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Organic carbon stocks in forest soils of the German Alps

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ABSTRACT

Forest soils are an important component of the global C cycle as they store large amounts of organic carbon (OC). Particularly in mountain forest ecosystems, soil organic matter is of crucial importance for site productivity and ecosystem services, but probably sensitive to climate change. Robust information about the OC stocks of mountain soils is rare due to their limited accessibility and large spatial heterogeneity. Our study covered the entire German Alps in a large-scale sampling campaign in 2011 and 2012, and provides soil organic carbon (SOC) stock data obtained from 150 forest soil profiles with different site conditions (elevation, aspect, air temperature, precipitation, parent material, soil type) and different intensities of historical forest utilization. The mean SOC stock of the investigated soils is 10.9 kg m^{-2}. The median value is 9.6 kg m^{-2}, indicating a skewed distribution of SOC stocks in forest soils of the German Alps. On average, 30% of the SOC stock is bound in the organic surface (O) layer, and 70% in the mineral soil. SOC stocks show a considerable dependency on site conditions (elevation, air temperature, precipitation, parent material). Soils in the German Limestone Alps show a significant OC stock gradient from W (Werdenfels) to E (Berchtesgaden region), which probably has been caused by more intense historical forest utilization in the latter compared to the former region. Soils at high-elevation sites with low air temperature and high precipitation have particularly large OC stocks. However, the elevation and climate effect is statistically significant only for precipitation due to the large variation of other factors with relevance for SOC stocks (*e.g.* parent material, soil type) in a given elevation/climate stratum. Histosols on consolidated calcareous bedrock and Histic Rendzic Leptosols have significantly larger SOC stocks than Rendzic Leptosols, Rendzic Cambisols, or soils on easily-weatherable parent material (marl, clayey sandstone, moraine). The fact that SOC stocks in forest soils of the German Alps are by trend larger at high-elevation sites with low air temperature and high precipitation suggests a sensitivity to the ongoing climate change and a risk of SOC losses for the predicted climate scenarios.

1. Introduction

Soils store the largest terrestrial pools of organic carbon (OC) (Batjes, 1996). Organic matter (OM) stored in forest soils is a particularly important part of the global C cycle as these soils are characterized by high OC concentrations and soil organic carbon (SOC) stocks (FAO, 2010; Lal, 2005; Nabuurs et al., 1997; Perruchoud et al., 2000). In Europe, the largest OC concentrations of forest soils are found in the European Alps (Baritz et al., 2010), where low air temperatures retard the decomposition of organic material, resulting in pronounced accumulation of soil organic matter (SOM) (*e.g.* Hagedorn et al., 2010a; Rodeghiero and Cescatti, 2005; Wiesmeier et al., 2013). Particularly in mountain forest ecosystems, which are especially vulnerable to climate change (Schröter et al., 2005) and often characterized by shallow, stone-rich soils, SOM is of crucial importance for site productivity, forest vitality, and important ecosystem services (*e.g.* protection against avalanches, soil erosion, mudflow, flooding; Brang et al., 2006) due to its function as rooting zone and nutrient supply as well as its water storage capacity (Hagedorn et al., 2010b; IPCC, 2007; Rounsevell et al., 1999). Quantity and quality of the SOM stock at a given site are subject to various abiotic and biotic environmental factors like climate, geological parent material, soil type, exposition, and vegetation (Homann et al., 1995; Jenny, 1929, 1941; Jobbagy and Jackson, 2000; von Lützow and Kögel-Knabner, 2009; Wiesmeier et al., 2012, 2013) as well as human interference (Christophel et al., 2013; Meister, 1969). Soil organic matter in well-developed mountain soils is supposed to be in a dynamic equilibrium (Schlesinger, 1990), but particularly sensitive to disturbances such as land-use and climate change (*e.g.* Bolliger et al., 2008; Hagedorn et al., 2010a, 2010b; Hiltbrunner et al., 2013). Robust information about the OC stocks of mountain soils is needed for the assessment of climate change effects in the European Alps, whose valleys often are densely populated, emphasizing the need of healthy protection forests (Brang et al., 2006). However, at present, only little reliable data is available concerning the OC stocks of soils in the Alps. At the moment, published data on OC stocks in soils of the German Alps (*e.g.* Bochter et al., 1981; Schubert, 2002; Thuille and Schulze, 2006) mostly derive from case studies carried out at different times and with different methods of soil sampling and analysis. Moreover, they often are calculated on estimated or modeled rather than on the basis of measured

