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Variability of soil carbon stocks in a mixed deciduous forest on hydromorphic soils

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ABSTRACT

Forests play an important role for carbon (C) storage and a large part of C in forest ecosystems is stored in the soil. Although large-scale inventories of soil C stocks have been published recently, detailed site-specific studies are still needed because C storage depends on various site specific soil, ecological and management factors. Quantification of soil C stocks is hampered by spatial and temporal variability. Here, we assess C stocks in an ancient forest site at a stand which has not been managed for > 60 years and analyse the spatial variability of C concentrations and stocks to evaluate inter-annual variability and elucidate possible causes. Samples were taken down to 1 m depth by auger cores in May of three consecutive years (2013, 2014, 2015) on regular hexagonal grids covering an area of 0.25 ha and 19 sampling spots. In addition, to address small scale variability, 36 auger cores were taken in November 2014 using a nested sampling design.

C stocks were on average 34 kg C m^{-2} (0–1 m depth). This is distinctly higher than soil C stocks reported for most other forest sites in similar climatic conditions, and is likely caused by the interplay of several parameters, i.e., hydromorphic soil conditions, high biomass production due to high soil fertility, stand structure (tree age, species and density), and the management history of the site. The coefficients of variation for C concentrations (> 50%) and for C stocks (30–50%) show that spatial variability is high. Geostatistical analysis revealed a larger scale component with ranges of 5–20 m and a small scale component represented by high nugget effects in the semivariograms (> 50%).

As hydromorphic soil types are widespread in NE Germany, large amounts of organic C could be sequestered into soil under unmanaged old forests, thus contributing to alleviating the rise in anthropogenic CO_2 concentrations in the atmosphere.

1. Introduction

Forests contain about 50% of all organic carbon (C) stored in terrestrial ecosystems and play, thus, a central role in the global C cycle (Dixon et al., 1994; Jobbágy and Jackson, 2000; Mund and Schulze, 2006; Scharlemann et al., 2014). The partitioning of stored C between aboveground biomass and soil varies strongly across climate zones. In temperate climate the major part of C in forest ecosystems is stored in the soil (Dixon et al., 1994; Gleixner et al., 2009; Scharlemann et al., 2014). On a global scale, much more C is stored in soils (2060 Gt organic C in soils down to 2 m, Batjes 2016, and 2344 Gt down to 3 m depth, Jobbágy and Jackson, 2000) than in terrestrial vegetation (450–650 Gt C) (Johnson and Curtis, 2001; Ciais et al., 2013) or in the atmosphere as CO_2 (830 Gt C). Hence, relatively small changes in the C storage of soils can have large impacts on the C content of the atmosphere and consequently on the concentration of the greenhouse gas CO_2.

C storage in forest soils is governed by factors related to ecological and management factors such as climate, soil, vegetation, forest management practices and disturbances (De Vos et al., 2015). These factors largely match the classical factors of soil formation according to Jenny (1941) (Time, Parent material, Topography, Climate, Organisms). In general, accumulation of organic matter in the soil is favoured by high precipitation, high soil water contents, and low temperatures (Pregitzer and Euskirchen, 2004; Baritz et al., 2010). Major soil factors for soil organic C (SOC) accumulation are soil type and soil development stage (Batjes, 2002; Grüneberg et al., 2010; De Vos et al., 2015), drainage status (Davis et al., 2004), soil texture including clay content (Baritz et al., 2010), pH value and cation exchange capacity (Six et al., 2002; Jandl et al., 2007).

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Vegetation factors influencing SOC content are stand age (Pregitzer and Euskirchen, 2004; Gleixner et al., 2009; Wäldchen et al., 2013), species composition (Langenbruch et al., 2012; Vesterdal et al., 2013; Wäldchen et al., 2013; Gruba et al., 2015), stand density as well as type, duration and history of forest management (Mund and Schulze, 2006; Jandl et al., 2007; Wäldchen et al., 2013). Forest management exerts a strong influence on medium term C storage in the soil and consequently the C sequestration potential of forests (Mund and Schulze, 2006; Jandl et al., 2007). Old forests which have not been used for many years may store large amounts of C, both in aboveground biomass as well as in the soil compartment (e.g., Luyssaert et al., 2008; Gleixner et al., 2009; Bisbing et al., 2010).

The assessment of C in forest soils is challenging due to the high spatial variability of C concentrations and stocks, both in the mineral soil (Schöning et al., 2006; Gruba et al., 2015) and in the organic humus layer (Kristensen et al., 2015). Consequently, the uncertainty in forest soil C inventories is high and, typically, many samples are necessary to report average values with sufficient confidence: several in-depth studies recommend at least 100 sampling spots for areas of 1000–10,000 m^2 (Conen et al., 2004; Schöning et al., 2006; Schrumpf et al., 2011). The number of samples which are necessary for complete quantification of C stocks and the optimum sampling design depend strongly on the covered area and spatial variability (Schrumpf et al., 2011). Therefore, knowledge about the spatial variability in an investigated site is crucial for a complete site characterization.

In contrast, temporal variability of soil C stocks seems to be comparably low: reported C sequestration rates in forest systems range from 5 (Schlesinger and Bernhardt, 2013), over 20 (Schulze et al., 2009), 30 (Post and Kwon, 2000), and 56 (Richardson and Stolt, 2013) to 68 g C m^{-2} $year^{-1}$ (Schrumpf et al., 2011). This corresponds to about 0.1–1% of total C stocks in forest soils and consequently temporal variability of C stocks is two orders of magnitude lower than spatial variability. However, the rates cited above are typically derived as long-term net sequestration rates. Over short time scales (within a year), soil C in the upper soil (0–20 cm depth) may show larger temporal variability due to seasonal development of fine root biomass and litterfall (Jurasinski et al., 2012). High spatial variability impedes the detection of temporal changes in soil C stocks, especially if C stock inventories of consecutive years are compared (Schrumpf et al., 2011).

