Below ground carbon inputs to soil via root biomass and rhizodeposition of field-grown maize and wheat at harvest are independent of net primary productivity

Juliane Hirte[a,b,*], Jens Leifeld[a], Samuel Abiven[b], Hans-Rudolf Oberholzer[a], Jochen Mayer[a]

[a] Agroscope, Agroecology and Environment, Reckenholzstrasse 191, CH-8046 Zurich, Switzerland
[b] University of Zurich, Department of Geography, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

ABSTRACT

Below ground carbon (BGC) inputs to soil, i.e. root biomass and rhizodeposition carbon (C), are among the most important variables driving soil C dynamics in agroecosystems. Hence, increasing BGC inputs to deep soil is a proposed strategy to sequester C in the long term. As BGC inputs are inherently difficult to measure in the field, they are usually estimated from yield in order to supply soil C models with input data. While fertilization intensity considerably affects above ground biomass, its influence on BGC inputs is largely unclear, especially with respect to the subsoil. Therefore, we determined net root biomass and rhizodeposition C of field-grown maize and wheat at harvest in different farming systems (bio-organic, conventional) and fertilization treatments (zero, manure, mineral) along an intensity gradient in two Swiss long-term field trials. Plants in microplots were repeatedly pulse-labelled with ^{13}C-CO_2 throughout the growing seasons and shoots, roots, and soil to 0.75 m depth were sampled at harvest. Despite a strong increase of above ground biomass with increasing fertilization intensity, BGC inputs were similar among treatments on both sites irrespective of soil depth. However, the proportions of rhizodeposition C of BGC inputs averaged 54 to 63% and were, therefore, much larger than the widely adopted 40% for field-grown cereals. They increased with soil depth and were highest under sole organic fertilization. The shift in whole-plant C allocation towards above ground biomass with increasing fertilization intensity entailed 10% higher C allocation below ground in organic than conventional farming for both maize and wheat. Our findings imply that yield-independent values provide closer estimates for BGC inputs to soil of cereals in different farming systems than yield-based functions. We further conclude that fertilization has only little potential to alter absolute amounts of BGC inputs to deep soil in order to sequester C in the long term.

1. Introduction

Increasing carbon (C) storage in agricultural soils has been proposed as a viable means to reduce atmospheric C and mitigate climate change (Dignac et al., 2017; Paustian et al., 2016). Global agroecosystems could sequester 2–3 Gt C yr^{-1} if C stocks increase by 0.4% in the upper metre of soil, thereby offsetting 20–35% of global anthropogenic greenhouse gas emissions (Minasny et al., 2017). As plant photosynthesis and C allocation below ground is the primordial pathway for C to enter soil, promotion of crop root systems, i.e. more and deeper roots, may play a decisive role in soil C sequestration (Kell, 2011; Lynch and Wojciechowski, 2015; Maeght et al., 2013; Pierret et al., 2016).

Below ground C (BGC) inputs to soil are among the most important variables driving soil C dynamics in agroecosystems (Keel et al., 2017a). They account for 30–90% of total organic C inputs to agricultural soils

(Kätterer et al., 2011) and reside in soil considerably longer than C derived from above ground crop residues and organic soil amendments (Rasse et al., 2005; Zhang et al., 2015). Moreover, they can be translocated deep into the subsoil (Canadell et al., 1996), where residence times might be longer than in the ploughed topsoil (Rumpel and Kögel-Knabner, 2011) due to less mechanical disturbance (Turkington et al., 2000) and lower decomposer abundance (Oehl et al., 2004; Sanaullah et al., 2016).

Plants allocate C below ground via root biomass and rhizodeposition (Kuzyakov and Domanski, 2000). They differ strongly in appearance, origin, and persistence in soil and, thus, require different means of determination (Kögel-Knabner, 2017; Kuzyakov and Domanski, 2000). Root biomass C mainly derives from long-chained polysaccharides (cellulose and hemicellulose) and lignin (Kögel-Knabner, 2002), while rhizodeposition C derives from a multitude of actively or passively

released compounds from living roots, mainly low molecular weight solutes (short-chained sugars, amino and organic acids), high molecular weight polysaccharides (mucilage), border cells and senescent parts of the epidermis, and root symbionts (Jones et al., 2009). Net rhizodeposition C refers to the part of root-released C that remains in soil after immediate microbial respiration (Pausch and Kuzyakov, 2018) and will be the focus in this work from here on.