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bulk density and coarse fragment data, which results in inaccurate estimates of SOC stock data (Wiesmeier et al., 2012). The situation is only slightly better for the Alpine regions of other European countries (*e.g.* Bolliger et al., 2008; Egli et al., 2009; Gingrich et al., 2007; Hagedorn et al., 2010a; Perruchoud et al., 2000; Rodeghiero and Cescatti, 2005).

Our study wants to reduce this obvious lack of knowledge by presenting results from a comprehensive assessment of the SOC stocks of forest soils in the German Alps (53% of the area of the German Alps is currently covered by forest; Mellert and Ewald, 2014) at the beginning of the 21st century. 150 profiles have been sampled and investigated within a short time interval (<20 months) with identical methodology. In contrast to many other studies, SOM stocks have been calculated for entire soil profiles from measured instead of modeled bulk density and coarse fragment values, which strongly improves the accuracy of the data (Schrumpf et al., 2011; Wiesmeier et al., 2012, 2013). With our study, we want to provide a reliable number for the SOC stock of forest soils in the German Alps. Additionally, by collecting numerous profile-specific data on important environmental variables, we intend to conduct a stratified evaluation and multivariate statistical analysis of the SOC stock data and an assessment of relationships between important environmental factors and SOC stocks.

2. Material and methods

2.1. Study region

The analyzed soil profiles have been excavated in four different approaches, but cover the entire German Alps (Fig. 1): Set 1 comprises profiles from 14 Alpine sites of the Bavarian Forest Soil Long-Term Monitoring Plot Network (Schubert, 2002). The sites had been selected to represent all major regions, bedrock, soil, and forest types in the German Alps. Set 2 comprises 20 profiles under managed forest from the study of Christophel et al. (2013) in which effects of long-term modest forest utilization on SOC stocks were investigated in a paired-plot approach including soils under managed forest and nearby relic patches of primeval forest. Set 3 comprises 68 soil profiles from a study in which the effects of long-term pasture on SOC stocks were investigated in a paired-plot approach including soils under pasture and nearby managed forest, and set 4 comprises 48 profiles which were part of elevation gradients or forest growth assessment studies. Each investigated profile can be assigned to one of four regions (Fig. 1): The *Flysch and Tertiary Region* (northernmost mountain ridges of the German Alps; elevation of highest mountain summits: 1500–1800 m; bedrock mostly easily-weathering Cretaceous or Tertiary silicate sediments, which are often covered by thick talus resulting in gentle relief forms); the *Werdenfels* and the *Berchtesgaden regions* (Western and Eastern Bavarian Limestone Alps, respectively; elevation of highest mountain summits: 2700–3000 m a.s.l.; bedrock mostly hardly-weathering Triassic marine limestone and dolostone sediments; resulting in pronounced peaks with steep, rocky slopes), and the *Mangfall Mts. Region* (Central Bavarian Limestone Alps; elevation of highest mountain summits: 2000–2200 m; bedrock Triassic and Jurassic sediments with different lithology [marl, shale, limestone, dolostone] and variable resistance against physical weathering, resulting in a marked variety of slope and summit morphology). Set 1 includes sites from all four regions, set 2 sites from Werdenfels and the Mangfall Mts.; sets 3 and 4 include sites from the Mangfall Mts. and the Berchtesgaden region.

