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Ghosts of the forest: Mapping pedomemory to guide forest restoration

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ABSTRACT

Soil morphology can provide insight into how ecosystems change following periods of extensive disturbance. Soils properties can often be linked to historic environmental influences (e.g., vegetation or climate) to provide a record of pedomemory. Identification and mapping of soil pedomemory properties show promise in providing context for ecological restoration. We have developed a novel use of digital soil mapping of spodic morphology to estimate historical forest composition in the high-elevation forests of the Central Appalachians. This region was extensively disturbed by clear-cut harvests and related fires during the 1880s–1930s. Hardwood forest species recovered much better than local conifers and generally encroached into historic populations of red spruce (*Picea rubens*) and eastern hemlock (*Tsuga canadensis*). Spodic soil morphology, which is often associated with subalpine and boreal conifer forests, was mapped using a random forest probability model and showed correspondence to red spruce — eastern hemlock distribution, as derived from local historic property deed witness tree records from 1752 to 1899. These data and resulting models indicate a greater spatial extent of spodic soil properties than documented in previous soil maps, which is more consistent with general theories of much more extensive historic spruce populations. The resulting maps and models provide guidance for field scale restoration planning for historically disturbed spruce–hemlock forests. Our results suggest that historic Euro-American disturbance probably induced conifer-to-hardwood state transitions at mid to high elevation coniferous ecological sites within the Appalachians. Where transitions have occurred, there appears to have been dramatic losses in forest floor thickness (O-horizons) and associated soil organic carbon stocks into atmospheric carbon pools. Spatial modeling of similar pedomemory properties and other soil-ecology linkages is likely to be a powerful tool to guide restoration in other regions as well.

1. Introduction

1.1. Soil pathways and pedomemory

Soil properties can help reveal the history of interactions between abiotic and biotic drivers at the Earth's surface. In soil science, this has been conceptualized as a state factor model where the state or properties of a soil are a result of interactions between climate, organisms, relief, and parent material over time (clorpt) (Dokuchaev, 1999; Jenny, 1941). The state factor model evolved to an ecosystem level model where soils and organisms have some parallel drivers, but also interact strongly (Amundson and Jenny, 1997; Jenny, 1961, 1980). Eq. (1) reformats Jenny (1941) 'clorpt' model into an ecological equation where different groups of the original soil forming factors interact over time to result in a set of ecosystem properties (including soil) at a given point in time.

$$l,\ s,\ v,\ a\ =\ f(L_0,\ P_x,\ t) \tag{1}$$

Ecological factorial; Jenny (1961).

The dependent factors in this case include ecosystem properties (l), soil properties (s), vegetation (v), and animals (a). The related state factors in an ecosystem based approach include the initial state (L_0) and external potentials (P_x), and time (t). Initial state L_0 includes the parent material (bedrock or substrate), initial relief, and water table. Climate and organism changes are grouped as the P_x variable, which represent the primary energy sources (sun), receptors (plants), and catalysts (e.g., water) that drive processes (Jenny, 1961). Amundson and Jenny (1991, 1997) have introduced these conceptual models into ecological sciences, with humans included in the factorial equation. In an ecosystem, soils bear the imprint and help record the history of organisms – including humans – as well as the climate. For conceptual

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and measurement purposes, we define an ecosystem as the living organisms and physical environment of a defined unit space or a plot (e.g., 20 × 20 m) that we can sample in the field.

Climatic and biological factors drive processes in soils that involve additions, removals, translocations, and transformations (Simonson, 1959) of materials in the soil column that have associated energies (Nikiforoff, 1959; Runge, 1973). When environmental drivers remain relatively constant over a period of time they can direct a soil down a developmental pathway toward expressions of specific horizonation (Johnson and Watson-Stegner, 1987). Changes in climate and/or organisms can alter the balance of processes and thus the pathway of a soil. At any one time, many processes are occurring in a soil, which can create complicated superimposed distributions of soil properties within a soil profile (Burrough, 1983).

The properties observed in soils reflect a record of information, often called soil memory or pedomemory, where the specific patterns of reorganization and transformation of the original soil parent material into new physical and chemical distributions in the soil profile can often be attributed to how historic climate and vegetation promote soil processes that result in a specific morphology (Hole, 1975; Lin, 2011; Targulian and Goryachkin, 2004). Related studies have linked mottling, iron chemistry, and other morphology to historic soil–water–landscape models (Coventry et al., 1983; Coventry and Williams, 1984; Fritsch and Fitzpatrick, 1994; Schwertmann, 1988). Others have found that vegetation communities interact with the soil over time to create soil property signatures recorded in the pedomemory useful in determining a site history (Hole, 1975; Phillips and Marion, 2004; Willis et al., 1997). Thus, a soil property like spodic materials can potentially provide a time–space record that can help decipher historic ecosystem vegetative reference conditions, which are an accepted basis for ecological restoration to a certain target community type and condition (Higgs et al., 2014; SER, 2004; http://www.ser.org/resources/resources-detail-view/ser-international-primer-on-ecological-restoration). Linking soil types with historic reference communities has become the basis for land management frameworks such as ecological site descriptions (ESD) (Caudle et al., 2013; USDA-NRCS, 2014). We aim to show how mapping key pedomemory properties linked to vegetative communities can inform restoration at a field ecosystem scale. We demonstrate this using an example along the ecologically important transition between northern hardwood and spruce–hemlock forest types in the Central Appalachian mountains of the eastern US (Byers et al., 2010).

