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Maize root decomposition in subsoil horizons of two silt loams differing in soil organic C accumulation due to colluvial processes

Juliane Struecker [a,*], Michael Kaiser [b], Jens Dyckmans [c], Rainer Georg Joergensen [a]

[a] Soil Biology and Plant Nutrition, University of Kassel, Nordbahnhofstr. 1a, 37213 Witzenhausen, Germany
[b] Environmental Chemistry, University of Kassel, Nordbahnhofstr. 1a, 37213 Witzenhausen, Germany
[c] Centre for Stable Isotope Research and Analysis, University of Göttingen, Büsgenweg 2, 37077 Göttingen, Germany

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ABSTRACT

To analyse mechanisms controlling sequestration of organic C in subsoil, a field experiment was carried out for two years. Soilbags with a mesh size of 100 μm, containing original soil material and maize root residues (C4 plant) were buried at three different depths (35, 45, and 65 cm) at two neighbouring arable sites and were sampled after 12, 18 and 24 months. The sites were a Colluvic Cambisol with high soil organic carbon (SOC) contents in the subsoil (12 mg g^{-1} soil), and the other a Haplic Luvisol with low SOC contents (4 mg g^{-1} soil) below 30 cm depth. We determined the effects of the site, depths, and time on bulk SOC, organic C associated with soil density fractions, and microbial biomass C (MBC) in the soilbags. MBC increased to a similar extent (2.5 fold) from the initial content to its maximum at all sites and depths. This increase relied largely on the added maize root residues, as about 50% of the MBC was maize-derived after two years. However, we detected distinct differences in the substrate use for anabolism compared to catabolism, which decreased with depth and was lower in the Haplic Luvisol than in the Colluvic Cambisol. Freshly added plant material seems to be highly accessible to microorganisms in subsoil, but its metabolic use was determined by the soil properties of the two sites. The addition of plant residues also had an impact on aggregation dynamics, resulting in an almost complete replacement of formerly aggregate occluded material (i.e., occluded light fraction) by maize derived material after 24 months.

1. Introduction

Two-thirds of the terrestrial C is stored in soils, which makes soil an important reservoir in the global carbon cycle (Batjes, 1996). This reservoir can either be a source or sink for CO_2 (Rumpel et al., 2002; Rumpel and Kögel-Knabner, 2011), which is of increasing interest due to climate change concerns (Bailey et al., 2002). The fact that >50% of soil organic C (SOC) is stored at a depth of 30–100 cm (Batjes, 1996; Lal and Kimble, 1997) has directed particular scientific attention towards subsoil. However, there is still limited knowledge regarding the mechanisms that control C sequestration and turnover in subsoil (Sanaullah et al., 2011; Cotrufo et al., 2013).

The high ^{14}C-based mean age found for organic compounds in subsoil (Rumpel et al., 2002; Rumpel and Kögel-Knabner, 2011) leads to the assumption that their mineralization rate is slower than in topsoil. There are strong indications that environmental conditions in subsoil are different from those in topsoil, such as less variation in temperature and reduced nutrient availability (von Lützow et al., 2006), which might lead to reduced substrate mineralization. These environmental factors also have an influence on the microbial community in subsoil, which usually shows smaller biomass and is less fungal dominated compared to topsoil (Fierer et al., 2003; Struecker and Joergensen, 2015). These changes in the microbial community and its functional diversity are presumably among the various factors controlling C sequestration in subsoil.

Another important factor is the limited input of fresh organic matter into subsoil (Fontaine et al., 2007). Only root-derived plant residues play a significant role in subsoils (Rumpel et al., 2002), which contain less labile and therefore less easily degradable compounds than shoot-derived residues (Rasse et al., 2005).

