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Soil organic carbon stocks and related soil properties in a primary *Picea abies* (L.) Karst. volcanic-mountain forest

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ABSTRACT

Although many published studies have evaluated soil organic carbon (SOC) stocks in forest soils, none have yet focused on primary (i.e., unlogged) spruce (*Picea* spp.) forests on volcanic rocks. Previous research in the Călimani volcanic mountain range, Romania, revealed a close relationship between soil morphology and the canopy disturbance history of a primary spruce (*Picea abies* L. Karst.) forest in the area. Here, six representative soil profiles were chosen from a large pedological study to test the hypothesis that the different disturbance regimes of the study plots had significant effects on SOC stocks. We used a combination of traditional soil core and excavation methods, modified for soil sampling and SOC stock estimations by horizons. In addition, chemical soil properties such as pH and the contents of Al, Fe, and Si in selected extracts (oxalate-extracted Al_o, Fe_o, and Si_o, pyrophosphate-extracted Al_p and Fe_p) were determined to detect diagnostic properties of the soils.

Total SOC stocks in the organic horizons plus mineral soil to the 0.5 m depth ranged from 18.2 to 32.0 kg C m^{-2}. In the 0–0.5 m depth, the SOC stocks were significantly positively correlated with the severity of the maximum-recorded canopy disturbance. The SOC contents in mineral soil down to the 1.0 m depth were positively correlated with the contents of $Al_p + Fe_p$, especially in the subsoil horizons. A strong positive correlation was found between pH_{KCl}, Si_o contents, $Al_p - Al_o$ contents, and the Al_o/Fe_o ratio. The soils were classified as Podzols and Andosols.

Our results indicate that in primary spruce-dominated forests on volcanic rocks, the regime of high-severity natural canopy disturbances may have positive effects on SOC accumulation in the mineral soil. The Al_o/Fe_o ratio may be a potentially useful proxy for the relative degree of leaching and podzolization in these soils.

1. Introduction

Approximately half of the global forest carbon (C) stocks are contained in soils (Pan et al., 2011), which make forest soils a highly significant component of the terrestrial C pool. Soils on volcanic materials are known for their potential to store soil organic carbon (SOC) in a disproportionally high amount compared to their spatial extent (Batjes, 1996; De Vos et al., 2015). Generally, two different mechanisms responsible for the high accumulation of SOC in volcanic soils may be distinguished: (i) the association of organic matter (OM) with the surfaces of short-range order minerals (i.e., protected SOC; Matus et al., 2014; Mikutta et al., 2009), and (ii) the complexation of OM with available Al (and Fe) into organo-metallic complexes (i.e., stabilized SOC; Matus et al., 2014; Takahashi and Dahlgren, 2016). Under vegetation with an acidic litter, the organic acids released from decomposition usually enhance the weathering of minerals to precipitate with the released Al and Fe, which is the prevailing process in Aluandic Andosols (Aran et al., 2001; Takahashi and Dahlgren, 2016; Tonneijck et al., 2010). The typical low pH of these soils is often deemed a secondary factor of OM recalcitrance and accumulation (Tonneijck et al., 2010). Nevertheless, high contents of organo-metallic complexes can also be found in the spodic horizons of some Podzols (IUSS Working Group WRB, 2015), where vertical leaching leads to the strong accumulation of C-rich substances in subsoil horizons (Aran et al., 2001; Ferro-Vázquez et al., 2014; van Hees et al., 2000). Though podzolization and andosilization might lead to different vertical distributions of SOC, some studies have indicated that the stabilization mechanisms of the associated OM in Andosols and Podzols can be relatively simillar (Aran et al., 2001; Mikutta et al., 2006), and both may contribute to the long-term sequestration of SOC that is needed for climate change mitigation (Rumpel et al., 2012).

