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Spatial controls of topsoil and subsoil organic carbon turnover under C_3–C_4 vegetation change

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ABSTRACT

Soil organic carbon (SOC) is often heterogeneously distributed in arable fields and so is probably its turnover. We hypothesized that the spatial patterns of SOC turnover are controlled by basic soil properties like soil texture and the amount of rock fragments. To test this hypothesis, we cultivated maize as a C_4 plant on a heterogeneous arable field (155×60 m) that had formerly been solely cultivated with C_3 crops, and monitored the incorporation of isotopically heavier maize-derived C into SOC by stable ^{13}C isotope analyses. To obtain a homogeneous input of C_4 biomass into the C_3 soil across the field, we chopped the aboveground maize biomass after harvest in autumn and re-spread it uniformly over the field. Subsequently, the soil was grubbed and then ploughed in the next spring. In addition, we assessed the spatial patterns of SOC stocks, amount of rock fragments and texture, as well as potential soil organic matter (SOM) degradability by ex-situ soil respiration measurements. Heterogeneity of maize growth was monitored as a covariate using laser scanning and satellite images. After two years, maize C had substituted 7.4 ± 3.2% of SOC in the topsoil (0–30 cm) and 2.9 ± 1.7% of SOC in the subsoil (30–50 cm). Assuming that monoexponential decay mainly drove this SOC substitution, this resulted in mean residence times (MRT) of SOC in the range of 30 ± 12 years for the topsoil and of 87 ± 45 years for the subsoil, respectively. Variation in topsoil MRT was related to potential CO_2 release during soil incubation ($R^2 = 0.51$), but not to basic soil properties. In the subsoil, in contrast, the variation of maize C incorporation into the SOC pool was controlled by variations in maize yield ($R^2 = 0.44$), which also exhibited a pronounced spatial variability (0.84 to 1.94 kg dry biomass m^{-2}), and which was negatively correlated with the amount of rock fragments ($R^2 = 0.48$, $p < 0.001$). We assume that heterogeneous input of belowground root biomass blurs the causal interactions between the spatial heterogeneity of soil properties and the related patterns of SOC turnover, and conclude that spatial patterns of SOC turnover are not easily predictable by standard soil analyses.

1. Introduction

The global soil organic carbon (SOC) pool contains about the same amount of carbon as the terrestrial vegetation and atmosphere combined (Batjes, 1996). Hence, changes in SOC turnover can easily affect the global carbon cycle. Models computing SOC turnover at field scale have the problem that simple averaging may produce inaccurate results because of pronounced spatial variations in soil properties (Simmer et al., 2014). Still, we have limited knowledge on the drivers of spatial variability of SOC turnover in topsoils, and how it translates into the subsoils (Mueller-Niggemann et al., 2012; Rumpel et al., 2002; Rumpel and Kögel-Knabner, 2011; Schmidt et al., 2011).

The concentrations and/or stocks of SOC mainly reflect the interplay between biomass input, gaseous output through mineralization, and leaching (Kindler et al., 2011). All these processes depend on the mineral soil assembly, with high Fe oxides and clay contents promoting SOC stabilization (Kögel-Knabner and Amelung, 2014; Lützow et al., 2007; Nichols, 1984). At elevated contents of rock fragments, however, the carbon input by the plants is concentrated in a smaller volume of fine earth than at subsites where the amount of rock fragments is small. As a result, the presence of rock fragments promotes carbon saturation at mineral surfaces, and more SOC is left behind as SOC in particle-size fractions (Bornemann et al., 2011). To understand the underlying relations, we have to monitor SOC turnover in the field at different soil mineralogical composition while keeping all other factors such as climate, management, and crop growth as constant as possible. The first

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instances can be hold when studying the spatial patterns of SOC turnover within an agricultural field that is heterogeneous with regard to its texture and distribution of rock fragments. Yet, different soil properties within a given field may well affect crop growth. Hence, plant growth should be monitored, and for minimizing its impact on SOC turnover, one option is to harvest all biomass and to redistribute it homogeneously over the field.

Stable C isotopes provide a powerful tool to quantify SOC turnover. As C_4 plants discriminate the ^{13}C isotope less during photosynthesis than C_3 plants do, changes in $\delta^{13}C$ natural abundance in SOC (through a change from C_3toC_4 vegetation), allows to trace the incorporation of new C_4 biomass into old C_3-derived SOC, and thus to calculate mean residence time (Bernoux et al., 1998; Derrien and Amelung, 2011; Marshall et al., 2007). As the MRT of SOC usually varies at a scale of years to decades, the stable ^{13}C isotope tracing technique requires sampling on a basis of at least yearly sampling intervals (Deng et al., 2016; Marschner et al., 2008; Novara et al., 2013). Since this may be too long for studying seasonal impacts on SOC turnover patterns, ex-situ soil incubations may complement the stable ^{13}C isotope approaches by assessing potential SOC degradability under controlled laboratory conditions by respirations measurements (Creamer et al., 2013; Follett et al., 2007).

We hypothesize that the spatial heterogeneity of basic soil properties (e.g., soil texture, content of Fe oxides, amount of rock fragments) controls the spatial patterns of SOC turnover. To test this hypothesis, we cultivated maize (C_4) on a field formerly cropped with C_3 vegetation only. We then assessed the spatial patterns of isotopic changes in SOC as an indicator of the mean residence time, and we determined potential degradability by ex-situ incubation in the laboratory. Since we were afraid that the linkages between SOC turnover and texture could be overlain by different biomass input, we homogenized at least the aboveground biomass input by chopping and re-spread it over the field. Additionally, we monitored plant growth using laser-scanning to be able to consider it as an additional control variable.

