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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,

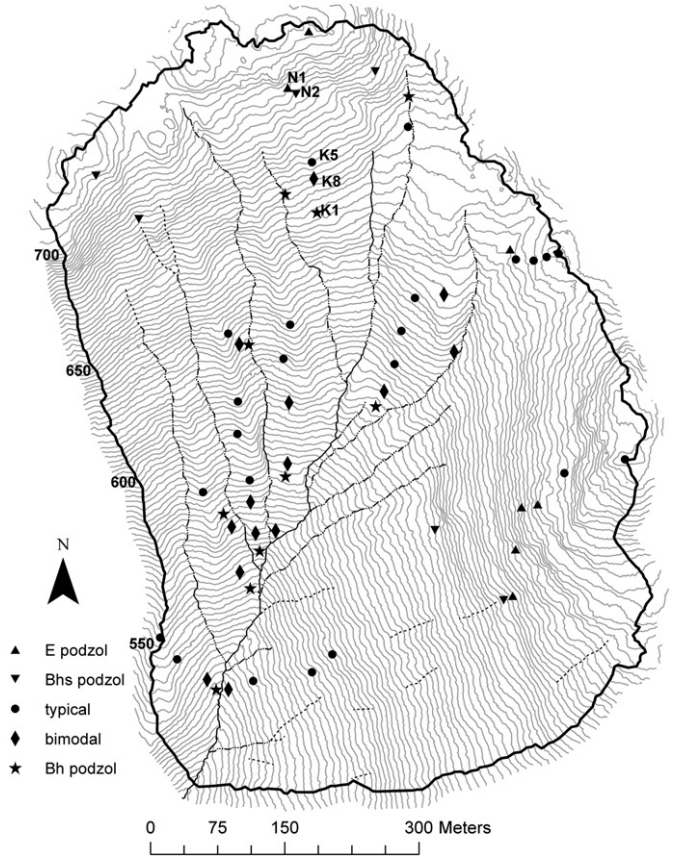

Fig. 1. Topographic map of Watershed 3. Contour interval is 2 m, with 50 m contours labeled. Soil sampling sites are shown by symbols representing soil groups, including (1) E podzol, (2) Bhs podzol, (3) typical podzol, (4) bimodal podzol, and (5) Bh podzol. Sampling locations featured in Figs. 4 and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

with varying slope positions and land surface shapes at which landform and soil profile description and sampling were conducted.

At each sampling point, five small reconnaissance pits were hand dug into the upper B horizon at 2.5 meter intervals on a 10 m long transect oriented along contour within the local landform designated for characterization. Variation in upper soil horizons (see Supplemental data) was used to indicate fine scale variability associated with microtopography and local natural disturbance. One of the five reconnaissance pits was chosen as best representing the average surficial soil horizonation and avoiding local disturbance due to tree throw and was extended to allow sampling and description into the C horizon.

Pedon description included measurements of depth to root restriction (C horizon or bedrock), depth to redoximorphic features and depth to water table or seepage, if encountered. Major genetic horizons were described by Munsell color, texture, structure, moist consistence, presence of redoximorphic features, rooting density, and coarse fragment content (Schoeneberger et al., 2002). In attempt to standardize designations for subdivisions of the B horizon, and write profile descriptions in the field (a subsequent study will address how subdivisions of the B horizon vary with respect to chemical properties) an 's' subhorizon was designated if the hue was 7.5YR or redder, an 'h' subhorizon was designated if the value and chroma were 3 or less. A Bhs horizon had both of these characteristics, while Bh horizons were designated for materials with a hue of 10YR and value and chroma both less than 3. Bhs, Bs, and Bh horizons were characterized by a greasy feel, consistent with their interpretation as spodic horizons. Transitional B horizons with a hue of 10YR and value or chroma greater than 3 were designated BC. Transitional CB horizons and C horizons had chroma of 2.5Y or 5Y. Rooting density was described semi-quantitatively as few (<1), common (1 to <5) or many (≥5) fine and very fine roots (<2 mm in diameter) per square centimeter. Volumetric coarse fragment (2 mm–75 mm) content was estimated visually on the pit face.

Soil samples for chemical analysis were collected by genetic horizon. All samples were air-dried, and sieved to remove particles >2 mm. Samples were analyzed for carbon and nitrogen on a CN elemental analyzer (CE-Elantech FlashEA 1112 Series NC Soil Analyzer) on subsamples ground to pass through a 0.25 mm sieve. The instrument was standardized using soil standards obtained from the North American Proficiency Testing program. Carbon concentration was used to revise field designations of Oa (≥20% C) and A horizons. Carbon content for each horizon was calculated by multiplying carbon concentration by horizon thickness, bulk density and one minus the proportional rock content. Bulk density was estimated following the relationship reported by Federer et al. (1993), which we confirmed for WS3 by analysis of 34 bulk density cores collected during our sampling (see Supplemental data).

Site characteristics measured at each transect point included aspect in degrees relative to true north and slope measured in percent with a clinometer in up and down directions 5 m from the sampling site. Profile curvature was calculated as the slope looking downslope from the sampling site minus the slope looking upslope from the sampling site, yielding a positive index for convex hillslope profiles and a negative index for concave hillslope profiles. Plan curvature was calculated by the angle in degrees along the contour to both sides of the sampling site, minus 180, yielding a positive index for divergent hillslopes and a negative index for convergent hillslopes. Forest composition was described by measuring the diameter of all stems greater than 10 cm diameter breast height within a 10 m radius of each sampling pit. Forest cover was characterized by basal area of sugar maple and yellow birch versus beech and conifers. These groups correspond with species groups found to correlate with carbon content and carbon to nitrogen ratio in surficial soil horizons in the region by Ross et al. (2011).

Ten pedons were located immediately adjacent to groundwater monitoring wells established by Detty and McGuire (2010a), allowing a direct comparison of depth and duration of saturation with soil morphology. Eight additional monitoring wells were constructed during this project to record water table fluctuation at locations spanning the complete range of soil morphological variation observed, yielding at least three wells in each soil type defined in this study. Wells were constructed of schedule 21 polyvinyl chloride pipe (3.18 cm outside diameter) with a 31 cm screen length consisting of 0.025 cm width lateral slots with 0.32 cm spacing between slots. The wells were installed so the screen straddled the interface between the B and C horizons, mostly between 40 cm to 100 cm deep. At a few of the drier sites where water table was not observed in this zone, additional wells with screens 100–200 cm deep were installed. Water table was recorded at ten minute intervals for at least one year with a 1.5 m Odyssey capacitance water level logger (Dataflow Systems Pty Ltd). Slug tests (Detty and McGuire, 2010b), fast response of water levels to storms, as well as fast recovery from pumping confirm that these wells properly record short-term dynamics of water level.

