Soil & Tillage Research 128 (2013) 104–109

Contents lists available at SciVerse ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Tillage effects on topsoil structural quality assessed using X-ray CT, soil cores and visual soil evaluation

A. Garbout [a], L.J. Munkholm [a,*], S.B. Hansen [b]

[a] Aarhus University, Department of Agroecology, PO Box 50, DK-8830, Tjele, Denmark
[b] Department of Nuclear Medicine and PET-Center, Aarhus University Hospital, DK-8000 Aarhus C, Denmark

ARTICLE INFO

Article history:
Received 4 July 2012
Received in revised form 9 November 2012
Accepted 17 November 2012

Keywords:
Tillage
Soil structural quality
X-ray CT
Visual soil evaluation

ABSTRACT

Soil structure plays a key role in the ability of soil to fulfil essential functions and services in relation to, e.g., root growth, gas and water transport and organic matter turnover. The objective of this paper was: (1) To quantify tillage effects on soil structural quality in the entire topsoil layer (0–20 cm) using X-ray CT, visual evaluation and traditional core methods; and (2) To correlate pore network characteristics from X-ray CT imaging with the results from the visual evaluation and the core method. Samples were taken in May 2009 from a long-term rotation and tillage field experiment on a Danish sandy loam. The tillage treatments were direct drilling (D) and ploughing (P). For X-ray CT scanning, we sampled large soil cores (Ø = 20 cm, height = 20 cm) from the top layer. Small 100 cm^3 samples were taken from the 4–8 and 12–16 cm layers for water content and bulk density measurements. Visual soil structure evaluation was carried out in the field at the same time as sampling. CT images ($0.39 \times 0.39 \times 0.6$ mm^3 voxels) were produced using a medical X-ray CT scanner. The visual assessment showed a good structural quality in the top 5–8 cm for both treatments ($Sq < 2$). A poorer soil structure was observed in lower part or the topsoil where a firm structure ($Sq = 2.9$) was observed for D and relatively friable structure ($Sq = 2.2$) for P. Lower bulk density was found for P than for D in the 4–8 cm layer (1.34 and 1.52 g cm^{-3}, respectively), whereas relatively high bulk density values were observed for both treatments in the 12–16 cm layers (1.50 and 1.56 g cm^{-3}, respectively). The X-ray CT image analysis showed that the P soil had more networks, branches and junctions but a lower degree of anisotropy and shorter average branch length than the D soil. The image data also confirmed a clear stratification of the 0–20 cm topsoil layer for both tillage treatments. The stratification of the direct drilled soil was in accordance with our expectations whereas it was surprising for the ploughed soil. The dense lower topsoil layer for the ploughed soil was probably caused by compaction during secondary tillage and natural consolidation, and aggravated by a poor structural stability due to a low organic matter content. The visual soil evaluation scores were negatively correlated to soil porosity and number of pore networks estimated from X-ray CT imaging and positively correlated to the macropore characteristics of branch length and pore thickness.

1. Introduction

Tillage strongly affects topsoil structure and thus the ability of soil to fulfil essential soil functions and services in relation to e.g. root growth, gas and water transport and organic matter turnover. Intensive primary tillage using a mouldboard plough fragments and homogenises the topsoil layer (typically 0–20 cm), whereas no-tillage or reduced non-inversion tillage results in a stratification of the topsoil layer (Boizard et al., in press; Franzluebbers, 2002; Munkholm et al., 2003). The stratification can be observed as a concentration of organic matter, nutrients and biological activity in the surface layer (Franzluebbers, 2002; Moreno et al., 2006), which positively affects soil structural properties such as friability and wet aggregate stability (Franzluebbers, 2002; Macks et al., 1996). Below tillage/seeding depth a densification is commonly found in no-till and reduced-till soil (Munkholm et al., 2003) with characteristic features like compact zones and a platy structure (Boizard et al., in press; Munkholm et al., 2003). A change to a more vertical pore space structure is also usually found when converting to no-tillage or reduced-tillage as summarized by Soane et al. (2012). A change to no-tillage or reduced-tillage thus leads to increased spatial variability in the entire topsoil, which means an evaluation of the entire topsoil layer will usually be needed to get comprehensive information on tillage effects on soil structure.

Traditional methods to evaluate tillage effects usually include tedious core sampling and laboratory analysis and sampling is

* Corresponding author. Tel.: +45 87157727; fax: +45 87154798.
E-mail address: lars.munkholm@agrsci.dk (L.J. Munkholm).

0167-1987/$ – see front matter
http://dx.doi.org/10.1016/j.still.2012.11.003

often carried out at one or relatively few fixed depth intervals. This means that the analysis covers only a fraction of the spatially heterogeneous topsoil layer. In recent years, the traditional methods have been supplemented with new simple visual methods (Ball et al., 2007; Shepherd, 2009) as well as advanced non-destructive X-ray computed tomography (CT) scanning technology (e.g. Munkholm et al., in press) The advantages of the visual methods are that they are simple, fast and that the evaluation is carried out individually for marked layers and then integrated over the whole topsoil layer. The X-ray CT technique has proved to be a non-destructive and very powerful technique to visualize and quantify soil structure at different scales (Garbout et al., 2012; Taina et al., 2008). Considerable effort has been concentrated on developing the method to quantify a range of pore network properties such as porosity, surface area, connectivity, tortuosity and branching (e.g. Peth et al., 2008; Vogel et al., 2010) and relate those characteristics to important soil functions such as water transport (Elliot et al., 2010), deformation under stress (Peth et al., 2010) and friability (Munkholm et al., 2012). Few researchers have applied the technique to visualize and quantify tillage effects on soil structure. Gantzer and Anderson (2002) used it to quantify tillage effects on macropores in the upper topsoil and Munkholm et al. (in press) used it to quantify effects on macropore characteristics in the lower part of the topsoil. At aggregate scale, Kravchenko et al. (2011) quantified tillage effects on intra-aggregate porosity using micro-X-ray CT. Tillage effect on soil structure in the entire topsoil layer (0–20 cm) was visualized by Munkholm et al. (2003) using X-ray CT. They used other methods to quantify the effects. The objective of this paper was: (1) To quantify tillage effects on soil structural quality in the entire topsoil layer (0–20 cm) using X-ray CT, visual evaluation and traditional core methods; and (2) To correlate pore network characteristics from X-ray CT imaging with the results from the visual evaluation and the core method. We hypothesized that ploughing produced a homogeneous topsoil structure whereas no tillage produced a clearly stratified topsoil structure. We also hypothesized a significant correlation between the visual evaluation scores and macroporosity and macropore complexity assessed from X-ray CT imaging.

