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The role of tree uprooting in Cambisol development

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A B S T R A C T

The role of tree uprooting in soil formation was studied in a natural forest in a Cambisol soil zone on both the fine pit-mound spatial scale and on the coarse forest ecosystem scale. The effect of a lack of pit-mound dynamics in managed forests was also assessed.

Properties of pit-mounds were studied in a 10.8 ha plot. From a total of 1562 pit-mounds, a representative sample of 51 was chosen for dendrochronological dating. Ages were determined to be between 9 and 191 years. The development of soils was studied for 14 pit-mounds of all ages. A total of 210 samples were taken from microsites at mounds, pits, and currently non-disturbed ground, from the depths 0–10, 15, 30, 50 and 100 cm. In addition, samples were taken from 9 profiles in managed forests in which tree uprooting dynamics have been prevented for at least 200 years (45 samples). Each sample was analyzed for 38 chemical and physical soil characteristics. Multidimensional statistical methods were used to evaluate the significance of (i) sampling depth, (ii) microsite, and (iii) age since the last disturbance on soil properties in the natural forest. Depth explained 12.1% of the variability in soil characteristics ($p<0.001$), while microsite and age explained 7.5% ($p<0.001$) and 1.8% ($p=0.048$) of the variability, respectively. The highest values of Ca, Mg, C and CEC weres found in pits, whereas mounds had the highest values of labile Al and exchangeable acidity. Currently non-disturbed soils had values close to the average between mound and pit values. Despite generally higher values of sorption complex characteristics, pits showed leaching of the sorption complex, leaching of C and mild clay illuviation up to about 100 years of age. Mounds showed increasing CEC values over time, as well as an increasing proportion of humic acids, with significant changes in the proportions of Fe (and Al, Si) forms. Some soil characteristics had a unimodal time course.

Unlike the natural forest, the managed forest soils had considerably higher contents of the crystalline forms of Fe, Al and Mn, reflecting a more advanced stage of soil formation. However, the different disturbance regimes did not affect the course of clay illuviation, sorption complex leaching, or the content of organic matter.

1. Introduction

Individual windthrows (i.e. a pit and related mound formed by the uprooting of a tree, hereafter referred to as a pit-mound) create microtopography in the terrain of natural forests (Cremeans and Kalisz, 1988). These resulting pit-mounds are ecologically exceptional microsites, with characteristic erosion–sedimentation regimes (Clininton and Baker, 2000). The presence of pit-mounds significantly affects the development of the herb layer as well as tree regeneration, thus influencing subsequent forest generation (Ilisson et al., 2007; von Oheimb et al., 2007). Pit-mounds affect both the development and the spatial variability of decomposer communities, the forest floor and mineral horizons (Schaetzl et al., 1989, 1990; Nachtergale et al., 2002; Phillips and Marion, 2004; Šamonil et al., 2008b, c).

The disturbance of soils resulting from pit-mound formation occurs on a fine spatial scale (on the order of 1–100 m^2). Pit-mounds usually amount to 10–35% of the total area in natural forests (e.g. Habecker et al., 1990; Bockheim, 1997; Ulanova, 2000; Šamonil et al., 2008a, 2010). Their long-term persistence affects processes in the ecosystem for hundreds and even thousands of years (Schaetzl and Follmer, 1990; Bormann et al., 1995; Šamonil et al., 2009). In time horizons on the order of 100–1000 years, pit-mounds affect every

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aspect of forest ecosystems (e.g. Brewer and Merritt, 1978; Karpachevskij et al., 1980; Skvorcova et al., 1983; Bowers, 1987; Vassenev and Targulian, 1995; Šamonil et al., 2009). Phenomena occurring on fine spatial scales can therefore function on coarse scales as well, and pit-mounds can affect whole ecosystem dynamics (Phillips, 2009).

In natural forests, pit-mounds are a natural part of the ecosystem development. However, in managed forests the formation of pit-mounds is mostly controlled by human activity. Hundreds of years of forest management in densely populated central Europe has imposed limitations on the disturbance of soils (trees are cut and are therefore less likely to be uprooted). Therefore, the question arises of how pit-mound dynamics affect soil formation at various spatial scales, and what impact its absence in managed forests has had on the development of soils. Most works so far have focused on the Podzols (Ives et al., 1972; Hole, 1975; Skvorcova et al., 1983; Habecker et al., 1990; Schaetzl and Follmer, 1990; Bormann et al., 1995; Vassenev and Targulian, 1995; Scharenbroch and Bockheim, 2007), and are not readily applicable in the different pedogenetic Cambisol environment. Moreover, results have not always been consistent (e.g. Veneman et al., 1984; Liechty et al., 1997) and authors have struggled with several limitations that considerably narrow the possible generalization of results.

The main such limitations are as follows:

(i) Pit-mound samples are not always representative of the locality;
(ii) Aging of pit-mounds is often absent or only roughly approximated, which prevents studying the course of soil formation;
(iii) The effects of predictors of soil development properties cannot be adequately distinguished nor their significance quantified. The one-dimensional statistical tests often used are not appropriate for the multidimensional character of soil development;
(iv) Some studies include only a limited number of soil characteristics, preventing a complex image of soil formation;
(v) Studies of pit-mounds are often performed on only fine spatial (from 1 to 100 m^2) and time (up to 300–500 years) scales. Results are then hypothetically extrapolated to the ecosystem scale (e.g. Bormann et al., 1995), or only extremely severe disturbances are assessed, in which the effect of soil disturbance on soil formation is masked by significant changes in the light, temperature, hydrology and competitive conditions within the forest stands (Dobson et al., 1990; Kölling and Prietzel, 1995; Nachtergale et al., 2002). The effects of long-term, chronic fine-scale soil disturbances by pit-mounds (Šamonil et al., 2009) on soil formation have not yet been studied on a coarse scale.

In this paper, we attempt to verify the hypothesis that pit-mounds significantly affect the development of soils in a Cambisol zone, at both fine and coarse spatial and time scales. The specific objectives of this study are (i) to assess the course of soil formation on the fine spatial scale of pit-mound microsites, (ii) to assess the significance of the absence of pit-mound dynamics in managed forests at the forest ecosystem scale, and (iii) to apply a methodological concept that would minimize the above mentioned limitations.

2. Materials and methods

2.1. Study area

This study took place in the Razula National Nature Reserve (hereafter Razula) in 2006–2009. Razula, with an area of 23.5 ha, is situated in the Outer Western Carpathians (Fig. 1) on the border between the Czech Republic and Slovakia, and has been under strict protection since 1933. N and NW slopes predominate, with inclinations of about 20°. The bedrock is composed of flysch rocks of the Soláň layer system (Menčík and Tyráček, 1979), i.e. sandstones, claystones and argillaceous shales deposited in thin layers (from centimetres to metres thick). The rocks are mutually finely mixed in the soils and regolith due to geomorphologic processes. There is negligible, if any, *ex situ* material (e.g. eolian dust) present in the soils. Prevailing soils are Haplic Cambisols (Driessen et al., 2001; Michéli et al., 2006), Dystrudepts according to Soil Survey Staff (1999), but weak argillans and/or stagnic properties are also present in some soil profiles. Soils have the following horizon sequence: litter (L, average thickness on undisturbed soils = 17 mm, standard deviation = 7 mm), fermented (F, AM = 24 mm, SD = 12 mm), humic (H, AM = 13 mm, SD = 8 mm), upper mineral (A, AM = 72 mm, SD = 27 mm), Cambic

Fig. 1. Study area in the Western Carpathians, with the Razula National Nature Reserve indicated.