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Structure and pore system in differently managed clayey surface soil as described by micromorphology and image analysis

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ABSTRACT

Water infiltration is a crucial process for functioning of vegetated buffer zones (BZ). Structure of a clayey surface soil of three differently managed BZs, i.e., 1) natural with no treatment, 2) harvested once a year and 3) grazed by cattle was investigated in this study. Soil macro pores (>50 μm) were characterized by qualitative description and quantitative image analysis of soil thin sections in order to assess their capability to water infiltration. Less than 10% of the macro pores consisted of rounded and irregular pores smaller than 300 μm indicating root activity. Instead, macro porosity was clearly dominated by elongated pores characterized by irregularity, expressing the complexity of the pore system. This pore pattern appeared in thin sections as weak or moderate ped separation suggesting good water infiltration when initially dry. Partial accommodation of pores may result in decrease of hydraulic conductivity, as these pores tend to close upon wetting and swelling. In the grazed site a platy structure was observed due to hoof pressure, which may further impair the hydraulic properties of soil. Moisture and temperature related processes (shrink–swell, freeze–thaw, and water saturation) are thought to be conducive to the aggregation and rearrangement of soil structure around the year, resulting in a complex pore system with low intra-aggregate porosity. In addition, wet periods typical of boreal soils result in clay dispersion and formation of aggregate-related pedofeatures of dense infillings, described as fine clay intrusions.

1. Introduction

Surface soil structure controls the infiltration of water into the deeper soil horizons. Poor water infiltration makes soil prone to surface runoff and, consequently, to erosion. Vegetated buffer zones (BZs) reduce erosion and nutrient transport from agricultural areas to water bodies. The functioning of the BZ is partly based on retarding the movement of water, which is conducive to sedimentation of soil particles and reduces the transport of particle bound phosphorus (Hoffmann et al., 2009). Therefore, soil structure of a BZ should allow adequate infiltration in order to decrease overland water flow. The pore system of the thin surface layer is most critical, because it is exposed to various stresses affecting its structural properties.

Field observations of soil properties and determination of bulk density and porosity using undisturbed core samples are the first steps in the investigation of soil structure. Also soil micromorphology has been used qualitatively for decades to study soil processes and genesis as well as soil structure, as it appears in nature (Brewer, 1976; Kubiena, 1938). In this approach, characteristics of solids, pores and various other soil features are observed in thin sections and described using terminology developed for this purpose (see e.g. Stoops, 2003). Computer aided digital image analysis of thin sections is an efficient tool to quantitatively study differences in soil structure under various management practices or treatments (Murphy et al., 1977; Ringrose-Voase, 1991). For example, changes in pore number, pore size distribution and/or pore shape pattern have been used to compare effects of conventional and zero tillage (Pagliai et al., 1984; Vandenbygaard et al., 1999), influence of earthworms (Vandenbygaart et al., 2000) and application of waste organic matter on soil structure (Pagliai and Antisari, 1992). Image analysis of thin sections as well as computed tomography and magnetic resonance images are modern tools that improve the understanding of soil physical properties and processes (e.g. Kodešová, 2009).

Automatically detected or visually observed pore characteristics are attributed to soil structure and processes acting in soil. As an example, generation of rounded pores (channels) is associated with biological activity, plant roots and burrowing animals. Shrinkage of drying soil generates planar voids (i.e. cracks due to normal stress release), and ice lens formation in freezing soil may generate elongated voids and platy or lenticular structure (Vandenbygaard et al., 1999). In aggregated soils, granules and crumbs tend to form packing voids that are winding, elongated and interconnected, whereas voids between the blocky peds or plates are planar flat voids. Massive structure or planar pores oriented parallel to soil surface may indicate compaction

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(Bullock and Murphy, 1980). The pore type is essential for root growth, water transport, and air exchange (Bouma et al., 1977; Pagliai et al., 2004; Vandenbygaard et al., 1999). Especially elongated continuous pores contribute to these properties (Pagliai et al., 2004). Although the relationship between pore type and its functionality is well established, characterization of pore systems under various soil types and climatic conditions is yet to be done.

Soils of Finland are characterized by boreal climate and cryic soil temperature regime. The annual precipitation is rather low (around 550 mm), but because the clay soils of the country commonly have a very low hydraulic conductivity in the subsoil they have plenty of redox concentrations and an aquic soil moisture regime, and often also stagnic soil color pattern (FAO, 2006). According to Soil Taxonomy they are thus classified as Cryaquepts (Yli-Halla and Mokma, 2001). The soil is wet several months annually and compaction is a major threat to soil quality during agricultural operations (Alakukku, 1996), and due to cattle trampling (Pietola et al., 2005). However, the topsoil experiences several wetting–drying cycles annually, caused by drought in summer and frost in winter, commonly to the depth of 50–100 cm (Yli-Halla et al., 2009). Clay mineralogy, consisting of mica and vermiculite, is conducive to shrink–swell phenomenon, with coefficients of linear extensibility (COLE) high enough to justify for the Vertic qualifier (FAO, 2006; Yli-Halla et al., 2009). These soil characteristics subject the soil to pedoturbation and structural alterations.