All sampling points were georeferenced using a Trimble Geoexplorer XT GPS unit with an external hurricane antenna and post processing to achieve approximately one meter precision. Topographic indices were extracted by analysis of a 5 meter DEM derived from a LiDAR survey flown by NCALM in November 2009. Upslope accumulated area (UA), topographic wetness index (TWI), defined as ln(a/tan b) where a is the upslope accumulated area and tan b is the local gradient (Beven and Kirkby, 1979), and topographic wetness index using the gradient 5 meter downslope (TWI_{d5}; Hjerdt et al., 2004) were calculated using GEASY (Software developed by Jan Seibert); algorithms are now present in SAGA version 2.0.5 open source GIS software (Olaya and Conrad, 2009). The full extent of the stream network was mapped with the Trimble GPS during wet conditions. Distance to stream (DTS), elevation above the stream (EAS), and gradient to stream (GTS) were calculated along the drainage path downslope of each sampling site using SAGA.

Correlation and analysis of variance (ANOVA) were performed in Minitab16 (Minitab 16 Statistical Software, 2010). Significance of topographic and morphological differences between soil groups was determined using the Kruskal–Wallis nonparametric ANOVA test. Multiple comparisons were performed with the Dunnett's test ($\alpha = 0.1$). Spearman correlation coefficients were calculated for horizon thicknesses and landscape parameters ($\alpha < 0.1$). Non-metric multidimensional scaling was calculated in PC-ORD v.5 (McCune and Mefford, 1999) as an ordination technique to examine the designation of soil groups and evaluate relationships with environmental variables.

3. Results

3.1. Soil horizonation and definition of groups

Sixty soil profiles were described, exhibiting a broad variation in the presence and thickness of major genetic horizons (Fig. 1; example profile descriptions are given in Table 1). Humic Oa horizons ranged from 0 to 60 cm while A horizons ranged between 0 and 14 cm. The thickness of E and Bs horizons, characteristic of podzols, ranged from 0 to 60 cm and 0 to 55 cm, respectively. The thickness of some horizons and horizon sequences were outside the range of values reported from previous soil studies at HBEF (Huntington et al., 1988; Johnson et al., 1991) or for ranges reported in official soil series descriptions (http://soils.usda.gov/technical/classification/osd/) for series previously mapped at HBEF.

In typical pedon descriptions (NRCS official series descriptions), the ratio of spodic (Bhs + Bs) horizon to E horizon thickness varied from 3.5 to 11. In watershed 5 (1.0 km west of WS3), Johnson et al. (1991) characterized average thickness as 2.7 cm for the E horizon, 3.9 cm for the Bhs horizon, 4.8 cm for the Bs horizon, yielding a spodic to E horizon thickness ratio of 3.2. In our study, we found broad range of spodic to E horizon thickness ratio of 0.7 to over 600.

Based solely on horizon thickness and sequences, we partitioned soil profiles into five groups — a typical podzol group that resembled profiles described in previous studies and in official series descriptions, and four variant groups with horizon sequences or thickness that

Table 1
Example pedon descriptions.

Top (cm)	Bottom (cm)	Horizon	Color	Texture	Structure	Consistence	Roots	Rocks %	Boundary	Redox. features	C %
N1 (E podzol)											
0	1	Oi									
1	1.5	Oe									
1.5	6	Oa1	7.5 YR 2.5/2		1FGR	VFR	M	1	AW		44.1
6	9	Oa2	10 YR 2/1	FSL	1FGR	FR	M	1	AS		32.0
9	24	E1	10 YR 5/1	FSL	massive	FR	F	5	CS		0.6
24	36	E2	5 YR 3/2	SL	1MSBK	FR	C	5	AS		1.6
36	54	Bhs	7.5 YR 3/2	SL	2MSBK	FR	F	5	AS		3.0
54	63	Cd	2.5 Y 5/3	FSL	2MCSBK	EXFI	–	3		2	2.1
A6 (E podzol)											
0	1	Oi									
		Oe									
1	5	Oa1	5 YR 2.5/1		2 FGR	VFR	M	–	AS		39.7
5	15	Oa2	10 YR 2/1		2FGR	VFR	M	–	AS		35.5
15	45	E1	10 YR 4/1	SL	massive	VFR	F	10	AS		0.7
45	55	E2	7.5 YR 3/1	FSL	1MSBK	FR	F	3	AS	2	0.8
55	89	C	2.5 Y 5/2	FSL	1 MCPL	FR	–	5	AS	2	0.9
89	95	Cd	2.5 Y 4/2	FSL	2MCPL	FI	–	10		1	0.2
N2 (Bhs podzol)											
0	1	Oi									
1	2	Oe									
2	5	Oa	5 YR 2.5/2		2FGR	VFR	M	–	AW		39.2
5	7	A	10 YR 2/1	FSL	1FGR	FR	M	–	AW		19.6
7	19	Bhs1	5 YR 2.5/2	SL	1MSBK	FR	M	1	CS		4.4
19	41	Bhs2	7.5 YR 2.5/2	SL	2CSBK	FR	M	1	CS		3.7
41	64	BC	10 YR 3/6	SL	2CSBK	FR	C	1	AS		3.2
64	90	CB	2.5 Y 4/3	SL	1MCSBK	FR	F	3	AS	1	1.1
90	110	C	2.5 Y 6/3	SL	Massive	FR	F	5		2	0.2
A5 (Bhs podzol)											
0	2	Oi									
2	3	Oe									
3	8	Oa1	5 YR 2.5/1		2FGR	VFR	M	–	AS		41.5
8	20	Oa2	5 YR 2.5/1		2MGR	FR	M	–	AW		37.3
20	66	Bhs	5 YR 2.5/2	FSL	1MCSBK	FR	C	1	AW		9.7
66	85	BC	10 YR 3/4	FSL	2MCSBK	FR	F	3	AS	2	2.5
85	98	Cd	2.5 Y 4/3	SL	2CPL	FI	–	3		2	1.2
I1 (typical podzol)											
0	2	Oi									
2	3	Oe									
3	6	Oa1	7.5 YR 2.5/2		2FGR	VFR	M	–	AS		47.2
6	8	Oa2	10 YR 2/1		2FGR	FR	M	1	AS		21.7
8	16	E	10 YR 6/1	FSL	2MSBK	FR	C	1	AW		1.0
16	25	Bhs1	5 YR 2.5/2	FSL	2MSBK	FR	M	1	AW		8.9
25	47	Bhs2	7.5 YR 2.5/3	FSL	2MSBK	FR	C	1	CW		6.1
47	63	BC	10 YR 4/3	FSL	1MSBK	FR	F	5	CW	1	1.7
63	83	C	2.5 Y 5/3	SL	1MSBK	FR	F	5	AS	2	0.9
83	96	Cd	2.5 Y 4/2	SL	2MPL	FI	–	3		2	0.3
H1 (typical podzol)											
0	2	Oi									
2	2.5	Oe/i									
2.5	5.5	Oa	5 YR 2.5/1		2FGR	VFR	M	–	AS		38.7
5.5	8	E	7.5 YR 4/1	FSL	2FSBK	FR	C	1	AS		2.3
8	21	Bhs	5 YR 2.5/2	FSL	2MSBK	FR	M	2	AS		6.0
21	41	Bs	7 YR 4/3	FSL	2MSBK	FR	C	3	CS		3.2
41	55	BC	10 YR 4/4	FSL	2MSBK	FR	C	3	CS		1.8
55	93	CB	2.5 YR 4/3	FSL	2MSBK	FR	F	3	AS	2	1.3
93	100	Cd	2.5 Y 4/2	SL	massive	XFI	–	5		2	0.5
I3 (bimodal podzol)											
0	1	Oi									
1	2	Oe									
2	4	Oa	10 YR 2/2		2FGR	VFR	M	–	AS		49.7
4	5	A	10 YR 2/1	FSL	2FSBK	FR	M	1	AS		16.2
5	10	E	5 Yr 4/2	FSL	Massive	FR	C	1	AS		1.7
10	13	Bhs1	5 YR 2.5/2	FSL	1FMSBK	FR	M	1	CW		5.1
13	37	Bhs2	7.5 YR 3/2	FSL	1FMSBK	FR	M	5	AS		3.9
37	67	Bs	10 YR 4/3	FSL	2MCSBK	FR	C	20	AS		2.5
67	81	Bh	5 YR 2.5/2	FSL	2FSBK	FR	F	20	AS	2	2.8
81	90	Cd	2.5 Y 6/3	FSL	Massive	FI	–				0.3
J1 (bimodal podzol)											
0	1	Oi									
1	2	Oe									

