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Geomorphic controls of soil spatial complexity in a primeval mountain forest in the Czech Republic

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ABSTRACT

Soil diversity and complexity is influenced by a variety of factors, and much recent research has been focused on interpreting or modeling complexity based on soil-topography relationships, and effects of biogeomorphic processes. We aimed to (i) describe local soil diversity in one of the oldest forest reserves in Europe, (ii) employ existing graph theory concepts in pedocomplexity calculation and extend them by a novel approach based on hypothesis testing and an index measuring graph sequentiality (the extent to which soils have gradual vs. abrupt variations in underlying soil factors), and (iii) reveal the main sources of pedocomplexity, with a particular focus on geomorphic controls.

A total of 954 soil profiles were described and classified to soil taxonomic units (STU) within a 46 ha area. We analyzed soil diversity using the Shannon index, and soil complexity using a novel graph theory approach. Pairwise tests of observed adjacencies, spectral radius and a newly proposed sequentiality index were used to describe and quantify the complexity of the spatial pattern of STUs. This was then decomposed into the contributions of three soil factor sequences (SFS), (i) degree of weathering and leaching processes, (ii) hydromorphology, and (iii) proportion of rock fragments.

Six Reference Soil Groups and 37 second-level soil units were found. A significant portion of pedocomplexity occurred at distances shorter than the 22 m spacing of neighbouring soil profiles. The spectral radius (an index of complexity) of the pattern of soil spatial adjacency was 14.73, to which the individual SFS accounted for values of 2.0, 8.0 and 3.5, respectively. Significant sequentiality was found for degree of weathering and hydromorphology. Exceptional overall pedocomplexity was particularly caused by enormous spatial variability of soil wetness, representing a crucial soil factor sequence in the primeval forest. Moreover, the soil wetness gradient was partly spatially correlated with the gradient of soil weathering and leaching, suggesting synergistic influences of topography, climate, (hydro)geology and biomechanical and biochemical effects of individual trees. The pattern of stony soils, random in most respects, resulted probably from local geology and quaternary biogeomorphological processes. Thus, while geomorphology is the primary control over a very locally complex soil pattern, microtopography and local disturbances, mostly related to the effects of individual trees, are also critical. Considerable local pedodiversity seems to be an important component of the dynamics of old-growth mixed temperate mountain forests, with implications for decreasing pedodiversity in managed forests and deforested areas.

1. Introduction

Soil complexity in natural ecosystems represents an area of considerable research with potential implications for soil geomorphology, biogeomorphology, pedology, ecology, and evolutionary biology. Surprisingly high local soil variability and diversity revealed recently in some forest ecosystems (e.g. Šamonil et al., 2011, 2014; Valtera et al., 2013; Carpenter et al., 2014) raises questions about soil forming factors that control or influence spatial patterns of soils.

The digital soil mapping paradigm, which relies heavily on soil-topography relationships identified via analysis of digital elevation models, is at least implicitly based on the idea that topography is a major control over soil spatial patterns (e.g., Thompson et al., 2001; Thompson and Kolka, 2005; Smith et al., 2006; Behrens et al., 2010a, 2010b). This control may be direct (the topographic or relief factor in classical pedology, based primarily on gravity-driven moisture and other mass fluxes), or indirect via topographic correlations at a landscape scale with parent geology, microclimate, and ecological habitats. The spatial resolution of topographic data is a key issue in this research, suggesting that if geomorphology has strong influences on soil

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variability at a local scale then more detailed topographic information could be critical if mapping or modeling this local variation is attempted.

Additionally, several soil and regolith studies have shown that highly localized, pedon-scale biogeomorphic impacts may profoundly increase local soil variability, particularly in forests (Crowther, 1987; Phillips and Marion, 2005; Phillips et al., 2005; Šamonil et al., 2008, 2011; Estrada-Medina et al., 2013; Shouse and Phillips, 2016). These effects are often persistent and result in divergent pedogenesis, rather than being commensurate with the time scale of the biotic effects. These studies show that the biomechanical and biochemical effects of individual trees are particularly important with respect to soil morphology and properties likely to result in taxonomic differences.

At the pedon scale, the impact of abiotic factors such as geology or landscape-scale topography (as opposed to microtopography) is stable; these factors change relatively slowly. On the other hand, dynamic factors such as biotic influences generally develop continuously and rapidly (Johnson et al., 1990). Changing soil forming factors acting synergistically often result in non-linear soil formation. Even in case of podzolization, i.e. an extremely strong weathering and leaching process (Buurman, 1984), a regressive component of pedogenesis resulting from change in vegetation (Barrett and Schaetzl, 1998; Nikodem et al., 2013) was observed counteracting the predominant progressive pedogenesis. Because of these multidirectional and usually mutually dependent connections, the idea of a single trajectory of soil development from initial to mature climax soils (Buol et al., 2003) has been gradually replaced by a concept of multiple variant trajectories of soil evolution (Johnson et al., 1990; Huggett, 1998). As a result, spatial soil variability can gradually decrease in convergent evolution, as traditional pedogenetic theory has supposed (Buol et al., 2003), or increase in recently observed divergent soil evolution (Phillips, 2001); both at the landscape (Phillips, 2001; Toomanian et al., 2006; Borujeni et al., 2010) and pedon (Šamonil et al., 2015, 2016) scale. Observed complex pattern of soils described in some recent studies was only partly explainable by variability of topography, geology or climate (e.g. Šamonil et al., 2014) which could be partly in accordance with the concept of deterministic chaos in Earth surface systems (Phillips, 2006), where historical and spatial contingency are among the driving mechanisms.

