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Root-length densities of various annual crops following crops with contrasting root systems

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ABSTRACT

The aim of this study was to evaluate how soil structure and root-length densities of annual crops can be influenced by preceding crops. Three different annual field crops (spring wheat, *Triticum aestivum* L., winter barley, *Hordeum vulgare* L. and winter oilseed rape, *Brassica napus* L.) were cultivated either after two continuous years of chicory, *Cichorium intybus* L., a perennial taprooted fodder crop or after annual crops with fibrous root systems (oats, *Avena sativa* L. and tall fescue, *Festuca arundinacea* Schreb). Biopores of two diameter classes (2–5 mm and >5 mm) were quantified per unit surface area by visual classification in 45–145 cm soil depth. Root-length density was estimated by using the profile wall method or by image analysis of roots washed from monolith samples. After chicory, the number of large sized biopores per unit surface area in the subsoil was greater than after annual crops with fibrous root systems. When grown after chicory, the root-length densities of annual winter crops below 115 cm soil depth were greater than after fibrous precrops. It is concluded that cultivation of taprooted crops with the ability to create larger sized biopores allows subsequent crops to establish more roots in deep soil layers, with potentially greater access to nutrients and water from the subsoil.

1. Introduction

The size and distribution of root systems largely determine the ability of arable field crops to acquire water and nutrients. Deep rooting is particularly beneficial for allowing water uptake from great soil depths during periods of drought (McKenzie et al., 2009; Gaiser et al., 2012). In agricultural production systems with limited input of soluble nutrients – such as organic agriculture – crops depend on extensive root systems to acquire nutrients from the solid phase of soil (Lammerts van Bueren et al., 2002). The distribution of plant roots in soil is strongly affected by soil physical conditions like, amongst others, bulk density (Ball et al., 2005; Gregory, 2006), aeration and aggregate stability (Anderson and Kemper, 1964; Voorhees, 1992). The structure of arable topsoils is modified by tillage operations. The subsoil, i.e. the layer below the ploughed horizon, cannot be reached by normal tillage machinery. In the subsoil, roots can have considerable influence on soil structure: while growing in diameter, roots exceed a pressure that results in a reorganization of the soil pore network (Kolb et al., 2012). After their decay, roots leave impression channels in the soil (Jones et al., 2004), termed biopores. Roots with a large diameter like the taproots of dicotyledonous plants have been reported to be able to grow through compacted soil easier than roots with small diameters (Materechera et al., 1992), thus having particular potential to create new large sized biopores which in turn can affect root growth of subsequent crops. The effects of precrops on subsequent crops can also be related to residual nutrients and water as well as disease control (Kirkegaard et al., 2008).

Moreover, burrowing soil animals such as anecic earthworms can influence the soil structure of arable fields. When the tillage intensity is reduced or periods of soil rest are established, the populations of anecic earthworms can be promoted (Curry et al., 2002; Peigné et al., 2009), which in turn can contribute to the formation of biopores (Ehlers, 1975; Joschko et al., 1989).

In the subsoil, large sized biopores have particular relevance as preferential pathways for root elongation (Ehlers et al., 1983; Nakamoto, 1997). Compared with the bulk soil, root growth in biopores was reported to occur at greater soil depths (McMahon and Christy, 2000). Where roots can re-enter the bulk soil from biopores as reported by Kautz et al. (2013), biopores can probably

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also increase root-length density in the bulk soil. However, also adverse effects of large biopores have been reported, especially when the soil is too compact to allow re-entry of roots growing through biopores into the bulk soil and clumping of roots in biopores occurs (Cresswell and Kirkegaard, 1995; Passioura, 2002; White and Kirkegaard, 2010). Moreover, lack of contact between roots and the pore wall can impede water and nutrient uptake (Stirzaker et al., 1996).

This study investigates how soil structure in arable fields can be influenced by preceding crops and how altered soil structure may influence root growth of field crops. The development of root-length over time and the depth distribution of root-length densities of three field crops, spring wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.) and winter oilseed rape (*Brassica napus* L.) were quantified in a field experiment. These crops were cultivated either after the taprooted chicory (*Cichorium intybus* L.) grown continuously for two years or after annual cultivation of oats (*Avena sativa* L.) and tall fescue (*Festuca arundinacea* Schreb.), both having fibrous root systems. We hypothesized that cultivation of a perennial fodder crop with a taproot system compared with annual cultivation of crops with fibrous root systems results in (i) a greater number of large sized biopores per area unit and (ii) increased root-length densities inside and outside of these biopores.

2. Materials and methods

2.1. Experimental field site

The field experiment was conducted at the Campus Klein-Altendorf experimental research station near Bonn, Germany (50°37′ N, 6°59′ E). The mean annual temperature is 9.6 °C and the mean annual precipitation is 625 mm. The soil is a Haplic Luvisol derived from loess (IUSS, 2006).

