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Long-term effects of grass-clover leys on the structure of a silt loam soil in a cold climate

Nicholas Jarvis[a,*], Johannes Forkman[b], John Koestel[a], Thomas Kätterer[c], Mats Larsbo[a], Astrid Taylor[c]

[a] Dept. Soil and Environment, Swedish Univ. Agricultural Sciences, Box 7014, 750 07, Uppsala, Sweden
[b] Dept. Crop Production Ecology, Swedish Univ. Agricultural Sciences, Box 7043, 750 07, Uppsala, Sweden
[c] Dept. Ecology, Swedish Univ. Agricultural Sciences, Box 7044, 750 07, Uppsala, Sweden

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ABSTRACT

Grass/legume leys are commonly included in the crop rotation in mixed farming systems in cold or humid regions in order to sustain the supply of nutrients and maintain soil fertility. Leys are also known to sequester soil organic carbon and also improve the structural stability and mechanical properties of soil. However, few studies have investigated the long-term effects of ley rotations on the architectural properties of the structural pore space in soil. We investigated the effects of grass/clover leys on soil structure in the topsoil and upper subsoil of a silt loam in a long-term field trial established in 1956 at Offer in northern Sweden. This experiment includes four treatments with varying proportions of ley (1, 2, 3 or 5 years) in 6-year rotations. We used X-ray tomography to quantify topsoil structural pore space at a resolution of 65 μm in the first year of arable cropping following the ley break, a few weeks after sowing in spring. Earthworm populations were quantified by both hand-sorting and chemical extraction, while near-saturated infiltration was measured as a proxy for soil structure in the upper subsoil. In the topsoil, the treatments with a greater proportion of ley had larger organic carbon contents, smaller bulk densities and larger porosities. However, effects of crop rotation on the pore space were limited to pores smaller than 65 μm, as no treatment effects were found for the volume, size distribution, connectivity or complexity of the X-ray imaged pore space, even though the grass-clover leys promoted larger numbers and biomass of topsoil-dwelling earthworm species. Furthermore, no positive effects of grass/clover leys on organic carbon content and soil structure were found in the subsoil. The macropore infiltration capacity in upper subsoil was generally very small (overall median value of 3 mm h^{-1}) indicating a lack of functional macroporosity below plough depth. Consistent with these results, no individuals of deep-burrowing earthworm species were found at the site, while previous observations showed only shallow rooting, both of which are attributed to the cold climate and poor subsoil drainage.

1. Introduction

Grass/legume leys are commonly included in the crop rotation in mixed farming systems in cold or humid regions in order to sustain the supply of nutrients and maintain soil fertility (Watson et al., 2002; Peyraud et al., 2009). Compared with continuous arable cropping, leys are also thought to improve soil structure (Watson et al., 2002; Ball et al., 2005) through several biological processes. In particular, due to larger litter inputs and reduced tillage disturbance, ley rotations usually support larger populations of earthworms (Schmidt et al., 2003; Jordan et al., 2004; Scullion et al., 2007; Van Eekeren et al., 2008; Riley et al., 2008; Ponge et al., 2013) whose burrowing has been shown to profoundly affect soil structure and functions (Bertrand et al., 2015). Biopores created by deep-burrowing anecic earthworm species or tap-rooted leguminous plants improve aeration and drainage and provide 'paths of least resistance' for roots to penetrate compact subsoils (Hatano et al., 1988; Stewart et al., 1999; McKenzie et al., 2009), which can result in deeper rooting of crops with more fibrous root systems (Kautz et al., 2010, 2014; Perkons et al., 2014). On the other hand, traffic-induced compaction may also occur in forage-based crop rotations (Douglas et al., 1992, 1998; Ball et al., 1997; Jorajuria et al., 1997; Schjønning et al., 2002a), which can lead to reductions in earthworm populations (Hansen and Engelstad, 1999; Radford et al., 2001) and restricted root development, especially in subsoil horizons (Schjønning et al., 2002a) where structural damage is difficult to ameliorate.

* Corresponding author.
E-mail address: nicholas.jarvis@slu.se (N. Jarvis).

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In the long term, soil organic matter contents tend to increase under ley cropping systems compared to continuous arable cropping (Haynes, 1999; Soussana et al., 2004; Kätterer et al., 2012; Christensen et al., 2009; Johnston et al., 2009) due to the smaller export of carbon, higher root/shoot ratios and a lack of stimulation of mineralization by tillage disturbance. This organic matter is complexed with finer soil particles, forming micro-aggregates in soil that provide long-term physical protection against decomposition (Six et al., 2002, 2004). As soil organic matter contents change only slowly in response to changes in land management (Kätterer et al., 2008; Johnston et al., 2009), long-term field experiments are required to characterize the effects of crop rotations on soil structure. Several such studies have demonstrated the beneficial effects of ley cropping systems on easy-to-measure physical properties such as bulk density (or porosity) as well as the mechanical properties of soil aggregates, such as their stability, tensile strength or friability, all of which are known to depend strongly on soil organic matter (e.g. Carter and Kunelius, 1993; Watts and Dexter, 1997; Haynes, 1999; Holeplass et al., 2004; Riley et al., 2008; Murphy, 2015). However, far fewer attempts have been made to quantify the effects of ley rotations on the architecture of the larger structural pores that influence a range of important processes in soils, including water and gas transport (de Jonge et al., 2009; Ball, 2013; Jarvis et al., 2016), microbiological activity, carbon turnover and nutrient cycling (Ball et al., 2005), pollutant leaching (Jarvis, 2007), plant root growth, nutrient use efficiency and crop yields (Ball et al., 2005; Johnston et al., 2009). Some previous studies have either used micro-morphological 2D thin-sectioning techniques or indirectly inferred the effects of leys on the structural pore space in soil from measurements of transport properties such as saturated and near-saturated hydraulic conductivity or gas permeability (e.g. Schjønning et al., 2002b; Lamandé et al., 2003). In contrast, fewer studies have directly quantified the long-term effects of land management on the characteristics of structural pore networks using modern 3D non-invasive X-ray scanning techniques (Young et al., 2001; Helliwell et al., 2013). Most previous studies have also focused on topsoil properties, so that much less is known or understood about the long-term effects of grass-clover leys on soil organic carbon and soil structure in the subsoil.