Table 1 (*continued*)

Top (cm)	Bottom (cm)	Horizon	Color	Texture	Structure	Consistence	Roots	Rocks %	Boundary	Redox. features	C %
J1 (bimodal podzol)											
2	3	Oa	5 YR 2.5/1		2FGR	VFR	M	–	AS		40.1
3	5	A	10 YR 2/1	FSL	2FSBK	FR	M	1	AS		18.1
5	7	E	7.5 YR 5/2	SL	massive	FR	C	3	AW		1.1
7	11	Bhs1	5 YR 2.5/2	FSL	2FSBK	FR	C	3	CW		5.8
11	23	Bhs2	7.5 YR 3/2	FSL	2MCSBK	FR	C	3	CW		4.7
23	35	Bs1	7.5 YR 3/4	FSL	2MCSBK	FR	C	3	AW	1	4.0
35	55	Bs2	10 YR 4/4	FSL	2MCSBK	FR	F	5	AS	2	3.7
55	62	Bh	5 YR 2.5/2	FSL	2FSBK	FR	F	5	AS	2	3.1
62	67	Cd	10 YR 5/3	SL	1CPL	FI	–	5		2	1.0
K1 (Bh podzol)											
0	2	Oi									
2	3	Oe									
3	7	Oa	5 YR 2.5/1		2FGR	VFR	M	–	AS		28.6
7	21	Bh1	10 YR 2/1	FSL	1FMSBK	FR	M	1	AS		8.9
21	31	Bh2	10 YR 2/2	FSL	1MSBK	FR	C	3	AW		4.5
31	48	Bh3	10 YR 3/3	FSL	2MCSBK	FR	F	15	AS		2.3
48	64	Cd	2.5 Y 5/4	FSL	2MCSBK	FI	–	20		1	0.4
H3 (Bh podzol)											
0	2	Oi									
2	3	Oe/i									
3	5	Oa	7.5 YR 2.5/2	FSL	2FGR	FR	M	–	AS		37.7
5	17	Bh1	10 YR 2/1	FSL	2FGR	FR	M	–	CS		12.3
17	33	Bh2	10 YR 2/2	FSL	1FSBK	FR	M	5	AS		7.3
33	68	C	2.5 Y 4/4	FSL	Massive	FR	–	65			0.9

Texture: FSL = fine sandy loam, SL = sandy loam.
Structure: 1 = weak, 2 = moderate, F = fine, M = medium, C = coarse, GR = granular, SBK = subangular blocky, PL = platy.
Consistence: VFR = very friable, FR = friable, FI = firm, XFI = very firm; EXFI = extremely firm.
Roots: M = many. C = common, F = few.
Boundary: A = abrupt, C = clear, S = smooth, W = wavy.
Redox features: 1 = concentrations only, 2 = concentrations and depletions.

were visibly distinct from the central concepts of established soil series previously recognized in the vicinity. We named these groups based upon the dominant subsurface horizon or combination of horizons distinct from typical podzols (sensu Sommer et al., 2000). Average profile composition for each group, given by mean thickness of horizons for all pedons described, is shown in Fig. 2 while the range of horizon thickness and statistical differences between groups are given in Table 2.

3.2. Morphology and location of soil groups

Typical podzols occurred throughout the watershed, accounting for 23 of the 60 pits sampled (Fig. 1). They were characterized by the presence of a thin E horizon, overlying one or two thicker spodic (Bhs, Bs) horizons, with value and chroma of the B horizons increasing with depth (Table 1; Fig. 2). In general, the thickness of each of these horizons, and the ratio of spodic to E horizon thickness was similar to that reported by previous studies and in official series descriptions.

Along the upper watershed divide, both immediately downslope of and between bedrock outcrops, pedons had thick Oa and E horizons and minimal B horizons overlying shallow bedrock. These were termed E podzols (Table 1, Fig. 2) and generally exhibited thicker E horizons and significantly thicker Oa horizons than typical podzols (Table 2). These soils were closely associated with bare bedrock outcrops and accumulations of organic matter directly on bedrock (i.e., Histosols) where mineral soil was lacking. Downslope of these E podzols, pedons were characterized by having a thin or no E horizon, and a thicker Bhs

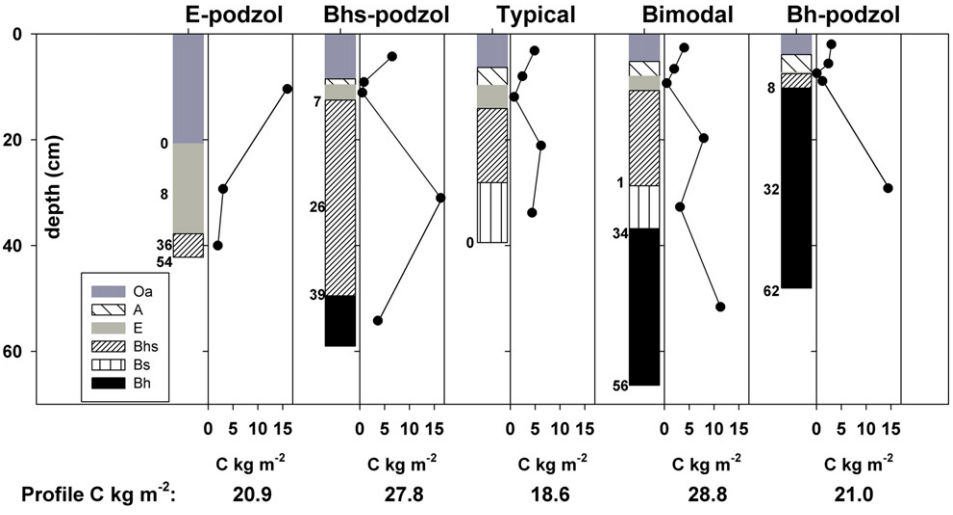

Fig. 2. Mean horizon thickness for each soil group. Percent of the time that selected horizons were saturated with water is shown for horizon boundaries and horizon mid-depths, averaged for all monitored profiles in each group. Mean carbon content (kg m^{-2}) is plotted at the mid-depth of each genetic horizon, with the sum for the entire solum listed below.

