Geoderma 332 (2018) 73–83

Contents lists available at ScienceDirect

Geoderma

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

Effects of cropping systems upon the three-dimensional architecture of soil systems are modulated by texture

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ARTICLE INFO

Handling editor: Yvan Capowiez

Keywords:
X-ray CT
Cropping systems
3D image analysis
Porosity
Pore size distribution
Pore connectivity

ABSTRACT

Soil delivers fundamental ecosystem functions via interactions between physical and biological processes mediated by soil structure. The structure of soil is also dynamic and modified by natural factors and management intervention. The aim of this study was to investigate the effects of different cropping systems on soil structure at contrasting spatial scales. Three systems were studied in replicated plot field experiments involving varying degrees of plant-derived inputs to the soil, viz. perennial (grassland), annual (arable), and no-plant control (bare fallow), associated with two contrasting soil textures (clayey and sandy). We hypothesized the presence of plants results in a greater range (diversity) of pore sizes and that perennial cropping systems invoke greater structural heterogeneity. Accordingly, the nature of the pore systems was visualised and quantified in 3D by X-ray Computed Tomography at the mm and μm scale. Plants did not affect the porosity of clay soil at the mm scale, but at the μm scale, annual and perennial plant cover resulted in significantly increased porosity, a wider range of pore sizes and greater connectivity compared to bare fallow soil. However, the opposite occurred in the sandy soil, where plants decreased the porosity and pore connectivity at the mm scale but had no significant structural effect at the μm scale. These data reveal profound effects of different agricultural management systems upon soil structural modification, which are strongly modulated by the extent of plant presence and also contingent on the inherent texture of the soil.

1. Introduction

Soil structure is dynamic and subject to modification by natural and anthropogenic actions, such as wetting-drying cycles and freeze-thaw action. These processes re-structure the soil with potential consequences for physical and biological processes (Rabot et al., 2018). Water flow and gas diffusion are both affected by the porous architecture (Naveed et al., 2016). The nature and magnitude of soil microbial activity are affected by the air-water balance in soil and the availability of nutrients, and microbial communities are strongly affected by their microenvironment in soil (Chenu, 1993; Helliwell et al., 2014). Soil microbes, along with plant roots, are implicated in aggregation processes via gluing and enmeshing activity (Tisdall and Oades, 1982). Microbial communities can contribute to aggregate stability and therefore help prevent de-structuring of soil structure (Chenu and Cosentino, 2011; Dorioz et al., 1993; Oades, 1993). This, in turn, might lead to the capacity of soils to adapt to changing environmental circumstances (Crawford et al., 2012; Feeney et al., 2006).

Tillage practices have a significant direct influence impact on soil structure, often increasing the macro-porosity of conventionally managed soils (Ambert-Sanchez et al., 2016). Conventional tillage can also result in depletion of nutrients and organic carbon within the soil (Coleman et al., 1997) and a decline in aggregated structure (Watts et al., 2001). Studies of a long-term (40+ years) field experiment at Rothamsted Research (Harpenden, UK) in which grassland was converted to arable and bare fallow managements has resulted in a decline of soil organic carbon and nitrogen (Gregory et al., 2016) and a decrease in microbial abundance under the different managements (Hirsch et al., 2009). These studies focused on soil biological and chemical properties (such as microbiota, pH, organic carbon). However,

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https://doi.org/10.1016/j.geoderma.2018.07.002
Received 16 February 2018; Received in revised form 28 June 2018; Accepted 2 July 2018
Available online 10 July 2018

there is no information on the structure of the pore networks of the soils under these long-term managements.

The aim of this study was to identify any effects of different cropping managements associated with contrasting degrees of plant presence on soil structure in the context of two soil textural classes. Three long-term field cropping systems were studied: grassland (perennial plant), arable (annual plant) and bare fallow (no plant). We hypothesized that cropping management influences the inherent soil structural properties by (i) the presence of plants resulting in greater soil porosity and range of soil pore diameters due to root action; and (ii) a more persistent presence of plants invokes greater porosity and structural heterogeneity, apparent as a wider range of pore sizes in perennial systems. Structural properties of the soils were determined at two spatial scales of sample and resolution, i.e. 'core' scale (435 cm^3 at 40 μm resolution) and 'aggregate' scale (circa 4 mm^3 at 1.5 μm resolution). To establish the functional consequences of such structures for water flow in the soils, we also estimated their saturated hydraulic conductivity at both scales using a pore-scale modelling approach.