Regardless of the global patterns in SOC accumulation and fluxes due to the changing climate and atmospheric composition, the forest-stand-scale patterns of SOC may substantially change over time and space depending on (i) management and the tree-species composition (e.g., Galka et al., 2014; Pötzelsberger and Hasenauer, 2015), (ii) the

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forest stand age or developmental phase (e.g., Seedre et al., 2015), (iii) natural disturbances, (e.g., Spielvogel et al., 2006), and (iv) soil evolution (e.g., Egli et al., 2008; Peña-Ramírez et al., 2009). Moreover, the SOC stocks can also be largely influenced by other factors such as the soil-water regime, geology, and topography (e.g. Bojko and Kabala, 2017; De Vos et al., 2015; Mora et al., 2014; Prietzel and Christophel, 2014). Although many studies have evaluated SOC stocks in volcanic soils (e.g., Egli et al., 2008; Panichini et al., 2017; Peña-Ramírez et al., 2009; Pichler et al., 2013) and in mountain spruce forests (e.g., Borůvka et al., 2009; Galka et al., 2014; Pötzelsberger and Hasenauer, 2015; Prietzel et al., 2015; Prietzel and Christophel, 2014; Seedre et al., 2015; Spielvogel et al., 2006; Thuille and Schulze, 2006), as far as we know no published paper has examined SOC stocks in a primary (i.e., unlogged) spruce-dominated forest on volcanic rocks. Fehér et al. (2007), for example, found that in the Gurghiu Mountains (Eastern Carpathians, Romania), the natural conditions, the vegetation, and high geological age of the volcanic substrate cause the processes of podzolization and andosolization to interact, yet with unknown effects on SOC stocks.

The Călimani Mts. are part of the large Călimani–Gurghiu–Harghita volcanic range of the Inner Eastern Carpathians. Previous research in the Călimani Forest Reserve has revealed close relationships of soil morphology and taxonomy to both topography and the canopy disturbance history of the primary spruce-dominated forest (Valtera et al., 2015). For the purpose of this study, we first completed an exploratory soil survey using the same methods on another enclave of primary spruce-dominated forest in the area (Svoboda et al., 2014) and then delimited a smaller set of study plots with comparable geomorphic conditions (i.e., similar topography, no water stagnation, moderate rock fragment contents), but covering the whole gradient of different natural disturbance regimes in terms of the severity of past canopy disturbances at the sites (determined by dendrochronology; Svoboda et al., 2014). The aims of the present study were to explore the soil properties and quantify SOC stocks in selected soils within this ecosystem in relation to the disturbance history of the forest stand. All the studied soil properties were selected for their strong links to the major soil processes expected at the sites, i.e. podzolization and andosolization (Fehér et al., 2007; Ferro-Vázquez et al., 2014; García-Rodeja et al., 2007; IUSS Working Group WRB, 2015). We hypothesized that the different disturbance regimes of the study plots had significant effects on SOC stocks.

2. Materials and methods

2.1. Study area

The research took place in the Călimani Mountains, Romania (47°6.115′ N, 25°7.129′ E), within the territory of the Călimani National Park. The Călimani Mts. are part of the large Călimani–Gurghiu–Harghita volcanic range of the Inner Eastern Carpathians. The central part of the Călimani Mts. is formed by the caldera of an original andesite stratovolcano, which collapsed at ca 7.1 Ma (Seghedi et al., 2005). Average annual temperature in the area varies from 2.4 to 4.0 °C, and average annual precipitation from 970 to 1150 mm (Giurgiu et al., 2001).

This study is part of a larger ecosystem research project on disturbance dynamics and soils in unmanaged, primary spruce (*Picea abies* (L.) Karst) forests within the Călimani Mts. (Svoboda et al., 2014; Valtera et al., 2013, 2015). A 40-ha core site was located at the northern (inner) side slope of the Călimani caldera structure (Călimani Forest Reserve; Giurgiu et al., 2001), and 4 smaller sites of several ha were distributed in a 4–7 km radius in the surroundings (see Svoboda et al., 2014). These sites likely represent the last remnants of the original, natural spruce-dominated forests in the Călimani landscape that were spared from direct human intervention and left to spontaneous forest development over the last few centuries (Giurgiu et al., 2001; Svoboda et al., 2014). Norway spruce (*Picea abies*) was the dominant tree species, with a lesser admixture of Stone pine (*Pinus cembra* L.) and a scarce occurrence of broadleaves (e.g., *Sorbus aucuparia* L., *Populus tremula* L., and *Fagus sylvatica* L.).