Numerous papers have documented physical properties of boreal clayey soils in terms of bulk density, saturated hydraulic conductivity and total and macro porosity (e.g. Alakukku, 1996; Aura, 1983; Pietola et al., 2005). In those studies, importance of macro porosity on water transport properties and plant growth has been recognized. Messing and Jarvis (1990) reported high seasonal variation in hydraulic conductivity due to structural changes of clay soils in Sweden. Clayey surface soils of Finland are prone to plastic deformation after winter (Räty et al., 2010a). The first shrinkage cycles in spring may cause irreversible changes in inter-aggregate pore system (Rasa et al., 2009). However, studies containing detailed characterization of soil pore system are less abundant. Sveistrup et al. (2005) studied morphological and physical properties of Norwegian silt/silt loam soils and addressed the importance of freezing and desiccation on structure formation of those soils. Yli-Halla et al. (2009) presented a detailed description of a clay soil of Finland, including micromorphology of vertically oriented thin sections, but concentrating on pedogenesis with the emphasis on subsoil horizons. Qualitative and quantitative characterization of the top soil pore system, most vulnerable to natural and human induced alterations, is still lacking.

The aim of this paper was to document soil properties, especially the complexity of the pore system, of three differently managed vegetated BZs on clay soil. To complete information received from undisturbed core samples, quantitative data of pore size, pore number, and shape were obtained using image analysis of soil thin sections. In addition, the micromorphology of thin sections was qualitatively described. This study adds to the scarce information of structural properties of boreal clay soils. More specifically, these results help to assess the effects of different management practices on surface soil properties and functioning of vegetated BZs.

2. Material and methods

2.1. Experimental field and soil sampling

The Lintupaju experimental field at Jokioinen, southwestern Finland (60° 48′ N, 23° 28′ E), is located in the premises of MTT Agrifood Research Finland. In 1991, an experiment on vegetated buffer zones (BZ) was started in the field, described in more detail in Uusi-Kämppä (2005). The 10-m wide BZs were established at the edge of the field sloping (12–18%) to a natural gully. The cropped field was continued to be used mostly for growing cereals and silage grass in rotation. The soil was silty clay (51% clay, 42% silt, 7% sand in the Ap horizon) and had a cation exchange capacity of 37 cmol kg^{-1}, determined with 1 M ammonium acetate, pH 7. The clay mineralogy determined on similar soils less than 1 km away was dominated by mica, vermiculite, chlorite and mixed-layer clay minerals, with feldspars and quartz as accessory minerals (Peltovuori et al., 2002; Yli-Halla et al., 2009). The soil was classified as a Vertic Stagnic Cambisol (Eutric) (FAO, 2006) or as a Typic Cryaquept (Soil Survey Staff, 2010).

For the present study, three BZs (former cultivated field) were sampled in May 2005. These BZs had been subjected to the following management practices (names in parentheses are used later on):

- 14-year-old natural vegetation with wild hays and flowers, scrubs and trees at natural state (natural). No management.
- 14-year-old vegetation with grass species (mainly timothy and meadow fescue), harvested with light lawn-mower once a year (harvested).
- 3-year-old vegetation with grass species (mainly timothy and meadow fescue), grazed by cattle (grazed) 72 and 234 cow grazing days per ha^{-1} yr^{-1} in 2003 and 2004, respectively. Before 2003, this area had been cultivated.

Undisturbed soil samples were taken in cores (100 cm^3 steel cylinders) from each site at 0–5 cm for analysis of soil bulk density and porosity ($n=3$). These samples were saturated with water in the laboratory and the dry bulk density was calculated using the volume of sample and weight of soil dried at 105 °C. The total porosity was calculated on the basis of bulk density and the density of solids. The amount of removed water at the suction of 6 kPa (sand bed) was used to determine the soil porosity larger than 50 μm in diameter. The content of total organic carbon was determined by dry combustion with a Leco CNS 1000 apparatus. For the preparation of soil thin sections, three replicates of undisturbed soil samples were carefully collected from the top soil (about 10 cm × 10 cm). The orientation was recorded and samples were sealed in aluminum foil and plastic to minimize changes in the soil structure due to evaporation and shrinkage.

2.2. Preparation of soil thin sections

The samples were dehydrated and embedded in perforated plastic containers (polyethylene). Water was removed from the soil by wet dehydration applying a graded series of acetone (Tippkötter et al., 1986). Unsaturated polyester resin (Palatal P50-01, Büfa) with acetone as a thinner was used for the embedding of these samples (Tippkötter and Ritz, 1996). Polymerization time was 7 weeks at room temperature including final curing for 2 days at 30 °C in the oven. Despite the rather high clay content of the samples, all of them cured well. In total, 9 vertical (soil surface to about 5 cm depth) and 9 horizontal (depth of 2.5 cm) thin sections (25–30 μm) were produced.

2.3. Image acquisition and analysis

The pictures for image analysis were taken by a digital camera (Canon EOS 350D; 8 megapixels) with fixed position and exposure setting. Thin sections were placed on a transilluminator equipped with lamps for the range of visible light so that the pore space was illuminated by transmitting light. Another set of images was collected under cross-polarized conditions to evaluate overestimation of soil porosity due to miss-detected quartz grains. The significance of miss-detected pores proved to be low (0.07–0.18% of total measured area) due to small particle size of mineral grains. Therefore, subtraction of cross-polarized photographs was not carried out. Histograms were generated for thresholding with Photoshop CS (Adobe) to transform these images to binary images. After various tests, the threshold value 128 appears to be suitable for most of the photographed images.