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Stand scale variability of topsoil organic matter composition in a high-elevation Norway spruce forest ecosystem

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ABSTRACT

Our knowledge about the effect of single-tree influence areas on the physicochemical properties of the underlying mineral soil in forest ecosystems is still limited. This restricts our ability to adequately estimate future changes in soil functioning due to forest management practices. We studied the stand scale spatial variation of different soil organic matter species investigated by ^{13}C NMR spectroscopy, lignin phenol and neutral sugar analysis under an unmanaged mountainous high-elevation Norway spruce (*Picea abies L.*) forest in central Europe. Multivariate geostatistical approaches were applied to relate the spatial patterns of the different soil organic matter species to topographic parameters, bulk density, oxalate- and dithionite-extractable iron, pH, and the impact of tree distribution. Soil samples were taken from the mineral top soil. Generally, the stand scale distribution patterns of different soil organic matter compounds could be divided into two groups: Those compounds, which were significantly spatially correlated with topography/altitude and those with small scale spatial pattern ($\text{range} \leq 10$ m) that was closely related to tree distribution. The concentration of plant-derived soil organic matter components, such as lignin, at a given sampling point was significantly spatially related to the distance of the nearest tree ($p \leq 0.05$). In contrast, the spatial distribution of mainly microbial-derived compounds (e.g. galactose and mannose) could be attributed to the dominating impact of small-scale topography and the contribution of poorly crystalline iron oxides that were significantly larger in the central depression of the study site compared to crest and slope positions.

Our results demonstrate that topographic parameters dominate the distribution of overall topsoil organic carbon (OC) stocks at temperate high-elevation forest ecosystems, particularly in sloped terrain. However, trees superimpose topography-controlled OC biogeochemistry beneath their crown by releasing litter and changing soil conditions in comparison to open areas. This may lead to distinct zones with different mechanisms of soil organic matter degradation and also stabilization in forest stands.

1. Introduction

High spatial variation over short distances is one characteristic feature of forest OC stocks (Moni et al., 2010; Schöning et al., 2006; Schulp et al., 2008; Spielvogel et al., 2009). This high variability is one reason for the limited understanding of OC stabilization in forest soils. Quantifying the spatial variability of forest soil OC stocks is necessary for an upscaling from the single patch to the forest stand level (Bierkens et al., 2000) and thus for accurate soil OC inventories (Lal, 2009; Sanchez et al., 2009; Wang et al., 2002). Explaining spatial patterns of OC as a function of local site variables would improve the development of local adjustment terms to the regional relationships (Banfield et al., 2002). Moreover, a better knowledge about factors controlling spatial patterns of forest soil OC stocks would provide useful information on the processes generating this variation (Liski, 1995) and enable to predict how natural and anthropogenic environmental changes may affect forest OC pools in the future (Ciais et al., 2005; Odum, 1969; Venteris et al., 2004; Weber and Bardgett, 2011).

The current literature contains contrasting results regarding parameters controlling soil OC distribution in forest ecosystems. Some studies found topography being the dominant reason for the formation of stand scale heterogeneity patterns of OC stocks in physically heterogeneous landscapes such as mountainous areas (Jian-Bing et al., 2006; Miller et al., 1998; Mueller and Pierce, 2003; Sinowski and Auerswald, 1999; Spielvogel et al., 2009; Pierson and Mulla, 1990). Other studies suggest that single tree influence (Liski, 1995; Ruark and Zarnoch, 1993; Spielvogel et al., 2014) and coarse woody debris or log proximity

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(Auerswald and Weigand, 1996; Martin and Timmer, 2006; Spielvogel et al., 2009) may be more important for the spatial pattern of OC stocks and other soil properties than topographic attributes, as individual trees and logs can create chemical and physical gradients that affect the spatial patterning of soil properties (Lavoie et al., 2012). Trees can create gradients in soil moisture (Godefroid and Koedan, 2010; Ludvig et al., 2004; Weber and Bardgett, 2011), temperature (Tang and Baldocchi, 2005), nutrient availability and turnover (Amiotti et al., 2000; Lodhi, 1977; Penne et al., 2010; Weber and Bardgett, 2011), and understory species composition (Lodhi, 1977; Penne et al., 2010) through distinct spatial patterns of litter accumulation (Amiotti et al., 2000; Penne et al., 2010), stem flow and through fall (Ford and Deans, 1978; Seiler and Matzner, 1995), light and precipitation interception (Palik et al., 2003; Pecot et al., 2005) and root distribution (Spielvogel et al., 2014; Tang and Baldocchi, 2005) all of which factors that likely impact the spatial pattern of forest soil OC stock.

These contrasting results may be the product of two factors biasing the evaluation of spatial distributions of OC stocks in forest soils: (i) Results of soil OC inventories may change with the considered scale of observation, as all soil processes take place only at a certain scale (Schöning et al., 2006). Therefore, the scale issue may be of major importance for the interpretation of the results, and studies on the spatial pattern of soil OC stocks should cover a range of spatial distances using different grid sizes or nested approaches within a certain grid. (ii) The spatial contribution to overall OC may differ among different soil organic matter components. We suggest that plant-derived soil organic matter components, entering the soil mainly by root litter decomposition (e.g. lignin) and microbial compounds (e.g. microbial neutral sugars) as well as components that are translocated via leaching exhibit considerably different stand scale distribution patterns. This may lead to distinct zones with different mechanisms of soil organic matter degradation and also stabilization in forest stands. To the best of our knowledge, no studies on the spatial distribution of different organic matter components and their spatial relation to topography, stand properties, as well as soil chemical and physical properties have been carried out so far. This is most probably due to the high analytical effort associated with the measurement of a large number of samples necessary for geostatistical approaches.