2. Materials and methods

2.1. Soils

Soil cores were collected in October 2015 at Rothamsted Research (Hertfordshire, UK) from two complementary long-term experiments: Highfield Ley-Arable experiment (LATLONG 51.8103N, -0.3748E), on a silty-clay loam textured soil developed on clay-with-flints over Eocene London Clay (Batcome series) and classified as a Chromic Luvisol by FAO criteria (hereafter referred to as clay soil, Table 1); and Woburn Ley-Arable experiment (LATLONG 52.0009N, -0.6137E), on a well-draining, sandy loam soil of the Cottenham Series (Hodge et al., 1984), classified as a Cambric Arenosol (FAO), (referred to as sandy soil, Table 1). The replication of the treatments was uneven and based on the inherent experimental plot design. Four cylindrical cores (68 mm diameter × 120 mm height) of the grassland and arable treatments and three replicate cores of the bare fallow treatment were extracted for the clay soil from the surface down to the height of the columns minus 1 cm (110 mm). Four cores of the grassland, arable with manure (25 t ha^{-1} $annum^{-1}$; hereafter referred to as arable manure) and bare fallow treatments and five replicate cores of the arable with inorganic fertiliser (10 kg N ha^{-1} y^{-1}; hereafter referred to as arable inorganic) were collected for the sandy soil. For both soil types, the arable treatment was under conventional tillage, ploughed to a depth of 23 cm, once a year. The arable fields for the clay and sandy soil was last ploughed respectively in September and October 2014 before sampling. The fallow plots were rotavated in June 2015 for the clay soil and tined in April 2015 for the sandy soil before sampling. All replicates were independent and derived from separate plots. All treatments had been maintained for at least 50 years. After sampling, cores were stored at 4 °C prior to further analysis.

2.2. X-ray computed tomography (CT)

Soil cores were scanned using a Phoenix v|tome|x M scanner (GE Measurement and Control solution, Wunstorf, Germany), set at 160 kV, a current of 180 μA, detector sensitivity of 200% and at a pixel/voxel resolution of 40 μm (resultant voxel volume = 64,000 $μm^3$). A total of 2900 projection images were taken at 250 ms per image using an averaging of 1 image and skip of 0. Total scan time per core was 24 min. After scanning, each core was dismantled, and the soil passed through a sieve series of 4, 2 and 0.71 mm. Three randomly-selected aggregates retained between the 2 and 0.71 mm sieves per core were scanned using a Phoenix Nanotom® (GE Measurement and Control solution, Wunstorf, Germany) set at 90 kV, a current of 65 μA and at a base resolution of 1.51 μm (resultant voxel volume = 3.44 $μm^3$). A total of 1440 projection images were taken at 500 ms period using an averaging of 3 images and skip of 2. The total scan time per sample was 69 min.

Reconstruction of all scanned images was processed using Phoenix datos|x2 rec reconstruction software. Scanned images were optimised to correct for any movement of the sample during the scan and noise was reduced using the beam hardening correction algorithm, set at 8. As a multi-scan routine was performed on the core samples, VG StudioMax® 2.2 was used to merge the top and bottom scans to obtain a single 3D volume for the complete core. For both core and aggregate samples, image sequences were extracted (dimensions described below) for image analysis. Core samples were scanned at the prevailing water content following sampling (approximately field capacity). Soil aggregates were derived from these cores following air-drying overnight and the moisture content recorded. The soil was passed through 4, 2 and 0.71 mm mesh size sieves while subjected to horizontal shaking for 3 min at 300 rotations min^{-1}. Twenty aggregates were randomly selected from between the 2 and 0.71 mm sieves, and conserved in sealed containers in the dark at room temperature.

2.3. Image analysis

Initial image analysis was performed using ImageJ (Schneider et al., 2012). For both soil cores and aggregates, a uniform region of interest (ROI) was defined for each sample; 40 × 40 × 40 mm and 0.981 × 0.725 × 0.604 mm respectively. Core ROIs were positioned centrally to limit inclusion of cracks or large stones created during the sampling process. Cubic ROIs for aggregates were not possible because of their variable geometry, so the largest ROI accommodated by all aggregates was chosen. The coordinates of these regions were adapted for each image volume/sequence. The image pre-processing consisted of: (i) cropping to the ROI; (ii) enhancing the contrast/brightness to 0.35%; (iii) application of a 2-pixel radius median filter; (iv) converting the image format to 8-bit; (v) saving the new image volume. Stones were segmented from the ROI volume in VG StudioMax® 2.2 using the surface determination tool.

All images were thresholded using the bin bi-level threshold approach by Vogel and Kretzschmar (1996) using the open source software QuantIm (http://www.quantim.ufz.de/). Each image within the image sequence has a single threshold value, to determine the

Table 1
Summary physical and chemical data of Highfield Ley-Arable experiment soils.

Treatment	Density[a]/g cm^{-3}	pH[a] (H_2O)/-log(g[H^+]L^{-1})	Organic carbon[a]/mg g^{-1} soil	Free organic carbon[b]/μg g^{-1} soil	Intra-aggregate organic carbon[b]/μg g^{-1} soil	Nitrogen[a]/μg g^{-1} soil	NaOH-EDTA extractable phosphorus[c]/μg g^{-1} soil
Fallow	1.30–1.45	5.1	0.8	150	380	100	235
Arable	1.30–1.45	5.8	1.3	370	490	150	517
Grassland	0.99	6.0	3.9	4690	3010	390	662

[a] Gregory et al., 2016.
[b] Hirsch et al., 2009.
[c] Neal et al., 2017.