In a long-term perspective, soils and landforms may both be generally considered in some cases as extended composite phenotypes (Phillips, 2009, 2016a). These systems are not only strongly affected by organisms during evolution, but they also have reciprocal effects on biota, and may be integral components of biotic evolution. Moreover, on macroevolutionary level strong feedbacks were found between Darwinian selection of organisms based on heredity and non-Darwinian organization of soils and landscapes (Corenblit et al., 2011). Quantification of local soil complexity in old-growth forests and revealing the structures of soil forming factors laying behind it are important for deeper understanding of mechanisms of biogeomorphic feedbacks in natural ecosystems. Thus the main aims of this study are: (i) to describe local soil diversity in one of the oldest forest reserves in Europe, (ii) to employ existing graph theory concepts in pedocomplexity quantification and extend them by a novel approach based on hypothesis testing and an index measuring graph sequentiality, and (iii) to determine the main sources of pedocomplexity in (fir)-spruce-beech forest ecosystem.

2. Material and methods

2.1. Study site

The research took place in the Boubínský Prales Reserve (hereinafter Boubin) in the Šumava Mts. in the south-west of the Czech Republic (Fig. 1). As the second oldest forest reserve in the Czech Republic and one of the oldest in Europe (Welzholz and Johann, 2007), the studied core zone of Boubin has been under strict protection since 1858 and has never been cut. The primeval forest occupies north-eastern slopes built of crystalline rocks of the Bohemian Massif, mainly primary schists, biotic and mica-schist gneisses. At an altitude of 930–1110 m a.s.l. the mean annual temperature is 5 °C and mean annual precipitation is about 1300 mm (Tolasz et al., 2007). Main vegetation types of mesic sites are montane acidophilous or nutrient-rich beech forests (*Calamagrostio villosae-Fagetum sylvaticae*, *Mercuriali perennis-Fagetum sylvaticae*) and montane acidophilous spruce forests (*Calamagrostio villosae-Piceetum abietis*). Wet sites are dominated by wet spruce forests usually with high cover of mosses (*Soldanello montanae-Piceetum abietis*; see Šamonil and Vrška, 2008; Chytrý, 2013).

2.2. Data collection and soil diversity evaluation

Soil survey took place on nodes of a grid with a lateral spacing of 22.125 m (distance derived from the National Forest Inventory in the Czech Republic, www.uhul.cz) within the studied 46 ha area. A fourth of these points (grid of 44.25 m) were located geodetically with an accuracy of ca. 0.05 m and marked by steel rods in the soil. This network of

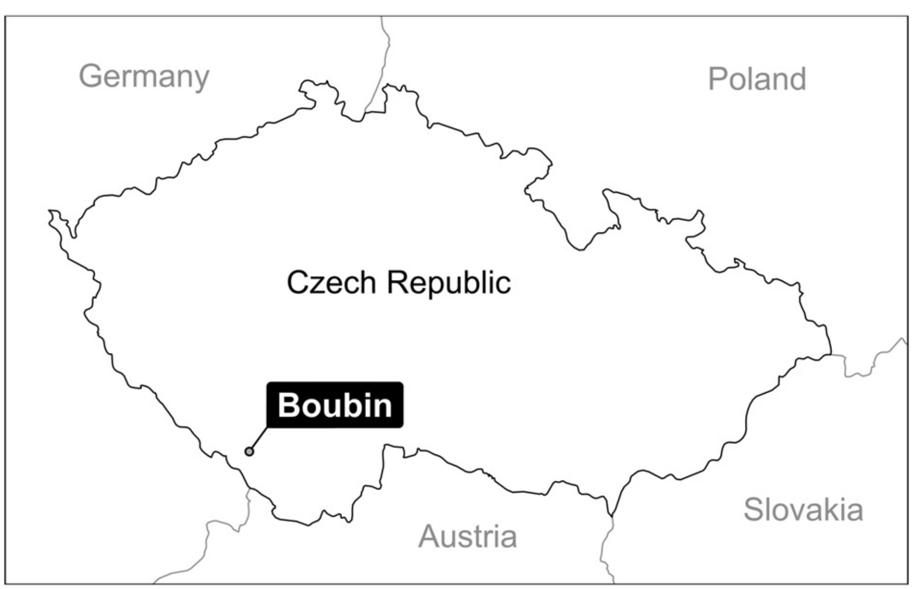

Fig. 1. Map of Central Europe with position of the studied locality.