The objectives of this study were (i) to investigate the stand scale spatial variation of different soil organic matter species investigated by ^{13}C NMR spectroscopy, lignin phenol and neutral sugar analysis and (ii) to relate the spatial distribution of these compounds to topography, stand properties (tree distribution, fine root biomass), and soil properties (soil bulk density, pH, pedogenic oxide concentration) in an unmanaged high-elevation Norway spruce (*Picea abies L.*) forest.

2. Materials and methods

2.1. Study site

The study site is located within the National Park Bayerischer Wald, Germany, with cool and humid climate (mean annual temperature: 5.7 °C; annual precipitation ranging from 1150 to 1300 mm, Elling et al., 1975). Main soil types at the study site were Leptic Cambisols (Dystric, Laxic) with intermixed patches of Stagnic Cambisols and Spodic Cambisols (IUSS Working Group Reference Base, 2006). The study site is forested with a mixed-aged Norway spruce (*P. abies* (*L.*) *Karst.*) stand with a mean tree age of 80 years. The site is situated in mid-slope position and formed of quaternary deposits (granite and gneiss debris). A detailed description of the site is given in Spielvogel et al. (2009); and soil characteristics are presented in Table 1. The soil horizons were classified according to the FAO Guidelines for Soil Description (FAO/UNESCO, 1990).

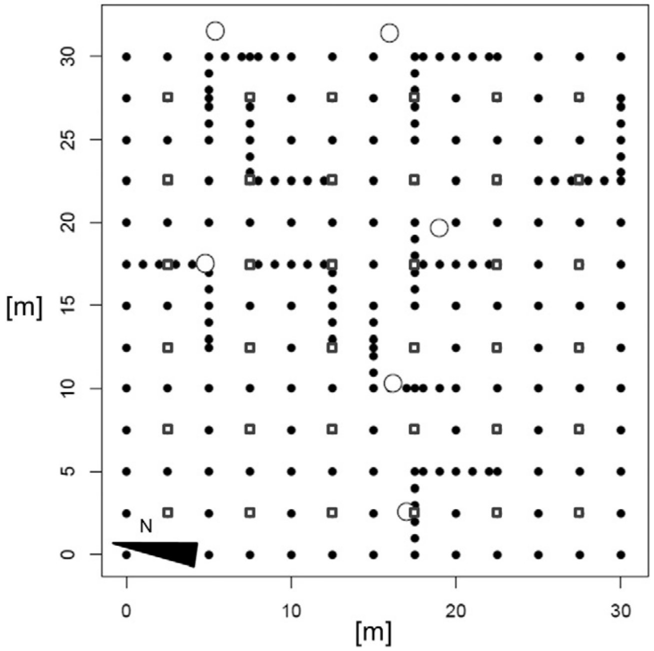

Fig. 1. Sampling design with sampling grid (primary stations and substations). White circles show position of trees; (i) samples from locations marked with a square (□) have been analyzed for bulk density (g cm^{-3}), OC (g kg^{-1} soil^{-1}) pH, Fe$_o$, Fe$_d$, as well as NMR, and (ii) samples from positions marked with a filled circle (●) have been additionally analyzed for neutral sugar content and lignin content, respectively.

2.2. Sampling design

Soils were first sampled at the nodes of a square grid of 30 × 30 m with distances of 5 m between the sampling points (main sampling stations) and one additional substation in the middle of each grid cell (Fig. 1), to enable the calculation of maps for each measured soil parameter. Subsequently, three treeless patches and six large, more or less freestanding Norway spruce trees were chosen. Treeless patches and zones around each individual tree were additionally sampled with distances of 1 m in two directions within the large grid (orthogonal to general slope inclination and parallel to general slope inclination) for detection of tree influence and small scale variability at the single tree scale (Fig. 1). Note: Different parameters were obtained with a different degree of spatial accuracy due to the varying measuring effort (see Fig. 1).

All main sampling locations were georeferenced with a post-processing Global Positioning System (GPS). The GPS measurements were corrected using SAPOS® GPPS (Geodätischer Präziser Positionierungsservice, Satelitenpositionierungsdienst des Landesamtes für Fernvermessung und Geoinformation Bayern (Ed.), dataset of 2004). The accuracy of the GPS is about 1 to 3 cm in horizontal projection and 1 to 5 cm in elevation.

Table 1
Basic properties of the topsoil of the studied high elevation Norway spruce site (arithmetic means and standard deviations in brackets).

Horizon	Depth/cm	Bulk density/g cm^{-3}	Sand/%	Silt/%	Clay/%	OC/g kg^{-1}	pH [CaCl$_2$]	Fe$_d$/g kg^{-1} soil	Fe$_o$/g kg^{-1} soil
Ah	0–15 (8)	0.64 (0.03)	44 (8)	31 (2)	25 (6)	68 (3)	3.8 (1.7)	22.0 (4.1)	17.2 (4.1)