. The greatest

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