2. Material and methods

2.1. Site description and management practices

The study was performed at a test site near Selhausen (50°52′05.26″N 6°27′11.04″E), located in North Rhine-Westphalia, Germany, 108 m a.s.l., in the Lower Rhine Embayment. Mean annual temperature and precipitation between 1961 and 2015 are 9.8 °C and 693 mm, respectively. The annual precipitation was 671 mm in 2012 and 640 mm in 2013. The annual mean temperature was 10.4 °C in 2012 and 9.9 °C in 2013. Data were obtained from the weather station of the Forschungszentrum Jülich.

From 2012, the test site was continuously cultivated with maize (*Zea mays* L., variety Atletas, KWS SAAT AG, Einbeck). As part of a C_3-to-C_4 plant-shift experiment, the test site had not been cultivated with a C_4 plant in the recent past (at least 30 years) before 2012. The test site of approx. 1 ha was dominated by quaternary fluvial sediments, covered with eolian silt deposit (Walter and Dorn, 2007). Due to the braided river system of the river Rur, which was temporarily present during glacial periods in the Pleistocene, sediments had accumulated inconstantly, which led to the present small-scale textural heterogeneity of parental material (Alberts-Arndt and Hilden, 1988). To explore this textural heterogeneity, the apparent soil electrical conductivity (ECa) of the test site was mapped with an electromagnetic inductance (EMI) sensor (EM38, Geonics Ltd., Mississauga, ON, Canada) in horizontal coil receiver mode (reaching to a depth of approx. 0.75 m; Fig. S1, supporting material). Mapping was done in a dry period in March 2012 to determine differences in soil moisture and thereby soil texture. At the locations with the highest and the lowest measured ECa values, a soil profile was dug to a depth of 1 m (Fig. S1 and S2, supporting materials). The main soil group was a Stagnic Cambisol (skeletic) (WRB, 2015).

2.1.1. Management practices

In April (prior to maize sowing in May 2013 and 2014), the soil was ploughed and harrowed homogeneously to distribute the maize biomass of the last year to a depth of 30 cm. The maize plants were harvested in October (2012 and 2013) with a straight pipe silage chopper and the whole aboveground plant biomass was left on the field. After distribution, the chopped residues were incorporated into the soil with a grubber. This promoted the replacement of old SOC by new SOC with a different stable carbon isotope signature at a given subsite. To avoid N limitations on SOC turnover (see also Meyer et al., 2017) and plant growth, we used an annual under-feet fertilization in May with diammonium phosphate (400 kg ha^{-1}), equal to 70 kg N ha^{-1} and 60 kg P ha^{-1}, followed by N fertilization with calcium ammonium nitrate, equal to 100 kg N ha^{-1}, in June. No organic fertilizer was applied.

2.2. Soil sampling and preparation

Soil samples were taken annually in April 2012 (i.e., before maize sowing), 2013 and 2014, in a regular grid, with additional sample points at locations where we expected high small-scale variability with regard to soil properties, resulting from EMI mapping (Fig. S1). Topsoil samples (n = 113) were collected from the plow horizon (0 to 30 cm) with a metallic cylinder with a length of 28 cm and volume of approx. 2300 cm^3. Subsoil samples (n = 37) were taken from 30 to 50 cm depth, when possible, also with the metallic cylinder in an open pit, otherwise (high content of rock fragments) with the aid of a soil auger (7 cm diameter).

To assess the shorter turnover of more labile SOC pools, we assessed the MRT of SOC in particle-size fractions (see details in chapter 2.4) of the plow horizon (0 to 30 cm) in two parallel transects. The two transects were established to connect the two profiles and thus to cover a large part of the total field heterogeneity (Fig. S1).

Fresh samples for soil incubations were taken, subsequently sieved (< 2 mm) and kept frozen at −18 °C prior to processing; for all other analyses, aliquots were dried at 40 °C for 48 h.

2.3. Maize biomass estimation

Maize biomass was estimated by terrestrial laser scanning (TLS) (Tilly et al., 2014) and from remote sensing images: By combining the height of the maize plants (TLS) and the normalized differenced vegetation index (NDVI) from the satellite WorldView-2 in a linear model (Hütt et al., 2014), we reached a high interrelation to the destructively determined dry, aboveground biomass (R^2 = 0.86). Assuming the spatial patterns of maize growth were similar in both years, we used the biomass map from the end of August 2013 (no further substantial gain of biomass after this date can be assumed) and extracted the locations, which were sampled in the soil sampling campaign (n = 113), with ArcGIS 10.3.1 (Esri, Kranzberg).

2.4. Soil laboratory analyses

Unless otherwise stated, all analyses were done in duplicate: SOC was analyzed on sieved (< 2 mm) and ground samples by dry combustion according to ISO 10694 (1995). Measured total carbon corresponded to SOC because the soil did not contain carbonates (soil pH < 6). As a result of the high variability of the amount of rock fragments, also SOC concentrations exhibited a high variability. We thus also calculated SOC stocks by considering bulk density and amount of rock fragments.

Soil texture (< 2 mm) was determined according to ISO 11277 (2009). For the determination of bulk density of fine earth (< 2 mm), samples were dried at 105 °C for 48 h. Likewise, rock fragments were