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Quantification of functional soil organic carbon pools for major soil units and land uses in southeast Germany (Bavaria)

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ABSTRACT

The management of soils as well as the impact of land use or climate changes are often evaluated in view of the storage of total soil organic carbon (SOC). However, as soil organic matter (SOM) is composed of different compounds with different degrees of stability and turnover times, there is the need for a soil- and land use-specific quantification of functional SOC pools. In this study, the amount of active, intermediate and passive SOC pools was determined for major soil types and land uses of Bavaria in southeast Germany. At 99 locations, soil horizons down to the parent material were fractionated according to the method of Zimmermann et al. (2007). The results showed that in cropland and grassland soils around 90% of total SOC stocks can be assigned to the intermediate and passive SOC pool. High SOC stocks in grassland soils are partly related to a higher degree of soil aggregation compared to cropland soils. The contribution of intermediate SOC in cropland soils was similar to that in grassland soils due to an increased proportion of SOM associated with silt and clay particles. The cultivation-induced loss of SOC due to aggregate disruption is at least partly compensated by increased formation of organo-mineral associations as a result of tillage that continuously promotes the contact of crop residues with reactive mineral surfaces. Contrary, forest soils were characterized by distinctly lower proportions of intermediate and passive SOC and a high amount of active SOC in form of litter and particulate organic matter which accounted for almost 40% of total SOC stocks. As both the amount of intermediate and passive SOC were lower in forest soils, we conclude that cropland and grassland soils may be more advantageous for long-term SOC storage in Bavaria. The high amount of labile SOC in forest topsoils poses the risk of considerable SOC losses caused by wildfire, mechanical disturbances or increasing temperatures.

1. Introduction

As soils constitute the largest terrestrial C pool, processes which affect the storage of soil organic carbon (SOC), such as changes of the land use, climate or soil management, have been investigated in numerous studies. However, in most studies only bulk SOC stocks were determined despite the fact that soil organic matter (SOM) is composed of several pools with different degrees of stabilization and hence turnover times ranging between a few years and several centuries. To account for the complexity of SOM, several soil fractionation approaches were proposed which aimed to isolate functional SOM pools with specific turnover rates, the active, intermediate and passive SOC pools (Cambardella and Elliott, 1993; Christensen, 2001; von Lützow et al., 2007; Kögel-Knabner et al., 2008; von Lützow et al., 2008). The active pool with short turnover times of 1–10 years is composed of fresh plant residues, root exudates, decomposer faeces and faunal or microbial residues and the main part of this pool in form of particulate organic matter (POM) can be isolated by density fractionation (Christensen, 2001; Six et al., 2002b; Gregorich et al., 2006). The intermediate and passive pool is characterized by OM with considerably longer turnover times of 10–100 years and >100 years, respectively. In these pools OM is stabilized against microbial mineralization by occlusion within soil macro- and microaggregates, selective preservation of recalcitrant compounds and formation of organo-mineral associations (Sollins et al., 1996; Christensen, 2001; Six et al., 2002b; von Lützow et al., 2006; Kögel-Knabner et al., 2008).

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In terms of long-term SOC storage and C sequestration, soils with high amounts of OM in the intermediate and passive pool are advantageous towards soils with a high proportion of active SOC (Jandl et al., 2007; Vesterdal et al., 2008; Lorenz and Lal, 2010; Prescott, 2010). One of the most promising approaches to obtain functional SOC pools is a combined physical and chemical fractionation method proposed by Zimmermann et al. (2007). This method isolates five soil fractions which can be assigned to active, intermediate and passive SOC pools and are related to the modelled pools of the Rothamsted carbon model (RothC) (Jenkinson and Rayner, 1977; Dondini et al., 2009; Xu et al., 2011; Shirato et al., 2013). Therefore, this method is not only suitable for a quantitative assessment of functional SOC stocks but also allows the modelling of the future development of SOC storage. However, a quantitative determination of functional SOC pools for different soil types or land uses applying the fractionation approach of Zimmermann et al. (2007) was rarely conducted. This would allow a more precise evaluation of the impact of different land uses and soil types on SOC storage.

In central Europe, most studies evaluated land use changes on the basis of total SOC stocks and often incorporated only the topsoil to a depth of 30 cm neglecting the fact that subsoils below the top 30 cm significantly contribute to SOC storage (Batjes, 1996; Jobbagy and Jackson, 2000; Harrison et al., 2011; Rumpel and Kögel-Knabner, 2011; Wiesmeier et al., 2012). Moreover, subsoil SOC stocks primarily constitute the intermediate and passive SOC pool and should hence be quantified (von Lützow et al., 2008). Recently, Poeplau and Don (2013) presented an analysis of the effect of major land use changes in Europe on SOC stocks based on 24 paired sites. The study also included a determination of functional SOC stocks according to Zimmermann et al. (2007) but this was restricted to the first 30 cm of the soils.