Table 2
Mean and range in soil morphology and landscape for E podzols (n = 7), Bhs podzols (n = 6), typical podzols (n = 23), bimodal podzols (n = 14) and Bh podzols (n = 10). Parameters distinguishing soil types from typical Spodosols are shown in bold. Letters represent significantly different means. Variable difference by soil group was determined using Kruskal and Wallis nonparametric ANOVA test. Multiple comparisons were performed with the Dunnett's test ($\alpha = 0.1$).

parameter	E podzols	Bhs podzols	Typical podzols	Bimodal podzols	Bh podzols
Oa thickness (cm)	20.8^{a} (7.5–60)	8.5^{ab} (3–17)	6.3^{bc} (0–17)	5.2^{bc} (0–13)	3.9^{c} (0–10)
A thickness (cm)	0^{a}	1.2^{a}(0–5)	3.4^{a} (0–14)	2.8^{a} (0–12)	3.4^{a} (0–8)
E thickness (cm)	17^{a} (2–40)	2.8^{bd} (0–14)	4.4^{ab} (0–11)	2.7^{b} (0–5)	0.3^{d} (0.2.6)
Bhs thickness (cm)	4.4^{ac} (0–18)	37^{b}(13–54)	14^{ab} (0–44)	18^{ab} (5–34)	2.7^{c} (0–24)
Spodic (Bs + Bhs) thickness (cm)	4.4^{a} (0–18)	37^{b}(13–54)	26^{b} (8–55)	27^{b} (8–57)	2.7^{a} (0–24)
Bh thickness (cm)	0^{a}	9.5^{ac} (0–57)	0^{a}	30^{b} (7–57)	38^{bc} (0–82)
Restriction depth (cm)	61^{a}(22–120)	88^{a}(49–120)	76^{a}(26–120)	78^{a}(53–120)	72^{a}(33–120)
Elevation (ft)	667^{a}(635–714)	674^{a}(611–717)	624^{a} (540–693)	585^{b}(533–652)	624^{ab} (534–680)
Slope (%)	32^{a} (9–74)	29^{a}(18–34)	27^{a} (2.5–47)	26^{a} (11–35)	23^{a}(13–35)
Profile curvature index	2.1^{a} (−20–+22)	-4.8^{a} (−19–+12.0)	-0.5^{a} (−24–+25)	-5.4^{a} (−26–+6)	-3.4^{a} (−13–+0)
Plan curvature index	4.6^{ab} (−138–+100)	-19^{ab} (−46–+12)	-6.8^{a} (−68–+113)	-19^{ab} (−96–+13)	-50^{b} (−116–+2)
UA (m^2)	555^{ab} (25–2300)	511^{ab} (84–1230)	228^{a}(31–1013)	416^{ab} (108–1334)	887^{b}(93–2890)
TWI	6.0^{ab} (4.8–9.5)	6.3^{ab} (5–7.6)	5.4^{a} (3.3–7.5)	6.3^{ab} (5.1–7.8)	7.1^{b} (5.0–8.6)
TWI_{d5}	6.8^{ab} (5.1–9.8)	7.1^{ab} (5.7–8.5)	6.3^{a} (4.8–8.4)	7.2^{ab} (6.0–8.9)	8^{b}(5.8–9.5)
DFS (m)	280^{a} (70–462)	206^{a}(71–447)	110^{ab} (20–360)	54^{b}(21–196)	41^{b} (2–89)
DFR/DFS	0.4^{a} (0–0.8)	0.7^{a} (0.1–1.3)	1.7^{ac} (0–10.1)	3.7^{bc} (0.4–19.2)	15.4^{b} (0.3–85)
EAS (m)	65^{a}(9–111)	79^{a}(19–106)	25^{a} (2–97)	11^{b} (4–41)	9^{b}(2–18)
smyb (m^2 ha^{-1})	4.7^{a} (0–18.8)	4.3^{ab} (0–18.8)	11.2^{ab} (0–28.9)	18.1^{ab} (0–38.3)	19.2^{b} (5.9–32.1)
conab (m^2 ha^{-1})	14.1^{a} (4.8–21.4)	14.0^{ab} (1.9–21.4)	13.9^{ab} (0–38.6)	6.6^{ab} (0.6–23.2)	5.6^{b} (0.3–10.6)

UA = upslope area, TWI = topographic wetness index, TWI_{d5} = downslope topographic wetness index, DFS = distance from stream, DFR = distance from ridge, EAS = elevation above stream, smyb = basal area in sugar maple and yellow birch, conab = basal area in conifers and American beech.

horizon relative to the typical podzols. These were termed Bhs podzols (Table 1, Fig. 2) and had a significantly larger spodic thickness than all other groups (Table 2).

Bh podzols were identified by field characteristics of a thinner Oa horizon, lack of an E horizon, and a B horizon dominated by the Bh (Table 1, Fig. 2). A Bh horizon was designated by having a value and chroma of 3 or less and a hue of 10YR. The low value and chroma is presumed to indicate illuvial accumulation of organic matter (Soil Survey Division Staff, 1993) while the yellowish hue suggests a low accumulation of sesquioxides relative to organic matter. In contrast, other groups typically had a redder Bhs and or Bs horizon with a chroma of 7.5YR or redder. Generally, Bh podzols were located in near-stream zones and on topographic benches, zones of lesser slope in lower and mid-hillslope positions (Fig. 1). Bimodal podzols were pedons that exhibited similar morphological features to typical podzols in the upper part of the profile, but had a Bh horizon at the B–C interface (Table 1, Fig. 2). This decrease in value and chroma in the deepest portion of the solum was not observed in the other types, nor is it reported in official series descriptions. The suggestion of maximum spodic expression, with low value and chroma material at both the top and bottom of the B horizon, with higher chroma spodic materials in between, led us to choose the term bimodal to describe these profiles. Bimodal podzols were topographically and morphologically intermediate to typical and Bh podzols, suggesting that they represent a transition between these two types. However, bimodal podzols were not always visibly present or sampled. On some transects the transition from typical to Bh podzol occurred over a space of a few meters, limiting expression of this portion of the catena.

Variation in spodic expression tended to be distributed throughout the watershed in a predictable manner depending upon landform and hillslope position. E and Bhs podzols tended to be found at higher elevations and further from the stream network (Table 2). Landform also varied between groups. Bh podzols were in more concave regions, with lower plan curvature, than typical podzols. Bimodal and Bh podzols also had a higher upslope accumulated area (UA) and topographic wetness index (TWI) than the other groups (Table 2). Groups also varied in vegetative cover. Bimodal and Bh podzols tended to have a larger proportion of sugar maple and yellow birch, while E podzols and Bhs podzols tended to be located in regions with coniferous species and American beech (Table 2).

