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Maize and wheat root biomass, vertical distribution, and size class as affected by fertilization intensity in two long-term field trials

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ABSTRACT

Root biomass is the most commonly studied root parameter to investigate below ground crop response to environmental conditions and carbon cycling in agroecosystems. Root growth is strongly regulated by site-specific growth conditions and resource availability, but only little is known about the extent to which root biomass, vertical distribution, and size class respond to fertilization intensity as compared to site. We determined coarse (> 2 mm) and fine (> 0.5 mm and ≤ 2 mm) root biomass of maize and wheat in three soil layers to 0.75 m depth in different farming systems (half and full organic, full conventional) and fertilization treatments (zero, manure, full mineral N plus half mineral PK, full mineral NPK) of the Swiss long-term field trials DOK and ZOFE, respectively, and evaluated the effects of fertilization intensity and site on root biomass, vertical distribution, and size class. In DOK, total root biomass was similar in organic and conventional farming systems. In ZOFE, wheat root biomass was 1.7-times higher under full mineral N plus half mineral PK fertilization than under zero or manure fertilization and intermediate under full NPK fertilization. Vertical root distribution and size class were only marginally affected by fertilization intensity on both sites. By contrast, total root biomass of maize and topsoil root biomass of both maize and wheat were higher but subsoil root biomass of wheat and fine root proportions of both maize and wheat were lower in DOK than in ZOFE. We conclude that roots respond more to site than to fertilization intensity and that absolute inputs of root biomass carbon to soil are similar in low- and high-intensity systems. Further, root-shoot ratios were inversely related to fertilization intensity, implying that estimations of below ground carbon inputs to soil from shoot biomass need to be differentiated by fertilization intensity. Deep (below 0.5 m) root biomass was 3-times higher for wheat than for maize, suggesting that crop choice is more important than fertilization intensity for carbon sequestration in deep soil.

1. Introduction

Growth and functioning of crop root systems are recognized as significant components of plant performance and crop yield (Monyo and Whittington, 1970; O'Toole and Bland, 1987; Palta and Yang, 2014; Weaver, 1926). The morphological traits of the root system are directly linked to the plant's ability to acquire soil resources such as water and nutrients. While deep-rooting enhances nitrogen (N) acquisition (Saengwilai et al., 2014), proliferation of highly branched lateral roots in the topsoil fosters phosphorus (P) uptake (Lambers, 2006). Roots are highly plastic and respond to environmental conditions by adapted growth and development, which has been increasingly recognized as a key element of yield improvement (Koevoets et al., 2016; Palta and Watt, 2009). A boost of crop yields by increasing input of external resources has reached its limits in high-intensity agriculture (Herder et al., 2010) and is largely impossible in low-intensity agriculture in developing countries due to economic and edaphic constraints (George et al., 2012; Lynch, 2007). Hence, optimized utilization of the root system and especially its plasticity to improve resource acquisition is a key research focus (Herder et al., 2010; Lynch, 2007; Topp et al., 2016).

Crop roots and their promotion are also discussed as a climate change mitigation strategy (Kell, 2012; Paustian et al., 2016). Enhanced root systems, i.e. more root biomass and deeper roots, can increase carbon (C) inputs to soil and sequester C in the long term (Kell, 2011; Lynch and Wojciechowski, 2015; Maeght et al., 2013; Pierret et al., 2016). In agroecosystems, 30–90% of total organic C inputs are

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Abbreviations: DOK, long-term system comparison of bio-Dynamic, bio-Organic, and Conventional farming; ZOFE, Zurich Organic Fertilization Experiment; BIOORG1, BIOORG2, bio-organic farming systems with half and full fertilization levels, respectively; CONFYM2, conventional farming system with full fertilization level; CONTROL, unfertilized control treatment; MANURE, farmyard manure treatment; N2P1K1, N2P2K2Mg, mineral fertilization treatments with full N level and half and full PK levels, respectively; EOM, extraneous organic matter

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supposed to be root-derived (Kätterer et al., 2011). In contrast to above ground C inputs that are usually confined to the topsoil (Schneider et al., 2006), crop roots are often distributed within the upper meter of soil (Fan et al., 2016) and can even reach depths of several meters (Canadell et al., 1996), thereby translocating C deep into the subsoil. With residence times twice as high as those of above ground crop residue- (Kätterer et al., 2011; Rasse et al., 2005) and manure-derived C (Zhang et al., 2015), root C is also more persistent in soil (Ghafoor et al., 2017; Menichetti et al., 2015).

Root biomass is the most commonly investigated parameter to quantify structural root C. While crop performance is predominantly related to length, number, positioning, and angle of root components (Koevoets et al., 2016; Lynch, 2007), root biomass, vertical distribution, and size class, i.e. classification into coarse and fine roots (Smithwick et al., 2014), provide specific information about below ground crop response to environmental conditions and C cycling in agroecosystems (Fageria, 2013).

Root biomass, vertical distribution, and size class can vary widely between sites (Bolinder et al., 1997; Pietola and Smucker, 1998; Plaza-Bonilla et al., 2014). In a comprehensive review, Rich and Watt (2013) highlight the effects of site conditions on crop root growth: Mechanical impedance of soil inhibits root elongation but increases root diameter while rising soil temperatures generally enhance root biomass. Reduced water availability promotes deep rooting of tolerant plants while excess water restricts primary root growth and accelerates root decay (Rich and Watt, 2013). However, the authors emphasize that the effects of individual factors on root growth in the field are impossible to disentangle. Furthermore, different species or varieties can perform very differently below ground on the same site (Ontl et al., 2013; Thorup-Kristensen et al., 2009).