2. Materials and methods

2.1. The experiment

Samples were taken from a long-term rotation and tillage field experiment on a sandy loamy soil located at Flakkebjerg Research Centre, Denmark (55°19′N, 11°23′E). The soil is based on ground morainic deposits from the last glaciations. The Flakkebjerg soil (0–25 cm) contains 15% clay, 14% silt, 12% fine sand, 27% coarse sand and 2.0% organic matter. The experiment was established in autumn 2002 as a split-plot design with four replications. The two factors were crop rotation as the main plot factor and tillage as the plot factor. In this study, we used rotation R3, which is a cereal-dominated rotation where the straw has been removed. In 2009, oats (*Avena sativa* L.) was established 24 April. The previous crop was winter barley (*Hordeum vulgare* L.) followed by a fodder radish (*Raphanus sativus* L.) cover crop that was killed by the frost late autumn 2008. The tillage systems included in this study were direct drilling (D), and ploughing (P). A chisel coulter was used in the D treatment and a traditional seed drill in the P treatment. In P, secondary tillage was carried out using a rotary harrow at the time of seeding. Mouldboard ploughing was performed 27 November 2011.

2.2. Soil sampling

Soil sampling was performed 4 May 2009 approximately two weeks after seeding. The soil had a water content close to field capacity. For X-ray CT scanning, we sampled two large soil cores (Ø = 20 cm, height = 20 cm) per plot from the top layer (i.e., 16 in total). Four 100 cm^3 samples were taken per plot from the 4 to 8 and 12 to 16 cm layers, respectively (i.e. 64 samples in total). These were used for water content and bulk density measurements.

2.3. Visual soil evaluation and soil porosity

Visual soil structure evaluation was carried out at the same time as sampling using the Visual Evaluation of Soil Structure (VESS) method (Ball et al., 2007; Guimarães et al., 2011). The topsoil (0–20 cm) was evaluated for aggregation, porosity and root growth and graded on a scale from Sq1 to Sq5 where Sq1 is best. Two assessments were carried out per plot, i.e. 16 observation points in total. The evaluation was carried out in May 2009 at the same time as soil core sampling, i.e. with soil water content close to field capacity.

The 100 cm^3 samples were weighed in field-moist condition and after oven-drying at 105 °C for 24 h. Dry bulk density (BD) was calculated from the weight of the oven-dry soil and total soil volume. Total porosity and air-filled porosity at sampling (ε_a) was calculated from the BD and weight at field-moist condition assuming a particle density of 2.65 g cm^{-3}. The use of this value was based on measured unpublished values from the same site in previous studies.

2.4. Image acquisition with X-ray CT scanner

The image acquisition was made at the PET Centre (Aarhus University Hospital) with the X-ray CT part of a Biograph 40 True Point PET/CT scanner (Siemens, Germany). The CT acquisition was performed as a helical scan using a voltage of 120 kV and an exposure of 450 mAs. After scanning and reorientation, 270 slices were produced, in coronal view. The CT images (16-bit grey-level) had a voxel dimension of 0.39 mm × 0.39 mm × 0.60 mm. The identical volumes of interest's (VOI) (same position and same volume, i.e. 4363 cm^3) were cropped from the original images in order to remove the sample cylinder from the images.

2.5. Image processing and analysis

The image analyses were made using the software ImageJ (Rasband, 2009). The images were selected and segmented using the automatic Otsu thresholding algorithm provided in the ImageJ software (version 1.45K) to isolate the soil pore space. This resulted in binary images from the original grey-level images. Subsequent, image analysis was carried out using the binary images. The detectable pore space (>0.39 mm pores) was separated into two categories: the pores connected to air and the unconnected or isolated pores. The pores were analysed using the *BoneJ* plugins (Doube et al., 2010). We measured: (i) the degree of anisotropy (DA); (ii) the pore thickness (Pthick); and (iii) the pore total volume (PV) and total surface area (PS). The DA is a calculated geometric characteristic (Odgaard, 1997), as preferential alignment along a particular axis can have significant impact on transport processes. The DA can take values from 0 to 1, with 1 indicating a high degree of anisotropy, as would be found for a group of aligned long structures.

The interconnectedness of the pore volume was characterized by network properties. First, we applied a thinning algorithm to reduce iteratively the diameter of pores until only a skeleton remained (Lee et al., 1994, and available as a plug-in, *3D skeletonize*, in ImageJ). This process was performed symmetrically to keep the skeleton lines in a medial position and preserve the connectedness of the pore volume. Secondly, we used the ImageJ plugin, *analyse skeleton*, to analyse these networks. In this way we recorded the