Our objective was therefore to investigate the effects of the frequency of grass/clover leys in the crop rotation on both the topsoil and subsoil structure. The study was carried out in a long-term field trial established in 1956 at Offer in northern Sweden on a silt loam soil. This experiment includes four treatments with varying periods of grass/clover ley (1, 2, 3 or 5 years) in a 6-year crop rotation. X-ray tomography was used to quantify the characteristics of the structural pore networks developed in the topsoil. This data was complemented with measurements of bulk density, organic carbon in the soil profile, earthworm populations and near-saturated infiltration rates into the upper subsoil.

2. Materials and methods

2.1. Field site and experimental design

A long-term cropping trial was established at Offer (63.1°N, 17.8°E) in 1956. The climate in the area is cold temperate, with an annual precipitation of 536 mm, a mean annual average temperature of 3.1 °C, mean monthly temperatures in January and July of −10.2 and 15.9 °C and five winter months with mean air temperatures below zero (averages for period 1961–1990, recorded at Sollefteå, ca. 20 km from the field site). The experimental design is a randomized block experiment containing six blocks. Each block comprises four plots (each 20 m by 8 m in size), one plot for each of four different crop rotations that differ with respect to the number of years of grass-clover ley (mixture of *Trifolium pratense* L., *Phleum pratense* L. and *Festuca* sp.) in the rotation (5, 3, 2 or 1 year of ley in a six-year rotation with arable crops in the remaining years; see Table 1). These treatments are termed *A*, *B*, *C* and *D* in the following. Treatments *A* and *B* also receive two applications of cattle manure during the six-year rotation, at a rate of 30 Mg ha^{-1} on each occasion, while treatment *C* receives a single manure application of 40 Mg ha^{-1}. The forage crops were harvested one to three times per year. More details of the experiment at the Offer site can be found in Carlgren and Mattsson (2001), Bolinder et al. (2010, 2012) and Simonsson et al. (2014). Due to the unreplicated experimental design, with only one plot per treatment with the same crop each year, we made measurements in consecutive years to avoid contrasting effects of the current crop on soil structure. However, this introduces potential within-treatment variation related to variation in weather conditions between the years. To minimize these effects, the sampling was carried out at the same time of year in both years (see Sections 2.2, 2.6 and 2.7). The effects of sampling year were also included in the statistical analysis (Section 2.8).

Table 1
Crop rotations at the experimental site.

Year	Treatment			
	A	B	C	D
1	Spring barley (+undersown ley)	Spring barley (+undersown ley)	Spring barley (+undersown ley)	Spring barley (+undersown ley)
2	Grass/clover	Grass/clover	Grass/clover	Grass/clover
3	Grass/clover	Grass/clover	Grass/clover	Spring barley
4	Grass/clover	Grass/clover	Spring barley	Potato
5	Grass/clover	Spring barley	Potato	Spring barley
6	Grass/clover	Spring barley/ rape/peas	Spring barley/ rape/peas	Potato

The soil is a Gleyic Cambisol developed in fluvio-glacial deposits. Soil pH increases from around 6 in the topsoil to ca. 7 at 1 m depth. The texture of the soil is silt loam. Bulk topsoil samples were taken for particle size analysis by the pipette method at 32 locations (four samples in each of eight plots), immediately alongside core samples extracted for X-ray scanning (see below). For these samples, clay contents varied between 23 and 40% (with a mean of 30%) and silt contents between 50 and 68% (with a mean of 57%). Although the available data is more limited, the texture in the subsoil is similar to the topsoil: the mean clay and silt contents at 30–50 cm depth measured for bulked samples taken from four pits per plot in four of the plots (one from each treatment) were 32% and 64% with coefficients of variation of 17 and 9% respectively. Based on visual inspection in these sixteen pits, the structure is platy in the upper subsoil, becoming more massive in deeper layers, with very few biopores. The platy structure is presumably a result of annual freeze-thaw processes (Taina et al., 2013), although traffic compaction may also have contributed (Sasal et al., 2006; Boizard et al., 2013). The soil is undrained and weak rust-coloured mottles are visible in the subsoil indicative of temporary waterlogging.

2.2. Core sampling

64 PVC cores, each with an inner diameter of 6.7 cm and a length of 10 cm, were sampled from the plough layer in two consecutive years. Half of the samples were taken in June 2013 and the other half in June 2014. In both years, we sampled the single plot from each treatment which was in the first year of arable cultivation after the break of the grass ley (see Table 1). The plots had been ploughed to ca. 20–25 cm depth the previous autumn and harrowed to ca. 6–8 cm depth about 3 weeks prior to sampling. In both years, eight cores were sampled per plot, four at the soil surface and four at a depth of 10–20 cm.

2.3. X-ray scanning

The PVC cores were imaged using the GE Phoenix X-ray scanner