Spearman correlations between horizon thickness and topographic variables (Table 3) reinforced the results from the ANOVA. Elevation, distance from stream, and elevation above the stream were positively correlated to the thickness of the Oa horizon. E horizon thickness was negatively correlated with UA, TWI, and TWI_{d5}, and positively related to the distance and elevation above the stream. Contrary to trends in Oa and E horizons, Bh horizon thickness had a significant negative correlation with the elevation above and distance from the stream and significant positive correlations with UA TWI, and TWI_{d5} (Table 3).

Ordination with non-metric multidimensional scaling was used to evaluate the distinctness of each soil group based on horizon thickness of each pedon and the relationship of groups to landscape variables (Fig. 3). Most soil profiles plotted in regions with other profiles classified in the same group in a two dimensional space of the ordination. Axis 1, which was most strongly correlated with TWI, separated Bh podzols, associated with high values of TWI on the right side of the axis from typical podzols, with low values of TWI on the left side. Bimodal podzols occupied an intermediate position along axis 1. Axis 2, best correlated with distance from stream and elevation, separated E podzols at greater distance from the stream and elevation from all of the other groups with relatively lower elevation and distance from the stream. Pedons classified as Bhs podzols mostly plotted below the E podzols on axis 2, but

Table 3
Spearman correlation coefficients for relationships between horizon thickness (cm) and landscape parameters. Only significant correlations ($p < 0.05$) are shown.

Parameter	Oa	A	E	Bh
Restriction depth	−0.26			
Elevation	0.38			
Plan curvature index				−0.33
UA			−0.42	0.43
TWI			−0.41	0.46
TWI_{d5}			−0.40	0.45
DFS	0.48	−0.40	0.42	−0.57
DFR/DFS			−0.44	0.56
EAS	0.41	−0.38	0.38	−0.56
smyb		0.31	−0.27	0.34
conab			0.45	−0.30

UA = upslope area, TWI = topographic wetness index, TWI_{d5} = downslope topographic wetness index, DFS = distance from stream, DFR = distance from ridge, EAS = elevation above stream, smyb = basal area in sugar maple and yellow birch, conab = basal area in conifers and American beech.

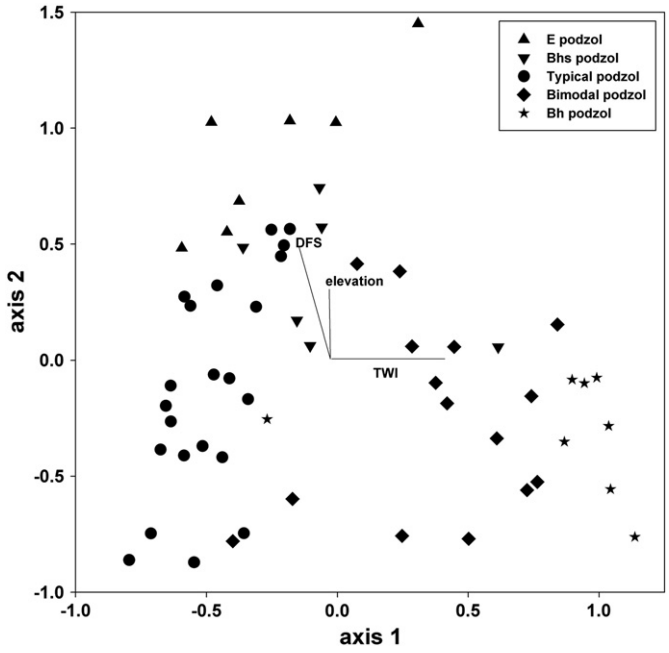

Fig. 3. Non-metric multidimensional scaling ordination analysis of similarity of soil profiles in a two dimensional space. Vectors represent the major landscape properties that distinguish the soil groups.

were generally the least distinct from the other groups in the two dimensional ordination space.

3.3. Solum carbon

Carbon pools by horizon and pedon showed substantial variation between soil types (Fig. 2), and spanned a similar range shown in another study that recognized a catena of lateral podzols (Sommer et al., 2001). In typical podzols, the carbon pool was greatest toward the upper part of the profile, in the O and Bhs horizons, with a solum total of 18.8 kg C m^{-2}. E and Bh podzols had similar solum carbon pools, at 20.9 and 21.0 kg C m^{-2}, respectively, with the greatest portion of the pool in the Oa horizon in the E podzol and somewhat deeper in the profile, in the Bh horizon of the Bh podzol. Bhs and bimodal podzols both had about 50% greater carbon pools than typical podzols, with 27.8 and 28.8 kg C m^{-2}, respectively. In the Bhs podzols, the Bhs horizon, by far the thickest horizon in the profile, had the greatest carbon pool, while in the bimodal podzols the Bh horizon at the base of the solum had the largest carbon pool (Fig. 2).

3.4. Groundwater relationships

Frequency and duration of water table presence within the solum varied by soil type. Fig. 2 shows the mean percent of time of water table at or above horizon mid-points and transitions, based on a full annual cycle of monitoring data, and averaged for all monitored profiles in each type. Typical podzols, consistent with previous descriptions of HBEF soils as well drained, did not show water table incursions above the B–C interface. Both E and Bhs podzols showed water table in the major subsurface horizons, with water table reaching the base of the E horizon 36% of the time in E podzols and 7% of the time in Bhs podzols. Water table reached the base of the Bhs horizon 54% of the time in E podzols and 39% of the time in Bhs podzols. Water table was most frequent in Bh horizons, reaching the top and bottom 34% and 56% of the time, respectively, in bimodal podzols, and 8% and 62% of the time in Bh podzols.

Fig. 4 illustrates short-term variation in depth to water table for one representative well in each soil type for a hillslope segment in the upper portion of the watershed (Fig. 1). Storm response was observed for a representative period spanning relatively dry summer conditions in August, 2011 into a wetter period through the end of the growing season in October 2011. The E podzol and Bhs podzols responded to all rain events during both portions of this record, with the water table reaching close to the soil surface during the largest event in the E podzol and within 12 cm of the soil surface in the Bhs podzol. Following cessation of rain, water table recession was quite rapid in the E podzol, with a somewhat longer recession in the Bhs podzol. In both wells, water table was not recorded in the solum during periods between events. In the typical podzol, there was no groundwater within the limit of the well at 165 cm during the summer, while water table fluctuated within the C horizon, between 100 and 150 cm depth, during the wetter period. In the bimodal and Bh podzols, water table was more sustained between events, with shorter vertical spans during most events, and more gradual recession slopes suggesting greater hydrologic storage. In the bimodal podzol, groundwater fluctuated within the C horizon, between 110 and 150 cm depth during the summer, rising to above the Bh–C interface at 80–100 cm during the wet period. The Bh podzol showed water table rising to within 10–20 cm of the soil surface, well into the Bh horizon, during both summer and fall time periods, receding to the Bh–C interface during the dry period, but remaining within the Bh horizon during the wetter period.

