Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds

Gerrit Angst[a,b,*], Johanna Messinger[a], Maria Greiner[a], Werner Häusler[a], Dietrich Hertel[c], Kristina Kirfel[c], Ingrid Kögel-Knabner[a,d], Christoph Leuschner[c], Janet Rethemeyer[e], Carsten W. Mueller[a]

[a] Chair of Soil Science, Technical University of Munich, Emil-Ramann-Str. 2, D-85354 Freising, Germany
[b] Institute of Soil Biology & SoWa RI, Biology Centre, Czech Academy of Sciences, Na Sádkách 7, CZ 37005 České Budějovice, Czech Republic
[c] Albrecht von Haller Institute for Plant Sciences, Georg-August-Universität Göttingen, Untere Karspüle 2, D-37073 Göttingen, Germany
[d] Institute for Advanced Study, Technical University of Munich, Lichtenbergstraße 2a, D-85748 Garching, Germany
[e] Institute of Geology and Mineralogy, University of Cologne, Zülpicher Straße 49a, D-50674 Cologne, Germany

ABSTRACT

Despite a large body of studies investigating soil organic carbon (SOC) stocks and potential influencing factors, the impact of contrasting parent material, particularly in the subsoil, has received little attention. To reveal potential effects varying parent materials exert on SOC stocks, we investigated chemical (^{14}C content and overall chemical composition via ^{13}C NMR spectroscopy) and plant/microbial related parameters (root mass, amino sugars) of bulk soil and soil organic matter fractions from topsoil, subsoil, and rhizosphere soil at three European beech stands (*Fagus sylvatica* L.) only differing in parent material (Tertiary sand, Quaternary loess, and Tertiary basalt).

The results suggest that the clay fraction, its amount being largely dependent on the respective parent material, took a central role in shaping differences in SOC stocks among the investigated sites by affecting soil organic matter stabilization via organo-mineral association and aggregation. This fraction was particularly relevant in the subsoil, where it accounted for up to 80% of the bulk soil SOC stocks that decreased with decreasing amounts of the clay fraction (basalt > loess > sand site). Determining the soil's nutrient composition, parent material likely also indirectly affected SOC stocks by changing rhizosphere traits (such as fine root density or mortality) and by attracting root growth (and thus organic matter inputs) to subsoil with higher nutrient contents, where *in situ* root inputs in the form of rhizodeposits were likely the prime source of plant-derived SOC. However, root inputs also contributed in large part to topsoil SOC stocks and were associated with higher abundance of microbial compounds (amino sugars), whose relative importance increased with increasing soil depth.

Independent of soil depth and site, amino sugars and the amount of the clay fraction, combined with parameters related to the input of organic matter (root mass and amount of the particulate organic matter fraction) explained more than 90% of the variability in SOC stocks, indicating a key role of these measures in impacting SOC stocks. Because parent material directly or indirectly influenced these parameters, we demonstrate the necessity to consider differences in parent material when estimating and predicting SOC stocks.

1. Introduction

Soil constitutes a potential carbon (C) sink (Post et al., 1982) and many studies have been investigating soil organic C (SOC) stocks on different scales and possible controlling factors (e.g., Baritz et al., 2010; Janssens et al., 2005; Jobbágy and Jackson, 2000; Jones et al., 2005; Saiz et al., 2012; Wiesmeier et al., 2014). On global or continental scale,

differences in SOC stocks have been linked to vegetation type and climate (Gray et al., 2016; Jobbágy and Jackson, 2000; Johnson et al., 2011; Saiz et al., 2012). On smaller scales, such as the stand scale, soil biota (particularly earthworms), soil acidity, or plant species (Mueller et al., 2015; Vesterdal et al., 2013) were identified as important driving factors. The influence of varying parent material, however, has received little attention (Barré et al., 2017; Heckman et al., 2009) and the way in

which substrate properties affect the input of organic matter (OM) or translate into SOC stabilization mechanisms (e.g., Wagai et al., 2008), such as organo-mineral association or aggregation (von Lützow et al., 2006, 2008), is a widely unresolved matter (Prechtel et al., 2009).