The determination of rhizodeposition C requires almost always the use of natural C isotopes, either in ^{13}C natural abundance or artificial labelling experiments (Jones et al., 2009; Pausch and Kuzyakov, 2018). While one-time pulse labelling does not provide information about rhizodeposition C that can be extrapolated to a whole growing season (Pausch and Kuzyakov, 2018), continuous labelling throughout the plant's life cycle is largely impossible in agricultural fields with small subpopulations designated for labelling. Hence, repeated pulse labelling in regular intervals over the entire growing season, either of the same (e.g. Martens et al., 2009) or different (e.g. Swinnen, 1994) subpopulations, serves as an adequate alternative to assess net rhizodeposition C at harvest (Kuzyakov and Domanski, 2000). However, only very few studies satisfy this requirement and, as a consequence, existing data on BGC inputs by crop plants into soil at harvest are largely limited to root biomass C.

Most work has been done with maize and wheat, which are two of the most important cereals and collectively cultivated on nearly 30% of the global arable land area (FAO, 2018). Root biomass C (assuming 45% C content) of field-grown maize ranges between 40 and 140 g m^{-2} (median of 13 studies: 90 g m^{-2}; Amos and Walters, 2006) and that of winter wheat between 40 and 125 g m^{-2} (median of 9 studies: 60 g m^{-2}; Hoad et al., 2001; Hu et al., 2018; Williams et al., 2013). The amount of additional C remaining in soil as rhizodeposition after one cropping season was found to be 30 g m^{-2}, or 30% of total BGC inputs, for maize (Balesdent and Balabane, 1992) and 2–70 g m^{-2}, or 5–70% of total BGC inputs, for wheat (median: 50 g m^{-2} or 45%; Gregory and Atwell, 1991; Keith et al., 1986; Martens et al., 2009; Swinnen, 1994). The recovery of BGC inputs as root biomass or rhizodeposition strongly depends on the method of separating roots from soil, e.g. sieve mesh size, and time of sampling, as finest roots and fragments of decaying roots inevitably add to the rhizodeposition pool when they are not recovered as root biomass (Pausch and Kuzyakov, 2018). Most data on BGC inputs refer to the topsoil as roughly two thirds of crop root systems concentrate in the upper 0.3 m of soil (Fan et al., 2016), prompting investigators to forgo the logistical challenges of studying subsoils (Campbell and Paustian, 2015). Hence, our knowledge about BGC inputs to deeper soil is extremely limited (Kögel-Knabner, 2017), which inevitably accounts for the use of undifferentiated proportions of rhizodeposition C in top- and subsoils in upscaling studies (e.g. Pausch et al., 2013).

Information on BGC inputs of field-grown crops at harvest is indispensable for soil C modelling (Keel et al., 2017b). Dynamic soil C models are increasingly used in national greenhouse gas inventories under the United Nations Framework Convention on Climate Change (Campbell and Paustian, 2015; Eggleston et al., 2006), e.g. in Australia (RothC; Skjemstad and Spouncer, 2003), Canada (CENTURY; VandenBygaart et al., 2008), Denmark (C-TOOL; Taghizadeh-Toosi et al., 2014), or Sweden (ICBM; Andrén et al., 2004). However, due to the scarcity of measured data, BGC inputs are usually estimated from net primary productivity (Campbell and Paustian, 2015; Kögel-Knabner, 2017) using some form of yield-based allometric function and associated C allocation coefficients for those plant C pools that are relevant for simulations of soil C stocks and changes (Keel et al., 2017b). Those include remaining straw, decaying roots, and rhizodeposits at the time of harvest; hence, the portion of already respired and lost root-derived C during the growing season is not accounted for. For example, the widely used approach established by Bolinder et al. (2007) for temperate crops assigns coefficients to the four C pools crop product, straw, root biomass, and extra-root material (i.e. rhizodeposition). These coefficients were derived from measured yield and published or assumed values for biomass C concentration, harvest index, root-to-shoot ratio, and rhizodeposition-to-root ratio. While yield is always determined at harvest, published data on root-to-shoot and rhizodeposition-to-root ratios most often refer to considerably earlier crop growth stages, namely flowering and the vegetative phase, respectively. In addition, the information on rhizodeposition used by Bolinder et al. (2007) was mainly derived from controlled experiments (Kuzyakov and Domanski, 2000; Kuzyakov and Schneckenberger, 2004). It is unclear, whether those data are applicable to field-grown crops at harvest. Further, allocation coefficients have been established for several functions for a wide range of crops or crop classes (Keel et al., 2017b) but are not differentiated by farming systems that differ in fertilization intensity. Hence, lower crop C inputs to soil via residues and rhizodeposition are expected from lower yields in organic than conventional farming (Lorenz and Lal, 2016).