Particularly at lower elevations of the German Alps, the original bedrock is often covered with Pleistocene moraine (Biermayer and Rehfuess, 1985) or Pleistocene as well as Holocene eolian dust (Küfmann, 2003), both deriving from local sources and long-range transport (*e.g.* gneiss, granite and schist fragments from the Central Alps; dust additionally from the Sahara desert). The climate in the German Alps is humid and cool, with the mean air temperature (MAT) decreasing and the mean annual precipitation (MAP) increasing with altitude at a rate of −0.5 °C and +40 mm/100 m elevation increase (Ewald et al., 2000; Fliri, 1975).

The natural vegetation cover and forest composition in the German Alps are characterized by considerable variability, depending on elevation, exposition, parent material, and soil type (Walentowski et al., 2004). Broadly speaking, the dominating natural forest types are mixed montane broadleaf–conifer forest, dominated by Norway spruce (*Picea abies*), Silver fir (*Abies alba*), and European beech (*Fagus sylvatica*) at altitudes below 1600 m a.s.l., and subalpine conifer forest, dominated by Norway spruce and Silver fir, between 1600 and 1900 m a.s.l. with a decreasing contribution of fir and increasing contribution of *Pinus mugo mugo* as elevation increases, subsequently followed by *P. mugo mugo* krummholz, alpine meadow, and ultimately barren rock at the highest elevations (>2400 m a.s.l.). During the recent centuries or millenia, vegetation and forest composition of the German Alps have been modified considerably by human activity (land use change from forest to pasture, species-selective cuttings, game management; *e.g.* Ewald, 2000; Meister, 1969; von Bülow, 1962).

2.2. Soil sampling

All soil profiles were excavated to 1 m depth or to the massive bedrock, whichever was reached first, characterized using the German soil

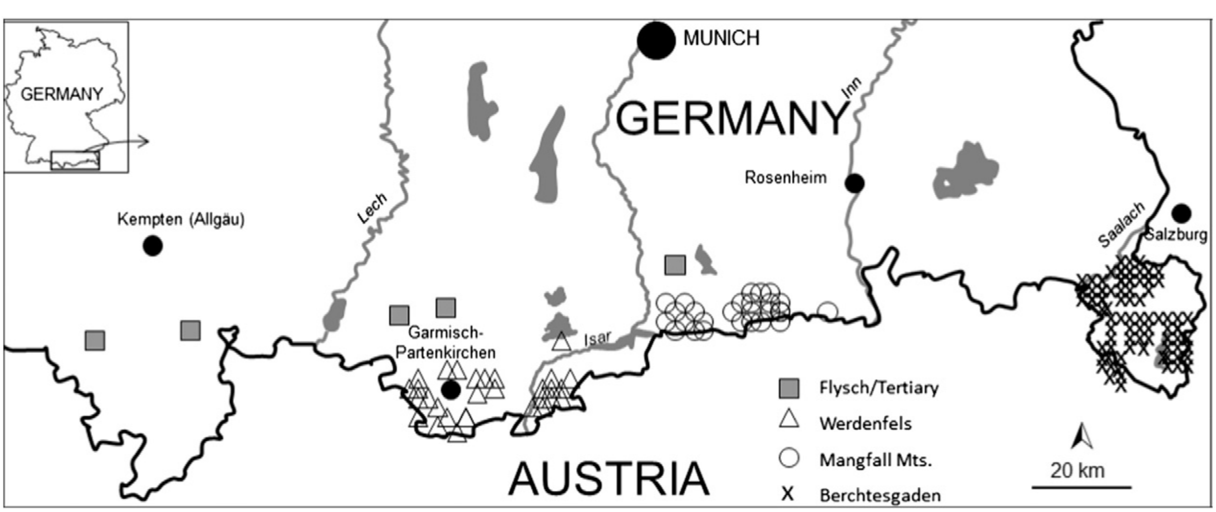

Fig. 1. Location of the 150 investigated forest soil profiles in the German Alps.