Despite the wealth of studies dealing with SOC stocks, most of these studies were conducted in the topsoil (~ upper 30 cm of the soil profile). The subsoil generally contains less SOC (Rumpel and Kögel-Knabner, 2011), but given the fact that its volume often exceeds that of the topsoil, these low SOC contents can considerably contribute to SOC stocks of the whole soil (Angst et al., 2016b; Jandl et al., 2007; Richter and Billings, 2015). An often very low ^{14}C content of SOC in the subsoil indicates its long residence time (also referred to as 'transit time'; Lorenz and Lal, 2005; Manzoni et al., 2009; Rethemeyer et al., 2005; Rumpel and Kögel-Knabner, 2011; Schöning and Kögel-Knabner, 2006) and an increase of subsoil SOC stocks thus appears to be of central importance for sequestering C and mitigating climate change (Jobbágy and Jackson, 2000; Lorenz et al., 2007). Organic matter inputs in the rhizosphere (by exudation and/or in particulate form) may already be relevant in the topsoil (Angst et al., 2016b; Tefs and Gleixner, 2012), but seem to gain importance with increasing soil depth (Rasse et al., 2005) and have been proposed to increase subsoil SOC stocks (Lorenz et al., 2007). However, the consequences of additional C input for the SOC already stored in deeper soil layers is still uncertain and has been controversially discussed (e.g., Fontaine et al., 2007; Lorenz and Lal, 2005). One reason for these uncertainties may be that studies including parent material variations are scarce. These variations may become particularly evident in the subsoil, where plant inputs are reduced and a direct effect of parent material mineralogy might be more directly perceptible as compared to the topsoil.

The aim of the present study, thus, was to disentangle the impact of different parent materials on the amount and distribution of SOC stocks in topsoil and subsoil by applying a combination of fractionation techniques and chemical methods. To control for the factors climate and vegetation, we chose pure mature European beech (*Fagus sylvatica* L.) stands with similar precipitation and temperature regimes, only differing in parent material: Tertiary sand, Quaternary loess, and Tertiary basalt. These substrates widely differ in their textural composition and nutrient supply. For example, sandy sedimentary materials can be expected to have substantially smaller nutrient contents than basaltic, more phyllosilicate rich rocks or soils developed from silt- and nutrient-rich Loess deposits (Anderson, 1988; Catt, 2001). These differences likely do not only influence the SOC preservation capacity of a soil (Hassink, 1997) but also litter production (and thus input of OM or contribution of root as compared to shoot-derived OM; Crow et al., 2009; Kögel-Knabner, 2002) via different levels of soil nutrients, such as phosphorus (Wright et al., 2011). The mentioned and other properties may not be uniformly distributed in developed soils with significant small-scale variability of SOC stocks (Chabbi et al., 2009; Schöning et al., 2006) and physical, chemical, and microbial soil properties that are often influenced by the distance to individual trees (Chang and Matzner, 2000; Koch and Matzner, 1993; Saetre and Bååth, 2000). We thus relied on a spatially resolved sampling design taking into account possible horizontal heterogeneities at increasing distance to individual beech trees. We fractionated the investigated soils into compartments assignable to specific stabilization mechanisms (recalcitrance, organo-mineral association, and aggregation; von Lützow et al., 2007) and evaluated the ^{14}C content of stabilized soil OM (SOM) by performing radiocarbon measurements on mineral-associated SOM in the clay fraction. We additionally fractionated rhizosphere soil and measured the root mass (combined fine root biomass and necromass) to account for the relevance of the rhizosphere. Residues derived from soil microorganisms located in the rhizosphere and elsewhere may substantially contribute to SOM in organo-mineral associations and aggregate formation (e.g., Castellano et al., 2015; Cotrufo et al., 2013), but their role in affecting SOC stocks is unresolved. We thus determined the amount of amino sugars as indicators for microbial residues. The

overall chemical composition of OM in the soil fractions, revealed by ^{13}C nuclear magnetic resonance spectroscopy (NMR; e.g., Baldock et al., 1997; Cepáková and Frouz, 2015; Kögel-Knabner et al., 1992), completed our analyses.

