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Influence of landscape position and transient water table on soil development and carbon distribution in a steep, headwater catchment

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ABSTRACT

Upland headwater catchments, such as those in the Appalachian Mountain region, are typified by coarse textured soils, flashy hydrologic response, and low baseflow of streams, suggesting well drained soils and minimal groundwater storage. Model formulations of soil genesis, nutrient cycling, critical loads and rainfall/runoff response are typically based on vertical percolation, development of soil horizons parallel to the land surface, mineral weathering inputs limited to the rooting zone and drainage from lumped catchment reservoirs (e.g., the subsoil) as the dominant source of stream flow. However, detailed study of the hydrologic reference catchment at Hubbard Brook Experimental Forest, NH, USA shows striking spatial patterns of soil development that reflect the influence of transient water tables within the solum in nearly all landscape positions. Shallow bedrock and variably low hydraulic conductivity in the subsoil promote lateral flow and development of soil horizons along hillslope flowpaths rather than in vertical profiles. We distinguished several morphologic units based on the presence of diagnostic horizons indicative of differing patterns of podzolization and carbon storage. The distribution of soils appears to be highly dependent on local drainability and frequency and duration of transient saturation within the solum. As such, monitoring of hydropedologic groups and transient water table fluctuations may prove to be a sentinel for the effects of climate change on spatial distribution of soils and retention/release of solutes from upland catchments.

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1. Introduction

Headwater streams are an important source of freshwater and other resources. Across the United States, they comprise about 50% of the stream length, defined as first order streams shown on 1:100,000 maps, and an even higher percentage in the humid, eastern portion of the country (Nadeau and Rains, 2007). If one considers that large portions of perennial first order streams are not shown on even more detailed 1:24,000 maps, the proportion of stream length represented by headwaters is likely to be vastly greater (Bishop et al., 2008). In essence, headwaters act as a reactive interface between terrestrial and aquatic ecosystems (Fisher et al., 2004; Lowe and Likens, 2005). This critical role in ecosystem function, as well as relative simplicity in conducting mass balance studies, is reflected by the prominence of headwater catchment investigations as cornerstones in hydrological, biogeochemical and ecosystem research (Likens et al., 1977; McGuire and Likens, 2011; Swank and Crossley, 1988).

As well studied as headwater catchments are, investigations from hydrological and biogeochemical perspectives are often not integrated and inadequately address internal spatial variation and context of study units within a landscape (Burt and Pinay, 2005; Lohse et al., 2009). Biogeochemical investigations are commonly conducted at the plot or small catchment scale, where point measurements are integrated to form a single picture without consideration of spatial differences or functional connections between landscape components (Turner, 1989). In contrast, hydrologic investigations are commonly organized along flowpaths or hillslopes, emphasizing the connections and translocation of water and materials between landscape elements (Ali and Roy, 2009), but do not as thoroughly consider cycling within soil or biologic systems at single points. Troch et al. (2008) argued that new hydrologic theory needs to embrace landscape heterogeneity and quantify mechanisms connecting soil and landscape evolution and hydrologic processes. To do so, we may be well served by revisiting our understanding of spatial patterns of soil variation and processes leading to soil development in headwater catchments, thus moving toward a functional, spatially explicit depiction (Schulz et al., 2006).

Lateral development of podzols has been recognized in a variety of settings, including soils developed in periglacial granitic debris in the

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German Alps (Sommer et al., 2000) and in sand dunes in northern Poland (Jankowski, 2014), although this concept has not been as well explored in North America. The role of hydrologic transport in translocation between catena elements has been recognized (Sommer, 2006) although explicit hydrologic monitoring has not yet been incorporated in studies of lateral soil development. It is important to recognize the role that hydrologic connection plays in sustaining or developing spatial patterns of soil variation and biogeochemical processes (Lin, 2011). Connected portions of the catchment could play a substantial role in biogeochemical processing (e.g., reaction rates) and export of material and thus disproportionally affect catchment export.

For example, the headwater catchments of the Hubbard Brook Experimental Forest (HBEF) in central New Hampshire, USA, have been characterized as steep, averaging 25% slope, with well drained, coarse textured Spodosols (Likens, 2013; Likens et al., 1977). Soils are typical of glaciated uplands in the northeastern US, with a catena of Lyman–Tunbridge–Becket Series, well drained Spodosols of increasing depth from bedrock dominated ridges to lower slopes with thicker glacial drift (Homer, 1999; Huntington et al., 1988). Streams are mostly perennial at gauged locations, although none of the gauged streams are shown on 1:100,000 USGS maps, and are characterized by low baseflow and fast response to precipitation inputs (A.S. Bailey et al., 2003). Groundwater has not been considered to play an important role in these streams (Likens, 2013; Likens and Buso, 2006), consistent with well drained soils formed in relatively shallow glacial till and flashy hydrologic response, suggesting minimal subsurface storage. However, with enhanced monitoring capabilities afforded by advances in relatively inexpensive water level recorders, Detty and McGuire (2010a) were able to amass a temporally and spatially rich dataset of shallow water table dynamics in a headwater catchment, Watershed 3 (WS3). They showed that shallow groundwater development is topographically controlled, occurring in some landscape positions throughout the year. This raises the possibility that soils may not be well drained throughout the watershed, and that soil development might be influenced by variable hydrologic regimes in different landscape positions. Further, it raises the question of whether a vertical flow model of inputs at the soil surface and outputs with drainage through the base of the soil profile, typically assumed by biogeochemical mass balance models (Belyazid et al., 2010; Gbondo-Tugbawa et al., 2001), and used in formulations such as critical loads modeling (Løkke et al., 1996; McNulty et al., 2007) is applicable in steep headwater catchments such as those at HBEF, typical of uplands across the northeastern USA. A predominance of lateral flows (downslope, roughly parallel with the land surface) in these ecosystems would suggest different translocation, leaching, and accumulation mechanisms that promote spatially organized processes ultimately providing hydrological and biogeochemical signatures at the catchment scale as flowpaths aggregate.