Concerning the fate of plant residues, it is largely unknown to what extent the added substrate is stabilized against microbial decomposition or contributes to the mineralization of stabilized SOC due to priming effects (Fontaine et al., 2007). The latter would be an adverse effect to the desired increase in SOC sequestration. The effects of substrate addition to subsoil have been investigated mostly in laboratory experiments (Kuzyakov, 2010) where not only substrate was added but also other environmental factors (e.g., gas conditions, temperature, moisture) were modified. This impedes the transfer of the results from such experiments to the field or ecosystem scale and underscores the need for more field experiments to analyse the decomposition of plant residues under subsoil conditions. One option is the burial of soilbags in the field (Sanaullah et al., 2011) that mimic hot spots of microbial

* Corresponding author.
E-mail address: juliane.struecker@uni-kassel.de (J. Struecker).

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activity (Schrumpf et al., 2013), being similar to naturally occurring hot spots along preferential flow pathways or rooting zones (Chabbi et al., 2009).

Degradation and fate of maize root amendments can be analysed by their incorporation into the microbial biomass but also by density fractionation, providing additional information on the stabilization of SOC (Schrumpf et al., 2013). The free light fraction (fIF) and occluded light fraction (oIF) consist mainly of organic debris present either free and easily available for microorganisms in the soil matrix (fIF) or occluded within aggregates (oIF) (Golchin et al., 1994; Cerli et al., 2012). In contrast to the fIF, the oIF consists of smaller and slightly decomposed organic particles, which are better protected against microbial degradation by occlusion in aggregates. Therefore, the turnover times of oIF are considered to be longer than those of the fIF (Schrumpf et al., 2013). The C in the heavy fraction (HF) is bound to the mineral fraction of the soil matrix (e.g. John et al., 2005) and, therefore, is considered to be stabilized against decomposition with turnover times of decades to centuries (Schrumpf et al., 2013).

In this study, we carried out a field experiment for two years. Soilbags with a mesh size of 100 μm, containing original soil material and maize root residues, were buried at three different depths (35, 45, and 65 cm) at two neighbouring arable sites and were sampled after 12, 18 and 24 months. The sites were a Colluvic Cambisol with high SOC contents in the subsoil (12 mg g^{-1} soil), the other a Haplic Luvisol with low SOC contents (4 mg g^{-1} soil) below 30 cm depth (Struecker and Joergensen, 2015).

The aim of this study was to test the following hypotheses regarding the fate and pathways of freshly added residues from maize roots as a function of soil depth and resource availability under field conditions: (1a) The mean residence times of maize root residues increase with depth and (1b) are lower in the Colluvic Cambisol than in the Haplic Luvisol, due to the higher microbial biomass in the former. (2a) Substrate incorporation into microbial biomass decreases with depth and (2b) is higher in the Colluvic Cambisol than in the Haplic Luvisol, due to higher resource limitations in the Luvisol (Struecker and Joergensen, 2015). (3) Irrespective of site and depth, the maize residues will remain mostly in the fIF, due to limited microbial degradation.

2. Material and methods

2.1. Site

Soil was sampled from two arable fields at the Hessian State Manor of Frankenhausen, northern Hessia, Germany (51°24′ N; 9°25′ E), the experimental farm of the University of Kassel. The area is characterized by a mean annual air temperature of 9.3 °C and a mean annual precipitation of 687 mm. The soils of site I (referred to as Cambisol or Cam) can be characterized as a Colluvic Cambisol according to the WRB (FAO, 2014). The Colluvic horizon of the Colluvic Cambisol covers the original soil surface of a Chernozem by about 70 cm, resulting in an Ap/M/fAh sequence. The soils of site II (referred to as Luvisol or Luv) can be classified as a Haplic Luvisol according to the WRB (FAO, 2014), although the Al horizon was eroded. This results in an Ap/Bt sequence. The soils of the two sites have been developed on loess and are within a distance of 400 m from each other, which means that climatic conditions are equivalent on both sites, although they have different SOC profiles due to erosion and deposition. Land use at both sites was also similar for at least 400 years, during which time both sites were used as grassland first and then as cropland since the early 20th century (Troßbach, 2000). Soil characteristics are shown in Table 1.

Both sites were converted from cropland to cattle pasture using a grass–clover mixture in spring 2013. There was no organic fertilizer added except cattle excretions. There is no evidence for the cultivation of C4 plants in the field history. As the cows did not receive additional fodder during the grazing periods, there was also no input of maize residues during the time of the experiment.