This study aims to quantify functional SOC pools down to the parent material for major soil types and land uses of the federal state of Bavaria in southeast Germany. On the basis of a comprehensive SOC data set (Wiesmeier et al., 2012), 99 locations were selected which represent the spatially most important soil classes within Bavaria subdivided to the main land uses cropland, grassland and forest (Fig. 1). For each location, all soil horizons down to the parent material were fractionated according to Zimmermann et al. (2007). The main objectives were to

(1) quantify the total amount of active, intermediate and passive SOC stocks for each soil class/land use;
(2) reveal environmental parameters which control functional SOC pools;
(3) evaluate land use types in terms of long-term SOC storage on the basis of the degree of stability derived from the soil fractionation.

2. Materials and methods

2.1. Study area

The state of Bavaria, with an area of 70550 km^2, is located in southeast Germany and comprises various landscapes. The northwestern part of Bavaria is dominated by the southern German escarpment landscape that adjoins low mountain ranges of the Bohemian Massif in the east. Southwards the Molasse basin ascends to the mountain range of the Alps at the southern border of Bavaria. Elevation ranges between 107 and 2962 m above sea level. Due to its location in central Europe, Bavaria exhibits a suboceanic climate that is characterized by a transitional situation between a maritime climate in the northwest and subcontinental influences in the east. Mean annual temperature and precipitation from the escarpment landscape in the northwest to the Alps in the south range between 9 °C and 4 °C and 550 and 2500 mm, respectively. Dominant soil classes are soils with well-developed B horizons (Cambisols) at 45% of the total area, soils with initial soil formation (Leptosols, Regosols) with 14% and soils with water stagnation (Stagnosols, Albeluvisols, Planosols) with 13% according to the German soil systematic (AD-HOC AG Boden, 2005) and the equivalent reference soil groups of the WRB system (IUSS Working Group WRB, 2006). Cropland accounts for 34% of the total land area of Bavaria, grassland for 16%, forest for 35% and other uses for 15%.

2.2. Compilation of SOC data

The selection of study sites for the determination of functional SOC pools for all major soil units and land uses in Bavaria was based on a map that combines high-level soil units with main land uses (Richter et al., 2007). Within Bavaria, the map comprises 38 soil units resulting from an intersection of soil type and parent material ("Bodenformen") with macroclimate. These soil units were subdivided according to the main land uses cropland, grassland and forest using the CORINE Land Cover data. This approach resulted in a total amount of 92 soil/land use units combining the factors soil type, parent material, climate and land use which were identified as major controlling parameters for SOC in Bavaria (Wiesmeier et al., 2013a,b). Due to the great effort of soil fractionation, all soil/land use units were excluded which were smaller than 1% of the area of Bavaria. For each of the remaining 33 soil/land use units three representative locations were selected using available soil material and data from different soil surveys and permanent soil observation sites in Bavaria compiled by the Bavarian Environment Agency and the Bavarian State Institute for Forestry (Fig. 1). The selected soil profiles were derived from permanent soil monitoring sites and a grid sampling of 8 × 8 km within Bavaria between 2000 and 2004 (Joneck et al., 2006). For each soil profile a representative location was selected within a radius of 500 m around the grid node to achieve a homogeneous sampling area in terms of vegetation, relief, soil type and parent material as well as a central position in the particular land use type. Agricultural and forest sites were selected with regard to a constant agricultural management and stand ages of at least 70 years, respectively. Anthropogenic disturbances in the subsoil were excluded in a pre-exploratory survey using a soil auger. For top- and subsoil horizons located down to a depth of about 35 cm, soil material was collected as a composite sample from four sub-locations located with a radius of 6.6 m and four sub-locations with a radius of 3.8 m around the main soil profile in order to cover the small-scale heterogeneity of the soils. Samples from soil horizons located below 35 cm were taken from the main soil profile. Organic and litter layers were sampled using a steel frame. At the main soil profile all horizons were additionally sampled using steel cylinders for the determination of bulk density. The content of rock fragments >2 mm was estimated visually in the soil profiles according to AD-HOC AG Boden (2005).

2.3. Fractionation of functional SOC pools

For each soil horizon down to the parent material at the 95 study sites, separation of functional SOC pools was conducted according to the fractionation approach of Zimmermann et al. (2007) (Fig. 2). Soil material was sieved to 2 mm and 30 g (for C horizons 50 g) were suspended in 150 ml of deionised water and dispersed using a calibrated ultrasonic probe-type (Bandelin, Berlin, Germany) with an output energy of 22 J ml^{-1}. This relatively low energy was applied to disrupt only weakly stabilized soil macroaggregates and to prevent the disruption of mineral-associated SOM (Amelung and Zech, 1999). The suspension was wet sieved over a 63 μm sieve until the rinsing water was clear and subsequently filtered through a