In contrast to the concept of allometry, recent findings suggest that BGC inputs are not proportional to net primary productivity in agroecosystems and are rather a function of year, species, and farming system (Hu et al., 2018; Taghizadeh-Toosi et al., 2016). Root biomass in low-intensity systems was found to be similar as or even higher than that in high-intensity systems (Chirinda et al., 2012; Hirte et al., 2018; Lazicki et al., 2016), whereas rhizodeposition C seems to follow the opposite trend (Chowdhury et al., 2014; Liljeroth et al., 1994; Qiao et al., 2017; Swinnen, 1994). Type and amount of fertilization might have a considerable impact on plant C allocation; hence, it is questionable whether BGC inputs can be easily derived from yield. However, to our knowledge, comprehensive field studies that focus on the effect of fertilization intensity on below and above ground plant C allocation do not exist.

Our objectives were, therefore, to (i) quantify net BGC inputs of field-grown maize and wheat at harvest in the top- and subsoil in order to provide data for use in soil C models, (ii) evaluate the effect of soil depth and long-term fertilization intensity on BGC partitioning to root biomass and rhizodeposition C, and (iii) evaluate the effect of long-term fertilization intensity on C allocation coefficients for crop product, straw, root biomass, and rhizodeposition. Our hypotheses were that (i) current assumptions on the amounts of rhizodeposits are not applicable to field-grown crops at harvest, (ii) the proportion of rhizodeposition C of total BGC inputs is independent from soil depth but increases with increasing fertilization intensity, and (iii) whole-plant C allocation decreases with increasing fertilization intensity. To test these hypotheses, we conducted a comprehensive three-year field study with maize and wheat in different treatments with increasing long-term fertilization intensity on two sites and determined the remaining C in the four plant C pools product, straw, root biomass, and rhizodeposition at crop harvest.

2. Materials and methods

2.1. Sites, treatments, and crops

We conducted the study on two Swiss long-term field trials: DOK (47°30′09″ N, 7°32′21″ E; MAT 10.5 °C, MAP 842 mm; established in 1978) and ZOFE (47°25′36″ N, 8°31′08″ E; MAT 9.4 °C, MAP 1031 mm, established in 1949). In DOK, eight farming system treatments that differ by type and amount of fertilization and plant protection are compared in a strip-split-plot design with four field replications (Mayer et al., 2015). In ZOFE, 12 fertilization treatments that differ by type and amount of fertilization are compared in a systematic block design with five field replications (Oberholzer et al., 2014). The seven- (DOK) and eight-year (ZOFE) crop rotations include cereals, maize, grass-clover ley, potato, cover crops, and soybean (DOK only). The soil is ploughed to 0.2 m depth. On both sites, soil type is a haplic Luvisol with 12% sand, 72% silt, 16% clay, 1.2 Mg m^{-3} bulk density, and 1.3% organic C in DOK and 59% sand, 23% silt, and 18% clay, 1.6 Mg m^{-3} bulk density, and 0.9% organic C in ZOFE in the plough layer. We chose the treatments BIOORG1, BIOORG2, and CONFYM2 in DOK, which realistically