Table 1
Organic C, ^{13}C, Total N, and C/N ratio for maize root residues before mixing. Soil organic C (SOC), ^{13}C, Total N, C/N, microbial biomass C (MBC) for original soil material and Organic C, Total N, and C/N ratio for the soil and maize root residue mixture before burial.

Maize root residues								
Organic C (mg g^{-1} roots)		^{13}C δ‰	Total N (mg g^{-1} roots)		C/N	MBC (μg g^{-1} roots)		
276		−12.5	4.3		64	0		
Soil without roots						Soil with roots		
Depth (cm)	SOC (mg g^{-1} soil)	^{13}C δ‰	Total N (mg g^{-1} soil)	C/N	MBC (μg g^{-1} soil)	Organic C (mg g^{-1} soil)	Total N (mg g^{-1} soil)	C/N
Cambisol								
35	14.4	−26.2	1.5	10	216	20.3	1.6	12
45	10.9	−24.2	1.1	10	133	18.5	1.2	15
65	9.0	−25.3	0.9	10	83	12.3	1.0	12
Luvisol								
35	10.8	−28.8	1.2	9.0	161	17.0	1.3	13
45	6.9	−26.6	0.65	11	49	12.8	0.72	18
65	5.4	−26.0	0.52	10	39	9.3	0.57	16

2.2. Soilbag experiment

Samples from both sites were taken at three different subsoil depths (35, 45, and 65 cm) in April 2013. The autochthonous, naturally occurring SOC contents and isotopic signatures unaffected by the added maize roots were determined from these samples. Afterwards each sample was mixed with 1.5 wt.% of dried and shredded maize root residues (1–2 mm), which equals a C addition of 4.2 mg g^{-1} and an N addition of 0.06 mg g^{-1}. All soil samples had the same dry mass (20 g) and were homogeneously mixed with the same amount of maize root residues (300 mg) after sieving of the soil (<2 mm). The mixture was filled into 5 × 5 × 0.5 cm mesh bags (mesh size: 100 μm). This mesh size prevented soil losses from the bags but allowed access by microorganisms. The possible ingrowth of fine roots was accepted as a compromise, allowing sufficient moisture exchange with the surrounding soil. Afterwards they were stored field moist at 4 °C until they were buried in June 2013. The bags were buried on their original field sites at their original depths with 9 field replicates. They were recovered after 12, 18, and 24 months with 3 field replicates per depth. The sampled soilbags were also stored field moist at 4 °C. At the end of the experiment, the soil surrounding the bags at a distance of 15 cm was also sampled, to investigate the effects of the buried soil/root mixture on the characteristics of the soil material in close vicinity to the buried samples. These samples were sieved <2 mm and stored field-moist at 4 °C.

2.3. Microbial biomass C

Soil microbial biomass C (MBC) was analysed by fumigation–extraction (Vance et al., 1987). Two grams of fumigated (24 h with ethanol-free $CHCl_3$ at 25 °C) and non-fumigated soil was extracted with 8 ml of 0.05 M K_2SO_4 (Potthoff et al., 2003) by 30 min horizontal shaking at 200 rev min^{-1} and filtered (hw3, Sartorius Stedim Biotech, Göttingen, Germany). Organic C in the extracts was determined using a multi N/C 2100S automatic analyser (Analytik Jena AG, Jena, Germany). MBC was calculated as E_C/k_{EC}, with E_C = (organic C extracted from fumigated soil) − (organic C extracted from non-fumigated soil) and k_{EC} = 0.45 (Wu et al., 1990).

For the determination of ^{13}C, 4 ml aliquots of 0.05 M K_2SO_4 extracts of fumigated and non-fumigated samples were freeze dried for about 3 days and were analysed by isotope ratio mass spectrometry (Elemental analyser Flash 2000, Thermo Fisher Scientific, Cambridge, UK; Delta V Advantage, Thermo Electron, Bremen, Germany).