We investigated selected plots inside a larger sized field experiment established on a site characterized by sugar beet and cereal cultivation since 1996. The field experiment was divided into two parts: a precrop phase with fodder crops (2008–2009) followed by a second phase with annual field crops (2010–2011). The fodder crops were chicory (*Cichorium intybus* L. 'Puna') with a taproot system and tall fescue (*Festuca arundinacea* Schreb. 'Hykor') with a fibrous root system. Chicory was sown May 6, 2008, with a sowing density of 5 kg ha^{-1} (385 seeds m^{-2}) and grown for two years continuously (Chi2y, Table 1). Tall fescue was sown April 15, 2009, with a sowing density of 30 kg ha^{-1} (1250 seeds m^{-2}) and grown for one year, after oats (*Avena sativa* L. 'Max') was cultivated in 2008 (Oat-Fes, Table 1). Both fodder crops were mulched three to five times per year. In spring 2010 the fodder crops were ploughed to 30 cm depth and spring wheat (*Triticum aestivum* L. 'Scirocco') was sown April 8, 2010, with a sowing density of 400 grains m^{-2} and a row width of 10.5 cm. After harvest of spring wheat, winter barley (*Hordeum vulgare* L. 'Highlight') or winter oilseed rape (*Brassica napus* L. 'Visby') were sown October 7 and September 17, 2010, with sowing densities of 330 and 100 kernels m^{-2} and 11 cm row width. Plot size was 6 m × 10 m and there were four field replications for each treatment.

Table 1
Cropping sequences under study.

Treatment	2008	2009	2010	2011
Chi2y	Chicory	Chicory	Spring wheat	Winter barley Winter oilseed rape
Oat-Fes	Oats	Fescue	Spring wheat	Winter barley Winter oilseed rape

The described field experiment was set up with identical design two years later directly adjacent to the first field experiment. In this second experiment, chicory was sown in April 2010 and tall fescue was sown in March 2011 with the same sowing densities as in the first field trial. This experiment was used for quantifying root-length densities of fodder crops to a maximum sampling depth of 2 m. All other data presented in this article were derived from the first field experiment.

2.2. Soil physical and soil chemical analyses

Soil chemical and physical parameters were analyzed in two field replicates. Undisturbed soil core samples (54 mm Ø, 40 mm height) were taken in spring 2010 in two field replicates at soil depths 15, 45, 60 and 75 cm, using a manual auger. Soil cores were used to determine the total porosity, air capacity and bulk density. For each depth, seven cores per replicate were extracted. The cores were water saturated from beneath, drained at −6 kPa matric potential in suction ceramic plates and oven dried at 105 °C for 24 h. The total pore volume (PV) was calculated from the relation of the bulk density and the soil particle density (in this case 2.63 Mg m^{-3}) using Eq. (1).

$$PV = 1 - \left(\frac{d_B}{d_P}\right) \quad (1)$$

where PV is the total volumetric porosity (m^3 m^{-3}), d_B is the bulk density of the soil (Mg m^{-3}) and d_P is the particle density (Mg m^{-3}). Air capacity was calculated as the difference of the total volumetric porosity and the volumetric water content at −6 kPa matric potential (Hartge and Horn, 2013).

Four soil samples per field plot were collected per plot in April 2010 and 2011 from 0 to 105 cm soil depth using a Pürckhauer auger and divided into the sections 0–30 cm, 30–45 cm, 45–75 cm and 75–105 cm. For analysis of soil C and N concentrations, sample aliquots were dried at 105 °C and ground with a vibratory disk mill (Retsch RS 1, <100 μm). Total concentrations of C and N were analyzed by dry combustion with a Fisons NA-1500 elemental analyzer. For quantification of mineral N concentrations (NO_3^- and NH_4^+) sample aliquots were stored at −20 °C until analysis with a Skalar Continuous Flow Analyser.

2.3. Biopores

Biopores established by roots can be blocked by the roots until they decay (Dexter, 1991; Jones et al., 2004). For this reason, areas designated for quantification of biopores (in areas of 50 cm × 50 cm each) were excavated in summer 2011, i.e. more than one year after plowing the fodder crops, when most of the precrop roots had decayed. A plane horizontal surface was created at 45 cm soil depth and cleaned from soil particles with a vacuum cleaner. Biopores of two diameter classes (2–5 mm and > 5 mm) were marked on plastic sheets that were placed on the horizontal soil surface. From 45 to 145 cm soil depth biopores were measured in 10 cm-steps as described.

2.4. Profile wall method

Root-length (RL) was estimated with the profile wall method (Böhm, 1979) in two field replicates. An excavator was used to install a trench with a depth of 2.30 m. A 100 cm wide soil profile wall was smoothed to maximum rooting depth (maximum depth of investigation 2 m) transversely to the plant rows with a spade and sharp blades. Roots exposed from the wall were removed by scissors. With a fine spray of water at 300 kPa pressure and using a small toothed scraper, a 0.5 cm thick soil layer was washed away