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Temporal variation in the strength of podzolization as indicated by lysimeter data

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ABSTRACT

This study examines trends in podzolization – both temporally and with depth – as indicated by translocation of dissolved organic carbon (DOC), iron (Fe) and aluminum (Al) in soil water. Water as saturated flow was captured by zero-tension lysimeters installed below the O, E and B horizons of six Spodosol pedons in Michigan, USA. Over a 2-year timespan, we sampled soil water on 36 different dates, resulting in 505 samples. All samples were analyzed for DOC, whereas Fe and Al contents were determined for a subset of 227 samples.

Cumulative water fluxes are high during both spring snowmelt and the fall (autumn) season, when much water is moving as saturated flow. Water flux *rates* are much greater during snowmelt, and when averaged over all horizons, 1.15 times more water is translocated through the soil during snowmelt than in fall, even though the latter is routinely twice as long. Translocation of DOC out of the O horizon is a dominant process in these soils during snowmelt, peaking in mid-snowmelt. It peaks again – even higher – in fall, as rains strip C from fresh litter. Overall, little DOC leaves the soil system; B horizons are effective traps for C being transported in soil water. Surprisingly, E horizons retain DOC in almost all seasons, but particularly in fall and early snowmelt, as water percolates through C-rich, fresh litter. The thick, bright, C-poor E horizons in these soils suggest that, over long timescales, in situ mineralization of C exceeds the net retention of DOC from the O horizons above. Translocation of Fe and Al in soil water also has a distinct annual bimodality, largely following that of DOC. This component of podzolization peaks in mid-snowmelt and again late in fall. On an annual basis, considerably more Al moves in soil water than Fe; 1.9 times more Al than Fe is translocated out of E horizons, and 1.8 times more Al is lost from B horizons. Our study supports existing pedogenic theory for the snowy midlatitudes, in which snowmelt is seen as a key period for podzolization. Daily rates of translocation of metals and DOC moving in saturated flow during snowmelt are considerably higher than for any other time of year. Our study also sheds new light on the importance of fall rains to podzolization. Although the daily rates of translocation for fall are much less than during snowmelt, the greater length of the season, the relatively high frequency of rain events, and the abundance of fresh C combine to make fall an important period for translocation of metals and DOC. Thus, our study highlights that podzolization here has a short but intense "pulse" during snowmelt, and a second, less intense but longer period during fall. Little podzolization occurs during winter, and during summer, translocation occurs only during infrequent, large storms.

1. Introduction

During podzolization, soluble organic materials and Al^{3+} cations, often in association with Fe^{3+} cations, are translocated from the upper profile, forming a distinct eluvial zone, to a lower, illuvial horizon (Petersen, 1976; DeConinck, 1980; Buurman and van Reeuwijk, 1984; Courchesne and Hendershot, 1997; Lundström et al., 2000; Schaetzl and Harris, 2011). The process is best exemplified in coarse-textured soils that have formed under vegetation that produces acidic litter, capable of releasing large quantities of soluble organic materials during decomposition (Van Breeman and Buurman, 1998; Schaetzl, 2002). Coarse-textured soils, when they occur in areas of cool, humid climate, also facilitate deep wetting and percolation, which enable the translocation of these soluble compounds to the lower profile. Acidic litter, such as is commonly found under vegetation like heath and coniferous forest, not only decomposes to produce large amounts of soluble organic compounds, but many of these compounds are able to complex free Fe and Al released from primary minerals by weathering (van Hees et al., 2000). This chemical process of complexation, or chelation, renders these cations soluble and available for translocation. Percolating water can then translocate these compounds to the lower profile. Research has shown that up to 80–85% of the soluble Al in E horizons of Spodosols is bound in organic complexes of this type (Petersen, 1976; Lundström,

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1993). Under ideal conditions, an acidic E horizon is formed quickly; it is impoverished in Al, organic matter and usually Fe (Franzmeier and Whiteside, 1963; Barrett and Schaetzl, 1992; Sauer et al., 2008). Below, a reddish brown to black B horizon, enriched in metals and organic matter, develops. If it becomes sufficiently enriched in these types of "spodic materials" (Soil Survey Staff, 2010), it can meet the criteria for a spodic horizon and the soil classifies as a Spodosol (or Podzol).

Podzolization and podzolic soils continue to be the focus of much research (Lundström et al., 2000; van Hees et al., 2000; Sauer et al., 2007). Such studies have traditionally used any of three different methodological approaches:

(1) Examination of podzolic soil morphologies. Because there are usually few mechanisms by which Spodosol morphologies, once formed, can get degraded, e.g., pedoturbation or erosion, contemporary soil morphologies are good indicators of the long-term strength of podzolization, the length of time that podzolization has been operative, or both (Jauhiainen, 1973; Barrett and Schaetzl, 1992; Schaetzl, 2002). This relationship is so reliable that numerical indexes have even been developed that quantify Spodosol morphology; these can be correlated to podzolization strength and/or longevity (Duchaufour and Souchier, 1978; Schaetzl and Mokma, 1988).
(2) Examination of the liquid extracts derived from solid phase soil samples. These extracts are formulated to remove the grain coatings, which assumedly capture the long-term record of illuviation (in the B horizon), or the degree to which the E horizon has been leached of potentially translocatable materials. To do this, soil samples, usually from the E and B horizons, are exposed to a chemical extractant, and the extract is then analyzed for Fe, Al, and/or Si; such data are then used to determine the amount of soil development. Three different kinds of extractants have traditionally been used to extract metal and Si cations in spodic soils (Schnitzer et al., 1958; McKeague and Day, 1966; McKeague et al., 1971; Petersen, 1976; Olsson and Melkerud, 1989; Skjemstad et al., 1992): (i) amorphous, poorly crystalline, and crystalline (commonly referred to as free) forms of Fe and Al oxides, are extracted using a sodium citrate-dithionite solution (Mehra and Jackson, 1960; Holmgren, 1967), (ii) organically bound forms of Fe and Al, normally referred to as organometallic complexes, are extracted using sodium pyrophosphate (McKeague, 1967; Bascomb, 1968; Higashi et al., 1981), and (iii) in poorly crystalline minerals such as ferrihydrite, allophane, and imogolite (known as imogolite-type materials, or ITM) plus organically complexed Fe and Al are extracted using acidified ammonium oxalate (Schwertmann, 1973; Daly, 1982; Kodama and Wang, 1989; Wilson et al., 1996). Ratios and mathematical differences of these kinds of data are often used to interpret the strength of podzolization and to infer more about the process itself (Schaetzl and Thompson, 2015).
(3) Examination of soil solutions, as captured by zero-tension or suction lysimeters (Holzhey et al., 1975; Ugolini et al., 1977a, 1977b; Herbauts, 1980; Litaor, 1988; Shepard et al., 1990). This method is particularly useful for the study of podzolization, because (1) most of what is being translocated is moved in solution, and (2) the process is sufficiently rapid that individual percolation events can produce measureable data. Metals and organic materials from soil water captured in lysimeters provide an instantaneous picture of the podzolization process, albeit for a single pedon. And the data can be isolated on a per-horizon basis. Longer-term data from lysimeter water can, therefore, provide an excellent picture of the kinds and amounts of soluble materials moving in the soil during podzolization, at different times of the year, for individual horizons, and under different pedogenic circumstances (Ugolini et al., 1977a, 1977b; Ugolini and Dahlgren, 1987; Ugolini et al., 1988; Brahy et al., 2000; Mossin et al., 2001).

In a companion paper, Schaetzl et al. (2015) reported on the timing and magnitude of percolation events in Spodosols at our study sites, using lysimeter data on water volumes to inform a hydrologic model. They observed that these soils are usually dry during the summer, when almost no deep percolation takes place, and slowly wet up in autumn. Although not empirically examined, they suggested that the autumn "wet-up" facilitates decomposition of fresh litter, liberating soluble organic materials for potential translocation. The soil-climate system here effectively stores winter precipitation in a thick snowpack, releasing this water rapidly during snowmelt (Schaetzl and Isard, 1991, 1996; Teoharov, 2002). Translocation of organic materials generated in autumn and winter in the O horizon is therefore most pronounced during snowmelt, during which they are driven by steady, cold, percolating water to the lower profile (Rothstein et al., under review).

The above research generated a number of additional questions about the seasonal dynamics of the podzolization process in the mid- and high latitudes. For example, we asked when the translocation of metal cations and soluble organic materials was most pronounced, what drives the process, and what may be the limiting thresholds and factors to podzolization during these periods of deep translocation? To answer these questions, we adopted all three approaches to podzolization discussed above. We examined static data on soil morphology for six Spodosol pedons to determine the amount and type of spodic development that is typical for the study area. Data from chemical extracts were used to add detail to the picture of soil development. Our main focus, however, was on the chemistry of soil water captured from these soils, as a way to assess the temporal (and seasonal) variations in the strength and character of podzolization. As such, this work — with its two full years of soil water data, often collected at short temporal intervals, and within strongly developed Spodosols, represents a comprehensive and direct study of podzolization.

2. Materials and methods

2.1. Study area and sites

Our six study sites are in Michigan's (USA) Upper Peninsula, about 37 km east of Newberry (Fig. 1). Here, Spodosols may be better developed than anywhere else in the Great Lakes region (Schaetzl et al., 2015). Presently, the region is forested, either in mixed hardwoods or red pine (*Pinus resinosa*) plantations. Reconstructed, presettlement vegetation records from the General Land Office (GLO) survey notes indicated that this area was forested with beech (*Fagus grandifolia*) – sugar maple (*Acer saccharum*) – hemlock (*Tsuga canadensis*) – yellow birch (*Betula allegheniensis*) forest (Comer et al., 1995) in the mid-19th century. Areas currently under pine plantation were replanted in the 1930s, following severe post-logging fires.

The climate here is cool and humid, with a frigid soil temperature regime and a udic-aquic soil moisture regime (Soil Survey Staff, 2010). The National Weather Service (NWS) station at Newberry reports an average of 812 mm of annual precipitation and a mean annual temperature of 4.7 °C. The area lies within a Lake Superior snowbelt, with Newberry receiving an annual average of 255 cm of snowfall (Schaetzl et al., 2015). Snowmelt generally begins in March or early April and continues until about the beginning of May. In some years, snowpacks can be quite thick and snowmelt can be rapid. Nonetheless, because the sandy soils remain largely unfrozen under the thick snowpacks, runoff is minimal.

Soils here are sandy Haplorthods and Durorthods with thick, bright E horizons and with varying amounts of ortstein in the spodic horizons below (Figs. 1, 2). Tongueing of the B horizon suggests that preferential flow is common. Water tables are deep, such that soil water can