The purpose of our study was to document variation in soil morphology at locations chosen to represent the range of landscape positions across a catchment. Soil observations were distributed across the range of landforms present, and oriented along hillslope transects to evaluate possible hydrologic controls on soil development. At a subset of soil sampling sites, water level recorders were installed to determine relationships between water table fluctuation and soil morphology. With this approach, we propose a hydropedological functional classification of soil units, with application for understanding biogeochemical processes within spatially distinct and connected portions of the catchment.

2. Methods

Hubbard Brook Experimental Forest is within the southern White Mountains of central New Hampshire, USA (43°56′N, 71°45′W). The climate is humid continental with average annual precipitation of 140 cm and 90 cm of runoff (A.S. Bailey et al., 2003). Bedrock is sillimanite-grade pelitic schist and calc-silicate granulite of the Silurian Rangeley Formation. The retreat of the late Wisconsinan glacier about 14,000 years ago left a mantle of sandy loam glacial till composed of a relatively uniform mixture of granitic, metasedimentary, and metavolcanic lithologies in the till across this portion of HBEF (S.W. Bailey et al., 2003). Soils have previously been characterized as well drained Haplorthods with 0.5 m average solum thickness (to the base of the B horizon; Likens et al., 1977). Vegetation is dominated by northern hardwood forest composed of *Acer saccharum* Marsh. (sugar maple), *Betula alleghaniensis* Britt. (yellow birch) and *Fagus grandifolia* Ehrh. (American beech). Shallow-to-bedrock soils are vegetated with conifer-dominated stands composed of *Picea rubens* Sarg. (red spruce), *Abies balsamea* (L.) Mill. (balsam fir), and *Betula cordifolia* Regel (mountain white birch). The forest was selectively harvested from 1880 to 1920 and damaged by a hurricane in 1938 and is not aggrading (Siccama et al., 2007).

This study focused on WS3 (Fig. 1), a 42 ha reference catchment, which has been a center for hillslope hydrology studies (Cedarholm, 1994; Detty and McGuire, 2010a, 2010b; Hooper and Shoemaker, 1986; Rosenthal, 1986). A stratified sampling technique was used to evaluate soil variation at a range of scales within the watershed. Soil sampling sites were established along hillslopes above the stream in areas of the catchment with varying stream network patterns, including the western portion with parallel tributaries, the central portion with a dendritic channel pattern, and the eastern portion with minimal surface channel development (Detty and McGuire, 2010a). In addition to transects, some single or paired sampling sites were located at sites of varying hillslope position and curvature to capture the range of surface topography observed in the catchment. Each group of sampling sites was designated by a letter and had 2–7 numbered sampled pedons,

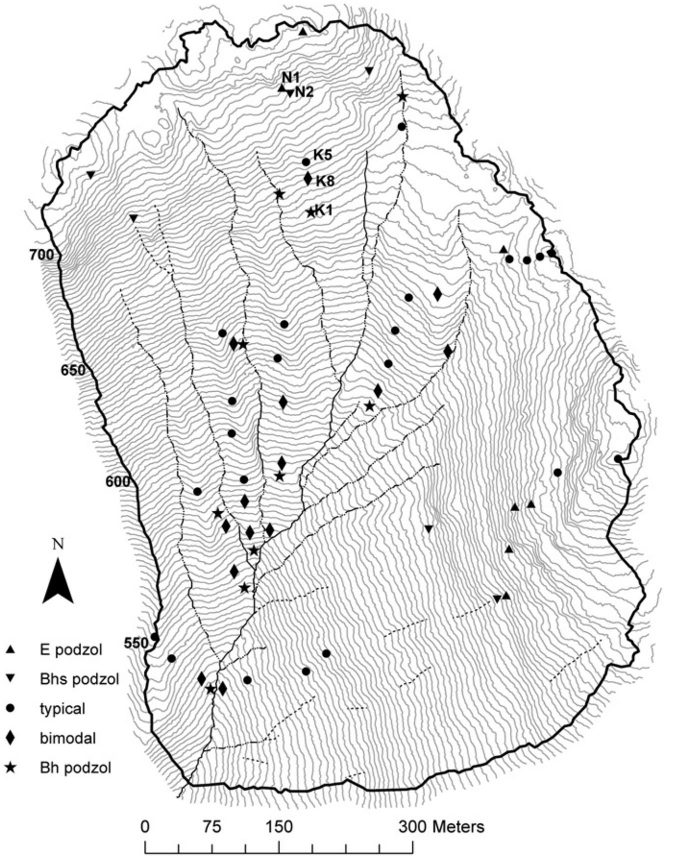

Fig. 1. Topographic map of Watershed 3. Contour interval is 2 m, with 50 m contours labeled. Soil sampling sites are shown by symbols representing soil groups, including (1) E podzol, (2) Bhs podzol, (3) typical podzol, (4) bimodal podzol, and (5) Bh podzol. Sampling locations featured in Figs. 4 and 5 are labeled.