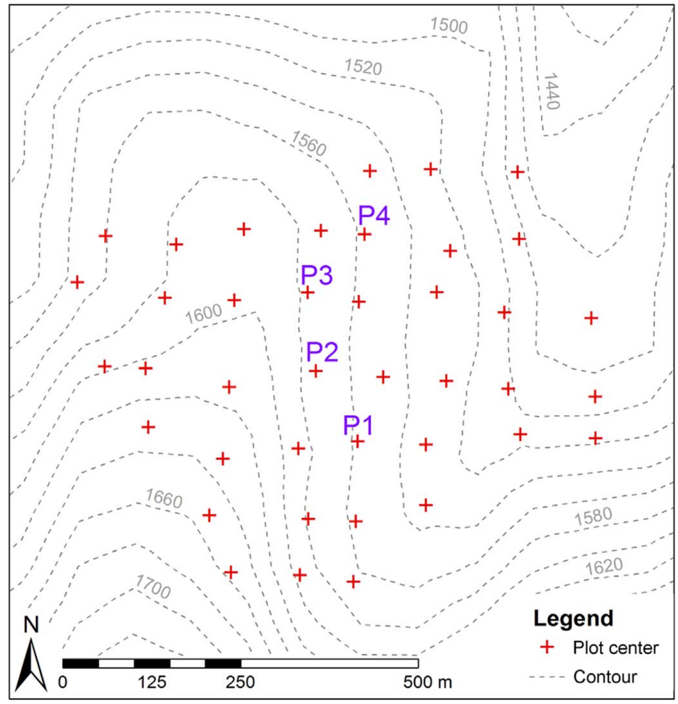

Fig. 1. Location of the study plots (P1–P4) selected at the core 40-ha site.

2.2. Study sites

In a previous paper, we studied the soil morphology using 200 shallow soil profiles on 40 plots at the core site (Valtera et al., 2015; Fig. 1). For the purposes of this study, we completed this dataset with data from another 60 soil profiles on 12 plots surveyed in 2011 using the same methods at two of the smaller sites in the area (Fig. 2). All plots were distributed in a randomized design within a regular 1-ha grid at the core site and 2-ha grid at the smaller sites (see details in Svoboda et al., 2014).

The bedrock at the study sites were andesites of Miocene age (Seghedi et al., 2005). According to WRB classification (IUSS Working Group WRB, 2015), the dominant soils at the core site were Podzols (Valtera et al., 2013), while Leptosols and Andosols prevailed at the two smaller neighboring sites (Fig. 2); these sites were subsequently treated as a single forest stand for the purpose of this study. In both forest stands, severe disturbance events (likely windstorms and/or bark beetle outbreaks) caused almost the complete canopy removal at scales of several ha ca. 85–115 years ago, with an uneven impact among plots (Svoboda et al., 2014). In 2010–2011, the average tree density at the sites was 603 trees ha^{-1} for trees ≥10 cm in diameter at breast height (DBH), with an average DBH of the trees of 32.0 cm (Svoboda et al., 2014; weighted averages).

2.3. Study plots

Based on the available data, a three-step selection procedure was applied on the original 52 plots: First, we rejected plots with soils having hydromorphic (gleyic or stagnic) properties (IUSS Working Group WRB, 2015), as well as with Leptosols or other soils with rock fragment contents ≥ 40% in the upper 0.5 m mineral soil. Then, we selected those of the remaining plots that have the most similar topographic settings, avoiding steep slopes > 25° as well as upper- and lower-slope topographic positions. Finally, we used plot-level