For the same hillslope section represented in Fig. 4, Fig. 5 presents annual cumulative exceedance curves for water table fluctuation. Over one full year of measurements, the typical podzol had water table fluctuations confined to the subsoil (C horizon), with water table present at the 165 cm depth limit of measurement about half of the time. The E and Bhs podzols had infrequent saturation within the solum, less than 25% of the time. Bh horizons in the bimodal and Bh podzols saw the most frequent saturation, with water table present at the base of the horizon 35% of the time in the bimodal podzol and over 70% of the time in the Bh podzol (Fig. 5). The relatively low slope of the exceedance curve in the vicinity of the B–C interface for the bimodal podzol suggests that a change in hydrologic properties at the base of the solum may influence shallow water table development and persistence at this site. However, the other sites showed steeper curves at the B–C interface, suggesting that limitations in conductivity of the C horizon may not be so important in development of shallow water table at these sites.

4. Discussion

4.1. A conceptual model relating soil morphology to water table variation

Soil characterization within WS3 showed a broad range of horizonation and spodic expression at the pedon scale. We have no reason to believe that variation in soils in WS3 is greater than that found in other areas of HBEF or of the larger White Mountain region. Rather, we suggest that not trying to fit pedon observations into previously designated soil series highlights the broader range in characteristics present under actual field conditions. This broader range in characteristics is typically ignored and regarded as atypical or as minor inclusions when encountered during soil survey activities. Our results suggest that these variations are not random, but occur in predictable positions and spatial patterns within the catchment. Oa horizons were thickest in shallow to bedrock areas where conifer species were more dominant. E horizons were also thickest in this portion of the catchment, partially reflecting greater production of organic acids in thick O horizons. However, anomalously thick E horizons typical of E podzols, as well as the variant patterns of spodic horizon thickness and location shown by Bhs, Bh, and bimodal podzols were related to variations in frequency and duration of transient water table expression, which was previously unrecognized in this steep upland landscape of coarse textured soils.

Previous monitoring of wells in WS3 (Detty and McGuire, 2010a, 2010b) showed that the C horizon had volumetric water content slightly below saturation between storm events, becoming saturated, with a

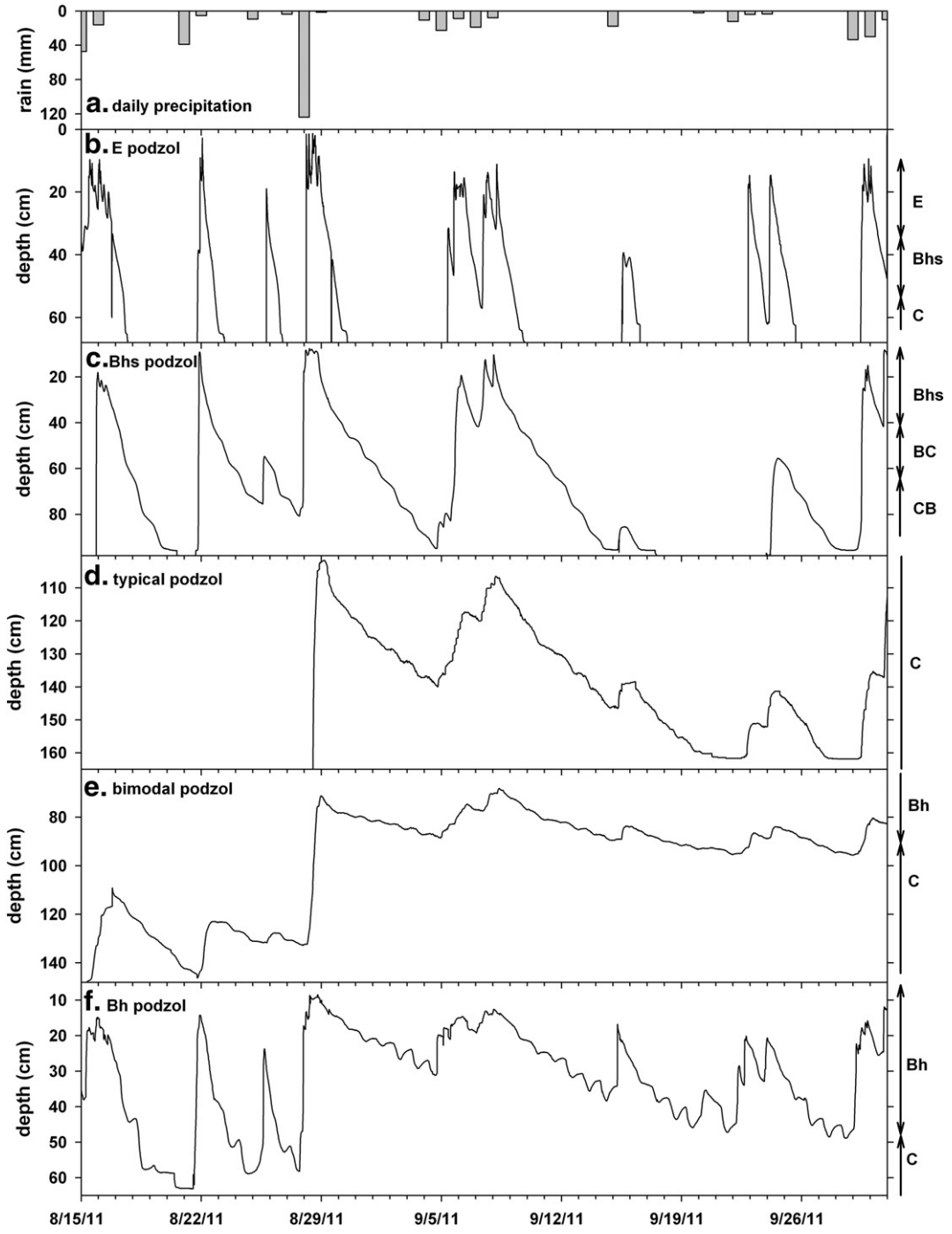

Fig. 4. Daily precipitation (a) and water table fluctuations in one example of each soil group including E podzol N1 (b), Bhs podzol N2 (c), typical podzol K5 (d), bimodal podzol K8 (e), and Bh podzol K1 (f). Horizons in the portion of the soil profile where the majority of the water table fluctuations occurred are shown at the right side of the figure. Data are shown from August 15 to September 30, 2011 to highlight event responses during a period spanning dry mid-summer conditions through wetter conditions at the end of the growing season.

water table rising into the solum during events. While contrasting patterns of horizonation and extremes in horizon thickness at the pedon scale were related to varying patterns of transient groundwater inundation, we did not find redoximorphic features within horizons where water table fluctuations were documented to be present by our water level recorders. For the most part, redoximorphic features were confined to BC, CB, and C horizons (Table 1), perhaps leading to the long-standing view of these landscapes as well drained. Redoximorphic features, or concentrations and depletion of iron, are typically used to indicate portions of the soil profile subject to seasonal high water table fluctuations (Veneman et al., 1998). In the upper portions of the watershed, where E and Bhs podzols show transient saturation, the short duration of inundation, mostly confined to event periods (Fig. 4) may keep dissolved oxygen levels high enough to prevent fluctuations in redox conditions necessary for redoximorphic features to form. Lower in the catchment, where Bh horizons in bimodal and Bh podzols are frequently invaded by the water table, matrix colors are quite dark, with low value and chroma (Table 1), perhaps masking any iron concentrations or depletions that may be present.