Nutrient availability has a large impact on root growth and has been studied with regard to several plant traits and processes, e.g. crop yield (Marcinkevičienė et al., 2013; Oikeh et al., 1999; Wang et al., 2014), crop nutrient use efficiency (Allard et al., 2013), root-shoot ratios (Anderson, 1988; Bonifas et al., 2005; Marschner et al., 1996), or C allocation (Allmaras et al., 2004). With respect to the effect of varying short-term fertilization rates on root biomass, findings are controversial: Highest root biomass was found under lowest (Durieux et al., 1994), intermediate (Oikeh et al., 1999), or highest (Iman et al., 2006; Marcinkevičienė et al., 2013) nutrient supply. Otto et al. (2009) did not find any effect of fertilization rate on root biomass. Extreme nutrient deficiency severely impairs root growth (Rich and Watt, 2013), whereas mild deficiency may enhance C allocation to roots and promote soil exploration by the root system (Lynch et al., 2012).

In agricultural practice, nutrient availability is driven by several overlying factors that may have long-term effects and differ between farming systems. While type and amount of fertilization affect nutrient availability directly, other management practices can influence nutrient availability indirectly. For example, legumes in the crop rotation provide additional plant-available N to the succeeding crop (Peoples et al., 1995), long-term application of organic soil amendments promotes biotic and abiotic soil properties that favour nutrient cycling (Mäder et al., 2002), while weed control reduces root competition for resources (Kiær et al., 2013). Long-term field trials with treatments that differ considerably in type and amount of fertilization and not only in distinct nutrient application doses offer a valuable opportunity to study crop response to environmental conditions close to agricultural practice (Mayer and Mäder, 2016). Only few studies have focused on the effect of farming system on root biomass. Low-input systems were found to yield similar or higher root biomass as compared to high-input systems (Chirinda et al., 2012; Lazicki et al., 2016; Steingrobe et al., 2001; van Noordwijk et al., 1994).

Long-term fertilization intensity, i.e. fertilizer nutrient input per area over a period of time, is one of the most frequently used indicators for agricultural intensity (Ruiz-Martinez et al., 2015). When denoted relative to a standard, e.g. recommended nutrient amounts for optimal crop yield in a given area, different treatments can be compared and ranked along a gradient irrespective of site. Fertilization intensity does not provide information about type or frequency of fertilization and can characterise both farming systems and fertilization treatments with varying long-term fertilization rates.

The effect of long-term fertilization intensity on root biomass on different sites has rarely been studied. Moreover, knowledge about the relative importance of fertilization intensity as compared to site for vertical root distribution and root size class is scarce. Our aims were, therefore, to (i) determine coarse and fine root biomass of maize and wheat in three soil layers to 0.75 m depth in different farming systems and fertilization treatments of two long-term field trials and (ii) evaluate the effects of long-term fertilization intensity and site on root biomass, vertical distribution, and size class.

2. Methods

2.1. Sites

The study was conducted between 2013 and 2015 on two Swiss long-term field trials, DOK (bio-Dynamic, bio-Organic, Conventional) and ZOFE (Zurich Organic Fertilization Experiment). The DOK trial comprises four farming systems (bio-dynamic, bio-organic, mixed-conventional, mineral-conventional) that differ by type and amount of fertilization, plant protection, and weed control (Mäder et al., 2002; Mayer et al., 2015). The systems are separated into half and full fertilization levels according to Swiss standards (Flisch et al., 2009) and are arranged in a strip-split-plot design with four field replications. The ZOFE trial comprises 12 fertilization treatments that differ by type and amount of fertilization (Oberholzer et al., 2014). The treatments are arranged in a systematic block design (Gomez and Gomez, 1984) with five field replications and plant protection and weed control is performed chemically in all treatments. On both sites, the soil is regularly ploughed and crop rotations include cereals, maize, grass-clover ley, potatoes, frequent cover crops, and, in DOK only, soybean (Supplementary Tables 1 and 2). Varieties need to comply with prevailing agricultural practice in Switzerland and recommendations for organic farming in DOK (tall genotypes with good weed suppression) and conventional farming (short genotypes with high kernel-/grain yield) in ZOFE. Climate and soil conditions of the sites are given in Table 1.

2.2. Treatments

In DOK, we chose the bio-organic systems BIOORG1 and BIOORG2 with half and full fertilization levels, respectively, and the mixed-conventional system CONFYM2 with full fertilization level. In ZOFE, we chose the unfertilized CONTROL, the farmyard MANURE treatment, and the two mineral fertilization treatments N2P1K1 (N1P1K1 in Oberholzer et al., 2014) and N2P2K2Mg with full N level each but half and full P and K levels, respectively. The chosen farming systems in DOK are representative of Swiss agricultural practice while the fertilization treatments in ZOFE, apart from N2P2K2Mg, reflect rather artificial conditions of distinct nutrient deficiencies. In the following, we will refer to both farming systems in DOK and fertilization treatments in ZOFE as treatments.

In order to rank the treatments by fertilization intensity, we calculated an index for each treatment as follows: For the years 1999–2012, fertilizer inputs of mineral N (N_{min}, i.e. N in mineral fertilizers and nitrate- and ammonium-N in organic fertilizers), P, and K relative to recommended amounts of (directly plant available) N, P, and K for Swiss agriculture (Supplementary Tables 1 and 2; from Flisch et al., 2009) were averaged across years and nutrient elements without weighting. We chose N_{min} over total N (N_{tot}) to account for the large proportion of organically bound and therefore not immediately plant available N in organic fertilizers. We acknowledge that a certain proportion of organically bound N is gradually mineralized; however, we