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Converse pathways of soil evolution caused by tree uprooting: A synthesis from three regions with varying soil formation processes

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ABSTRACT

Post-disturbance pedogenetic pathways were characterized in three landscapes representing different degrees of weathering and leaching. Tree uprooting has been the main form of disturbance in all three landscapes. We hypothesized that the pedogenetic effect of trees due to uprooting is mainly governed by the regional degree of pedogenesis, which in turn affects soil and landscape evolution.

The three regions were characterized by a chronosequence of treethrow pit-mound pairs, from fresh to almost leveled forms. Two sequences originated from the Czech Republic, one on Haplic Cambisols and one on Entic Podzols. The third and the oldest chronosequence, in Michigan, USA, was on Albic Podzols (dating back to 4080 BCE). We analyzed 38 chemical and physical soil properties for 700 samples from 42 pit-mound pairs in these regions. Ordination and regression techniques allowed us to evaluate the effect of sample depth, microsite (pit, mound, and undisturbed control position), and age of the soils formed after uprooting.

Depth was the most significant variable in all regions ($p < 0.001$), followed by microsite location, and then age (time since disturbance). The significance of these variables decreased with increasing weathering and leaching intensity. The results suggest that intense pedogenesis, as at the Michigan site, decreases the polygenetic impacts of uprooting on soil development pathways. On Haplic Cambisols, disturbances increased the local variability of pedogenic processes by changing melanization and hydromorphic processes, as well as by mineral alteration. Conversely, on Albic Podzols, we found comparative chemical uniformity in post-uprooting pedogenesis between microsites, despite rapid podzolization in pits and slower podzolization on mounds. The general chemical convergence of pedogenesis in these landscapes towards vertically-dominated podzolization may limit divergence of pedogenic pathways after a disturbance. The formation and translocation of labile organic matter-sesquioxide complexes in the uppermost podzolic horizons in Entic Podzolś was a key threshold, in that it changed the pedochemical, ecological and biogeomorphic role of the treethrow features in the soil and landscape evolution. Although treethrow pits were accumulation sites for soil elements in Haplic Cambisols and Entic Podzols, they were microsites of intense leaching and elemental loss in Albic Podzols.

1. Introduction

Tree uprooting is the most evident and significant biogeomorphic disturbance agent in many forest soils (Fig. 1, Schaetzl et al., 1989; Phillips and Marion, 2006; Pawlik et al., 2016a). For example, in temperate, central European, primeval forests approximately 30% of all trees die as a result of uprooting, and theoretically, within 500–3000 years every site in such forests is likely to be disturbed by uprooting (e.g., Skvorcova et al., 1983). So-called rotation periods, showing how often an area equivalent to an entire area is disturbed (Pickett and White, 1985), are comparable or even shorter in other temperate or boreal forests (review by Šamonil et al., 2010a).

From a general theoretical perspective, biomechanical soil disturbances are an important source of the kind of local, transient changes that are usually associated with deterministic chaos. A self-organizing, chaotic, and unpredictable mode of soil behavior may be a substantial component of the usually-assumed non-chaotic mode (Walker et al., 2010; Phillips, 2013c). Both chaotic and non-chaotic modes contribute soil evolution on all scales, but their individual effects are little known. Focusing on non-chaotic soil behavior in experiments,

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Fig. 1. An extremely large, complex root plate formed by uprooting on Entic Podzols during the Kyrill storm in Zofin, Czech Republic, in 2007. Tape represents 1 m. Photo by Pavel Šamonil.