Large-scale inventories of C stocks in forest soils are increasingly available (Baritz et al., 2010; De Vos et al., 2015). In these studies, the characterization of soil C stocks is based on a few soil pits per site. Despite these large-scale inventories, the spatial coverage of Europe is far from exhaustive with large gaps between inventoried sites. Special site conditions such as specific management practices and/or tree species compositions are not wholly covered in these inventories. Therefore, more detailed studies of soil C stocks in forest soils at specific sites are necessary.

Here, we assess C stocks in a relatively old forest in NE Germany which has not been used for > 60 years. A previous assessment based on data for one year (2013) yielded relatively large soil C stocks (> 30 kg C m^{-2}, 0–1 m depth) for this forest patch, compared with much lower C stocks in managed forest plots in the immediate vicinity. These high C stocks were presumably mainly driven by soil properties and forest management history (Buczko et al., 2014). Additional sampling campaigns were conducted in the two subsequent years (2014 and 2015) to widen our data base. We hypothesize that observed differences in soil C stocks between consecutive years are caused predominantly by small scale spatial variability.

2. Material and methods

2.1. Study site

The forest site Eldena in Greifswald (Mecklenburg-Vorpommern, northeast Germany) is a nature reserve since 1961 and large parts of the 407 ha forest area are under restricted use. Within the forest, plots with different management history and stand structure lie close to each other on similar soil types. A comparative assessment of the impact of stand structure, stand age, and forest management on soil C concentrations and stocks has been presented in a previous study (Buczko et al., 2014). The history of vegetation and management is documented for the period of about the last 2000 years (Spangenberg, 2008). At present, the major part of the Eldena forest consists of near-natural stands dominated by beech (*Fagus sylvatica*) or common ash (*Fraxinus excelsior*), with tree ages of up to 200 years (Spangenberg, 2008).

The climate at the site is maritime with average annual precipitation of 592 mm and mean annual temperature of 8.8 °C (1981–2010) (July 17.7 °C, January 0.6 °C) (extracted from 1 × 1 km raster products provided by the German Meteorological Office). The geological substrate consists of ground moraines originating from the youngest phases of the Weichsel glaciation (Mecklenburg phase, 13,700–13,000 year b.p.). The sediments are mainly glacial till sediments, partly overlain by cover sands, which formed periglacially after the retreat of the glaciers. In some places in the Eldena forest, fluvial sands occur whereas in local depressions peats have formed (Kwasniowski, 2001). The glacial till sediments are mostly decalcified near the soil surface resulting in loamy sediments. Due to the high ground water table and the presence of impervious clayey soil layers, the area of the Eldena forest is dominated by hydromorphic and stagnic soil types (Kwasniowski, 2001).

We assessed the C storage in the forest soil at a plot with a documented forest continuity of > 2000 years and a maximum tree age of about 200 years (with natural undergrowth of younger trees). The upper crown layer is dominated by beech (*Fagus sylvatica*) and oak (*Quercus robur*), the latter as relict from former utilization as forest pasture. Hornbeam (*Carpinus betulus*) and sycamore (*Acer pseudoplatanus*) occur as codominants and in the understorey. The plot lies within a part of the forest that has not been managed since 1961 and will not be in the future since it is protected as a strict forest reserve. Before that date, it has been used for centuries as forest pasture in combination with coppice-with-standards. Regular forestry management started in 1820 with the ban of forest pasture. Shortly after World war II intense wood harvesting took place in the whole Eldena forest. Since about 1950, the investigated plot has been out of forest utilization. Stand density in 2013 was 227 trees ha^{-1}, basal area was 43.2 m^2 ha^{-1}, and standing wood volume amounted to 699 m^3 ha^{-1}. At the study plot the soil type is predominantly brown earth – pseudogley (stagnic luvisol). At a representative soil profile within the plot, the Ah horizon extended from 0 to 25 cm depth and had loamy sandy texture (Sl3), the Bv from 25 to 65 cm, also with loamy texture (Sl3 – Sl2), the Sw horizon 65–85 cm with sandy silt texture (SU3), and below 85 cm depth, the Sd, also sandy silt texture (SU3). However, the thickness and depth of soil horizons varied considerably across auger core sampling locations.

2.2. Soil sampling and laboratory analyses

Samples were taken during students' master field courses at four dates in 2013, 2014 and 2015: in each of these years during May, and in 2014 additionally at the beginning of November. At each of the spring sampling dates, a soil profile pit was excavated to describe the soil profile. In those profiles, three 100 cm^3 soil core samples per soil horizon were taken for determination of bulk density, soil texture and C content. These data were also used to derive a pedotransfer function for bulk density based on soil depth and C content.

For each spring campaign the sampling spots were arranged in a hexagonal grid with 19 auger core locations (Fig. 1). The sampling spots shared distances of 10 m along the radial lines of the hexagon. In order to elucidate in more detail the small-scale variability, in November 2014 a nested sampling scheme was employed: around each of 6 of the 19 regular sampling spots (one on each outward running line of the hexagon), 6 sampling spots were chosen randomly with distances between 0.5 and 6 m to the main spots (Fig. 1). Since the exact mid-points