2. Materials and methods

2.1. Study sites and soil sampling

Composite and volume soil samples were taken in May 2014 at three different study sites located near the city of Göttingen in central Germany. The study sites were covered by European beech forests, featured similar climatic conditions (average annual precipitation and temperature of ca. 650 mm and 9.2 °C in 1981–2010; Deutscher Wetterdienst, station 'Göttingen') but developed from different parent materials. The Haplic Cambisol at the site 'Hannoversch-Münden' (51° 26′ 25.64″ N 09° 41′ 24.25″ E, 270 m a.s.l.; termed 'sand site') developed from Tertiary sand and had a pH of 3.7–4.2 with Hemimor as forest floor type (65% sand, 27.3% silt, and 7.7% clay in mineral soil). The Haplic Luvisol at the site 'Rüdershausen' (51° 34′ 51.52″ N 10° 14′ 43.03″ E, 200 m a.s.l.; termed 'loess site') developed from Quaternary loess deposits, had a pH of 3.6–4.1, and a Leptomoder forest floor type (3.2% sand, 87.5% silt, and 9.3% clay in mineral soil). The Eutric Cambisol at the site 'Dransfeld' (51° 28′ 35.60″ N 09° 45′ 32.46″ E, 470 m a.s.l.; termed 'basalt site') developed from Tertiary basalt, had a pH of 3.7–4.8, and a Mullmoder forest floor type (1% sand, 87.5% silt, and 11.5% clay in mineral soil; forest floor data taken from Kirfel et al., unpublished data). All profiles were similar with respect to clay mineralogy (determined by X-ray diffraction) with dominance of illites, primary/secondary chlorites and smaller amounts of kaolinites present throughout the profiles. Some minor differences in the relative abundance of primary/secondary chlorites occurred across the study sites. However, these contribute only marginally to the cation exchange capacity of the soils because their interlayers are blocked with Al-octahedrons. Differences in the relative abundance of illites occurred at the sand site, where it was higher in the subsoil as compared to the respective topsoil. Smectites could not be confirmed at any of the study sites. At each study site, three different replicate soil ditches were dug reaching down to the parent material. One end of each ditch originated at the stem base of a mature European beech tree. Soil samples for all analyses were taken in 10 cm (from now on referred to as 'topsoil'; Al horizon at the loess and Ah-Bv horizon at the sand and basalt sites) and 85 cm depth (from now on referred to as 'subsoil'; Bt horizon at the loess and Cv horizon at the sand site; 60 cm at the basalt site due to solid parent material beneath this depth, Bv horizon) at two spots per depth increment to account for spatial variability: directly at the stem base of the tree and at 135 cm distance. The upper sampling spots were set to 10 cm depth to allow a representative volumetric sampling unbiased by varying topsoil thicknesses using the same steel rings (diameter: 8.5 cm, height: 6.0 cm). Soil samples for calculation of SOC stocks only (see section 2.8), were collected in between the two vertical sampling spots at 35 and 60 cm depth. At the sand and basalt sites, these sampling depths were located in the B horizons, while they were part of the A horizon at the loess site. We sampled one composite rhizosphere soil sample at each transect from the whole extent of the densely rooted upper soil layers in between the two horizontal sampling spots (~ top 40 cm of the soil profiles). Rhizosphere soil was defined as the soil sticking to a root after it had been thoroughly shaken (Cieslinski et al., 1998; Gomes et al., 2003). In the laboratory, the soil samples were air-dried and passed through a 2 mm-sieve. Soil densities were calculated from the volume samples considering soil moisture and coarse particles > 2 mm. The sampling design enabled us to compare SOM properties in the topsoil vs. the subsoil vs. the rhizosphere soil, evaluate possible spatial variability and influence of the distance to individual trees, and investigate differences between sites differing in parent material.