For distinguishing the historic transition between northern hardwood and spruce–hemlock, we chose the podzolization pathway (Lundström et al., 2000a,b; Sauer et al., 2007; Schaetzl and Harris, 2011) as our pedomemory indicator because of its association with similar moist conifer forest and heathland species composition globally (Hole, 1975; Miles, 1985; Willis et al., 1997; Lundström et al., 2000a; Sauer et al., 2007). In a typical cool, moist conifer site where Spodosols form as a result of podzolization, the soil morphology generally is a sequence of Oi–Oe–Oa surface horizons forming a mor forest floor, then a leached E horizon, and a sequence of Bh–Bhs–Bs–BC subsurface horizons (Fig. 1) (Soil Survey Staff, 1999; Soil Survey Staff, 2010). The podzolization pathway includes multiple soil processes that promote aluminum, iron, and organic matter mobilization and translocation to deeper soil depths in acidic, permeable parent materials. Thick surface O horizons also frequently form at the soil surface in these typically moist conifer systems (Hix and Barnes, 1984; Lietzke and McGuire, 1987; Lundström et al., 2000a). Leaching is usually associated with soluble organic acids from the forest floor and actively mining ectomycorrhizal communities causing mineral weathering and the ultimate transport of aluminum, iron, and organic matter from near surface soil horizons (O, A, E) into subsurface (B) soil horizons (Blum et al., 2002; Giesler et al., 2000; Hoffland et al., 2004; Jongmans et al., 1997; Lundström et al., 2000b; Schaetzl and Harris, 2011; Schöll et al., 2008; van Breemen et al., 2000).

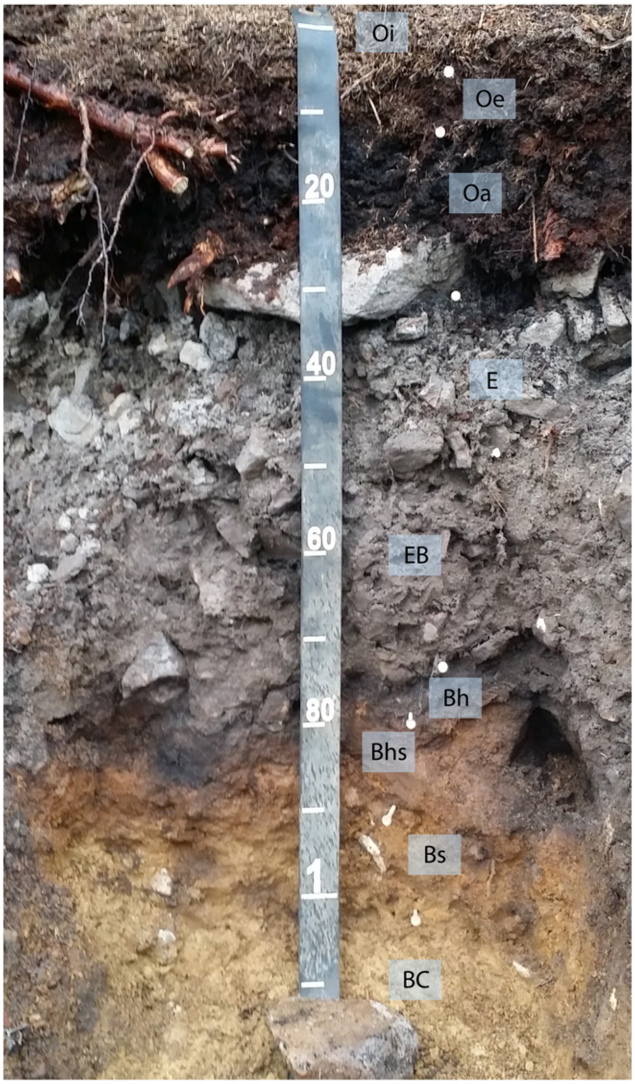

Fig. 1. Well expressed podzol soil morphology in a red spruce forest in WV.

Much of the organic carbon distribution in Spodosols can be lost in 30–100 years just by converting cool, moist acidic conifer forest stands to differing species compositions (prairie or hardwood) that favor more decomposition (Barrett and Schaetzl, 1998; Hix and Barnes, 1984; Hole, 1975; Miles, 1985). The most pronounced losses in organic carbon occur in the forest floor O horizons, which generally get thinner in conversions. Conversely, studies have also demonstrated that conversion from mesic hardwood forests (mostly *Quercus* spp., *Betula* spp., and *Fagus* spp.) to Norway spruce (*Picea abies*) and/or scots pine (*Pinus sylvestris*) initiates O horizon buildup and podzolization within a century (Herbauts and Buyl, 1981; Miles, 1985; Ranger and Nys, 1994; Sohet et al., 1988). Common garden experiments studying replanted monoculture plots of various tree species have also documented tree species gradients of influence on soil organic matter accumulation and acidity. On the two extremes, *Acer* spp. and *Tilia* spp. promote increased base cation activity which favors heterotrophic organic matter decomposition, whereas *Pinus* spp. and *Larix decidua* enhance acidic Al and Fe activity which limit decomposition of soil organic matter (Hobbie et al., 2007). Garden experiments also showed higher tree litter calcium content appeared to increase pH, decomposition, and earthworm activity that resulted in less forest floor mass (Reich et al., 2005; Hobbie et al., 2006). Hobbie et al. (2006) also recorded that plots with spruce and fir species had lower mean annual soil temperatures and less litter decomposition. Although general differences in litter