mathematical models and interpretations can result in simplifications or even false results in soil and biogeomorphic studies (see Peckham, 2009). The predominance of a self-organizing component in the evolution of a soil landscape leading to divergent evolution is the most evident such example (Phillips, 1993), which represents a converse direction and an important alternative to the traditionally-assumed convergent evolution (see Phillips, 2001). Although differences in initial conditions and local perturbations are gradually smoothed in convergent evolution, leading to decreased soil spatial variability, differences nonetheless persist and can even increase, producing a more variable soil cover; this is one example of divergent soil evolution. In any case, when pedogenesis is dynamically unstable and chaotic, the effects of small disturbances such as those associated with pedologic influences of individual trees become exaggerated over time (Phillips, 2000, 2013a, 2013b; Toomanian et al., 2006; Milan et al., 2009; Borujeni et al., 2010; Phillips and Van Dyke, 2016). Using pedomorphology data, Šamonil et al. (2015) found possible divergent soil evolution after tree uprooting in Albic Podzols, wheres other soil units expressed different post-disturbance evolutionary pathways. These findings suggest a regionally-specific role of tree uprooting in pedogenesis, although the direction of post-uprooting erosion-sedimentation processes and the specifics of microclimate within treethrow pits and mounds seem to be universal (the mound is generally drier, has a higher radiation balance and a wider amplitude of temperature with comparison to the pit, see Beatty and Stone, 1986). However, such pedomorphic results only minimally inform us about complex soil formation processes, and need to be validated by pedochemical analyses. Datasets from different soil regions can fundamentally help improve still-unsupported theoretical derivations regarding the switching of soil behavior modes on pedon scales, the role of deterministic chaos, and the directions of post-disturbance evolutionary trajectories in soils.

Most of the case studies on uprooting so far have focused on Spodosols, and most of the research has been on single sites in the US, Canada and Russia (Skvorcova and Ulanova, 1977; Schaetzl, 1990; Small et al., 1990; Bormann et al., 1995; Kramer et al., 2004). Only few such studies are truly comparative, using pedochemical data from different soil regions (Skvorcova et al., 1983; Vassenev and Targulian, 1995). Nonetheless, these studies suffer from a relatively low amount of data and inaccurate (or lack of) dating of uprooting events. These geographical and methodological limitations fundamentally reduce our ability to study post-disturbance pedogenetical pathways and do little to help derive conceptual generalities regarding the effect of uprooting disturbances on pedogenesis and eco-evolution dynamics (Corenblit et al., 2011; Pawlik et al., 2016b). Here, we focus on this still unsolved issue and compare the pedogenetic impacts of uprooting on dated chronosequences from multiple landscapes.

Our primary hypothesis is that trees do not affect pedogenesis through uprooting in a universal way, but rather various or even opposing post-disturbance evolutionary trajectories can arise, depending on the intensity of regional soil evolution processes. This hypothetically causes regionally-specific feedbacks in the tree-soil coevolution system (see Šamonil et al., 2014). The specific purposes of this study are to evaluate the effects of sample depth, microsite (pit, mound, and undisturbed control position), and age of soils since tree uprooting in three different soil regions. Using these data, we aim to build a general conceptual model of post-uprooting pedogenetical pathways. This model is made possible by existing tree uprooting research performed in three soil regions, where since 2006 (regions of Haplic Cambisols, Entic Podzols and Albic Podzols) we precisely dated a number of uprooting events (Šamonil et al., 2009, 2013), studied the formation of the forest floor on treethrow microsites (Šamonil et al., 2008a, 2008b), and assessed pedomorphic (Šamonil et al., 2015), biogemorphic (Šamonil et al., 2016; Phillips et al., 2017), and limited pedochemical processes (standard laboratory extract methods used solely on Haplic Cambisols by Šamonil et al., 2010b in studies of post-uprooting pedogenesiswere deepen using voltammetry of microparticles and diffuse reflectance spectroscopy by Tejnecký et al. (2015). These modern methods allowed us to develop a much deeper understanding of composition of mixed chemical extracts of Al, Fe, Si, and Mn).

2. Materials and methods

2.1. Study sites

Our three soil regions are in the Czech Republic (CR)–the Razula and Zofin forest reserves–and the Upper Peninsula of Michigan, USA (Fig. 2 and Table 1). The regions all have humid climates, and together they roughly span a gradient of texture and intensity of pedogenesis (see von Zezschseitz et al., 1973), with (1) strongly weathered, leached and acidic Albic Podzols on pure sandy outwash in Michigan (2) intermediate severity of podzolization, including clay destruction, on acidic Entic Podzols on loamy sand granite residuum at Zofin, and (3) clay formation without its destruction on Haplic Cambisols (Michéli et al., 2007) on loam or clay-loam flysch residuum at Razula (Fig. 3; Table 1) Precipitation decreases along this gradient. Mean slope inclination ranges from 8° (Zofin) to 19° (Razula). All forests are