The five soil groups defined in this study can be related to each other via a conceptual model (Fig. 6) based on an idealized transect that shows the relative position of each soil group along a hillslope. The crest of the slope is a bedrock outcrop and the depth of glacial till generally increases with downslope position. The schematic diagram shows

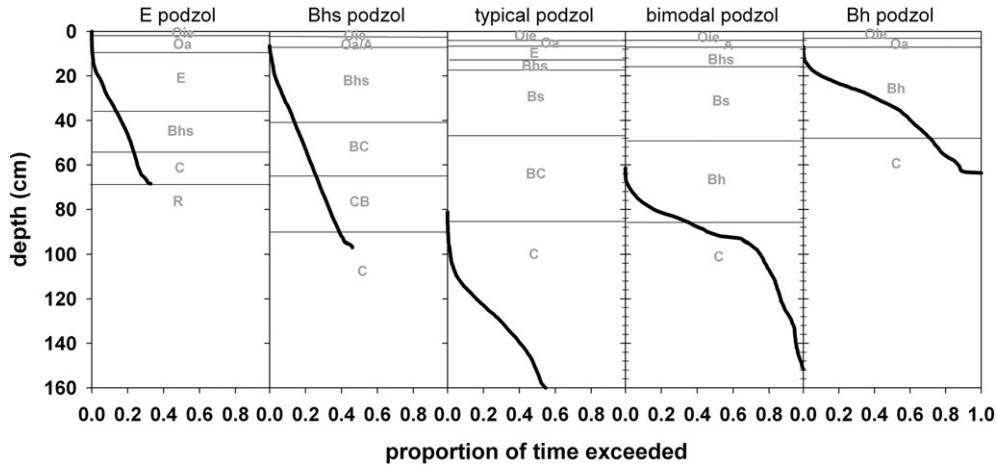

Fig. 5. Cumulative exceedance curves showing the proportion of time that water table was above each point in the profile for the same representative catena featured in Fig. 4. Exceedance curves are based on a full annual cycle of water table measurements recorded at ten minute intervals.

the transitions and lateral connections from one soil group to another. For example, material from the E podzol has illuviated into the Bhs podzol with translocation laterally downslope. The two co-occurring pedons together represent the complete podzolization process. This type of lateral podzolization has been previously documented in Germany in granitic (Sommer et al., 2000) and sandstone (Sommer et al., 2001) catchments. The terms E-Spodosol and Bs-Spodosol were used and we have adapted similar nomenclature for our soil groups. Their work clearly showed the lateral development of a Bs-Spodosol (similar to our Bhs podzol) downslope of an E-Spodosol (identical to our E podzol). Mass balances of Fe and Al, along with horizon thicknesses and ratios of thickness of spodic deposition areas to eluvial source areas, were used to confirm lateral rather than vertical soil profile development. Sommer et al. (2000, 2001) also observed lateral flow ('interflow') in their study watersheds, although they did not quantify it. In our conceptual model, the solid arrow between the E and Bhs podzols (Fig. 6) indicates translocation via lateral groundwater flow, which we documented to occur in this portion of the landscape briefly but frequently on an event basis (Figs. 4, 5).

In the typical podzols, and the upper portion of the bimodal podzols, flow is dominated by vertical percolation through an unsaturated profile, as indicated by the dashed arrow, and soil development occurs at the pedon scale, independent of lateral translocation. These areas are consistent with the paradigm of the pedon being the unit body of soil development. However, in the lower portion of the bimodal profiles, extending to the full Bh podzol profile downslope, lateral translocation of materials from upslope again becomes the dominant process, confirmed by increasing presence of transient saturation in Bh horizons (Figs. 4, 5). Thus, at the hillslope scale, portions of hydrologic transport and soil development are variously influenced by vertical, unsaturated drainage and lateral saturated flow. Overall, it is necessary to consider the hillslope scale as well as the pedon scale in order to understand soil development in this landscape.

This conceptual model to explain soil variation observed at WS3 is equivalent to the concept of a translocation catena discussed by Sommer and Schlichting (1997). Portions of the catena, including the typical podzols and upper portion of bimodal podzols are typified by leaching as a primary mode of translocation of materials. Other portions are characterized by direct interpedon transfer of materials between adjacent pedons, as in the E and Bhs podzols. In the case of the lower bimodal and Bh podzols, this portion of the catena is dominated by accumulation of spodic materials either indirectly from upslope soils via deeper groundwater inputs from the subsoil of typical podzols, or by direct translocation within groundwater in the solum between bimodal and Bh podzols. Overall, this variety of processes and connections between catena elements contrasts with the usual paradigm, of which the Lyman–Tunbridge-Becket catena (Homer, 1999) is a good example. Each of the soil series in this catena develops independently under vertical leaching in excessively to well drained conditions, with variation along the catena simply representing an increase in soil depth.

4.2. Causes of lateral flow

Despite steep topography and coarse textured soils, lateral flowpaths in this headwater catchment are common and are determined by watershed structure, i.e., depth to bedrock and parent material, C horizon

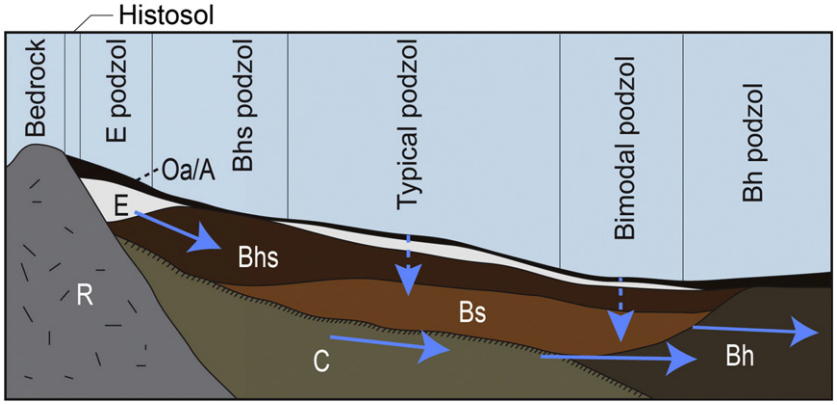

Fig. 6. Conceptual model showing the distribution of soil groups along a representative hillslope. Cumulative distribution functions showing duration of watertable expression for representative soil profiles.

character, and surface topography. Shallow bedrock at the upper elevations forces transient water table development on an event basis. Runoff in this portion of the catchment is further enhanced by bedrock outcrops, which act as impervious surfaces, increasing the throughflow in shallow soils within intervening swales. Lower on the hillslope, the depth to bedrock (or thickness of glacial drift) is greater and the transitions from typical to bimodal to Bh podzols are characterized by an increasing prevalence of transient water table in the solum. Increases in TWI, resulting from increasing UA, support the notion that surface topography via flow convergence and larger drainage area is driving the typical to bimodal to Bh podzol transition (Table 2; Fig. 3). In two locations, we found a transition from typical to bimodal to Bh podzols in a midslope bench, with the bimodal podzol at the break in slope and the Bh podzol in the bench. In these cases, the increase in TWI was a function of the decrease in slope more than an increase in UA.

As an alternative to topographic controls, variation in the character of the C horizon may also lead to a subsurface control of the typical to Bh podzol transition. Our observations of the C horizon have been consistent with the official description of the Skerry and Becket series that give a wide range of saturated hydraulic conductivity in the substratum, varying with the presence of sand lenses in an otherwise predominantly loamy material. Thus portions of the watershed with lower hydraulic conductivity at the B–C interface may promote the development of a transient water table in the solum. This would not be predicted by surface topographical analysis but is similar to the effect of fragipans in generating lateral flow (Gburek et al., 2006). Fragipans, firm pedogenic subsurface horizons, are not recognized in the study region although firm glacial till subsoil has been described as densipans (Cd horizons), thought to be of geogenic origin (Homer, 1999). In our experience in WS3, subsoils appear to be more firm during periods of low moisture conditions. Thus, this character appears to be transient and does not seem to be useful in predicting subsurface constraints on hydraulic conductivity.

4.3. Biogeochemical implications

Lateral translocation and immobilization of organic carbon with transient water table fluctuations suggest a temporally and spatially dynamic behavior within the catchment, reminiscent of the concepts of hot spots and hot moments controlling biogeochemical processing (McClain et al., 2003). Bhs and bimodal podzols stand out as potential hotspots with high C content (Fig. 2), especially lower in the profile, within zones of frequent and fluctuating saturation (Figs. 4, 5). A companion study documented prominent, persistent spatial variation in surface water chemistry within WS3 (Zimmer et al., 2013). In particular, segments of the stream stand out with contrasting patterns of relatively high or low dissolved organic carbon (DOC), as well as metals involved in podzolization such as Fe and Al. Spatial arrangement of soil units among subcatchments monitored by Zimmer et al. (2013) may explain these patterns, with portions of the stream network expressing positions along the catena (Fig. 6) that differ with respect to zones of transport (e.g. E podzols), where illuvial carbon is low and DOC is high, or zones of accumulation (e.g. Bhs and Bh podzols), where illuvial carbon is high and DOC is low. Accumulation of C tends to be in the portions of the hillslope with water table fluctuations, or more active flowpaths, in the solum, suggesting that these zones could be important regulators of export of C and other solutes.

The distinction between zones of leaching versus accumulation along portions of the hillslope catena reflects event and seasonal differences in water table fluctuation. In this case, one might speculate that climate change induced alteration in patterns of water table duration and frequency with respect to soil horizons could lead to a destabilization of previously established catenary sequences along specific hillslopes. Such dynamics could provide a mechanistic explanation for temporal trends in DOC export observed in some catchment studies (Laudon et al., 2011; Roulet and Moore, 2006).

Other processes besides C export and storage may be dependent on the relative position along a mixed translocation catena. Zimmer et al. (2013) showed that groundwater seeps in WS3 were more concentrated in solutes that reflect products of mineral weathering reactions, including Ca, Na, and Si. Similarly, seeps have been found to be places where sugar maple trees and calciphilic ground flora are most prevalent, especially in relatively infertile parent materials such as unglaciated sandstone-derived soils on the Allegheny Plateau (Bailey et al., 2004; Horsley et al., 2008). Thus, portions of the hillslope with upwelling groundwater (e.g. Bh podzols) may have the cation exchange complex within the rooting zone recharged by base cations liberated by mineral weathering in upslope soils, or from deeper within the subsoil or bedrock.

Portions of the hillslope catena subject to transient saturation within the solum (Figs. 4, 6) should be investigated as potential hotspots for biogeochemical cycling of nitrogen as well. Preliminary work suggests strong gradients and temporal variability in chemical composition of the soil atmosphere, with lowest concentrations of O_2 and highest concentrations of CO_2, N_2O, and CH_4 in Bh podzols (Werner, 2011). These soils have frequent water table incursions in the solum during growing season storm events. Werner (2011) suggested that variation in depth and extent of anoxia in these soils could promote nitrification, denitrification or methanogenesis at various times, leading to the variation in soil atmosphere compositions measured.

The observed hillslope patterns raise an issue with biogeochemical models that ignore lateral translocation, considering only inputs from the soil surface, vertical leaching, and drainage from the base of the soil. For example, critical load models, commonly used to evaluate susceptibility of ecosystems to atmospheric acid deposition are based on a mass balance formulation of this configuration, with weathering inputs limited to the rooting zone of the modeled cell (McNulty et al., 2007; Sverdrup and De Vries, 1994). Regional critical loads analyses are assumed to be valid for well drained soils, with the notion that well drained soils are the dominant condition for upland portions of the landscape, and follow this model of inputs from the surface and outputs from the subsurface independent of adjacent cells. However, if weathering products are translocated between soils, this would change the spatial pattern of the mass balance results, with some portions of the landscape receiving proportionally more or less buffering from mineral weathering reactions, depending on whether they are on source or sink portions of the catena. And in the case where inputs are derived via groundwater flows from below the soil zone, there may be an overall bias in critical load estimates that only consider reactions within the solum, with model results suggesting that systems are less buffered than they really are.

5. Conclusion

We found that soil horizon variation was reflective of landscape position and frequency, duration, and depth of transient water table incursions within an upland headwater catchment formerly considered to be characterized by well drained soils. Lateral flow of groundwater, and translocation/immobilization of materials such as organic C can be variably caused by shallow bedrock, a contrast in hydraulic conductivity at the B–C interface, or simply as a threshold with increasing upslope area and/or topographic wetness index. Overall lateral flowpaths and soil development are more prevalent in the upper portions of the watershed with E and Bhs podzols controlled by shallow bedrock and outcrops, and in toeslopes and the near-stream zone where bimodal and Bh podzols can be found in zones of high TWI. Position along a mixed catena with portions more or less reflecting leaching, translocation, and immobilization has important implications for soil development and biogeochemical processing. Understanding the spatial arrangement of soil units within such catenas at the catchment scale may help to explain spatial patterns in soil and surface water chemistry and runoff generation processes. Such understanding could lead to more realistic formulations

of models that account for the variable source areas, which must be taken into account to properly estimate mass balance. The interacting processes of soil development and hydrologic dynamics suggest that greater interdisciplinary approaches and choice of appropriate scales of study are required for ecosystem level understanding.

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