Spatial Distribution of Carbon in the Subsurface of Riparian Zones

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Soil C supplies vary spatially within and among riparian wetlands. Understanding this variability is essential to assessments of C-dependent riparian wetland functions such as water quality enhancement and C storage. In this study, we examined the distribution of C with depth across the riparian landscape. Our objectives were to describe the spatial distribution of various C forms in the subsurface of riparian wetlands, and to identify the watershed, landscape, and soil characteristics that govern the distribution of these forms. Twenty-two riparian sites, mapped as alluvial or outwash soils, were examined along first- through fourth-order streams. Soils were described from pits and auger borings along transects established perpendicular to the stream. Roots and buried A horizons represent the majority of C in the subsurface, representing an important source of C for riparian zone functions. Buried A horizons and C-rich lenses, indicative of alluvial soils, were identified in 21 of the 22 sites. Higher order riparian zones tended to have greater quantities of alluvium. Roots were generally distributed to the greatest depths close to the streams where alluvial deposits were thickest. All first-, second-, and third-order riparian zones were mapped as outwash soils on county-scale soil surveys. These sites, however, contained predominantly alluvial soils, suggesting that soil surveys at the 1:15,840 scale are inadequate for identifying alluvial soils along lower order streams. To assess the best predictors of alluvium distribution within riparian zones, 11 watershed characteristics were examined. A forward stepwise regression revealed that watershed size and floodplain width are two of the most important indicators of the quantity, width, and depth of alluvium, and subsequently subsurface C, within glaciated riparian zones.

Abbreviations: FOM, fragmental organic matter.

Soil C stocks are variable within and among riparian zones. The quantities and forms of C vary spatially, especially in the subsurface. Recent studies have documented the presence of C-rich layers at depths >1 m in riparian zones (Hill et al., 2000; Blazejewski et al., 2005). In addition, a range of morphologic C forms such as masses and coatings have been identified in riparian soils (Blazejewski et al., 2005). Understanding the spatial distribution of these C forms is essential for scientists and regulators to accurately assess C-dependent functions of different areas of a riparian wetland.

Soil organic matter in riparian zones is an important source of slow–release nutrients for plants and an energy source for microbial nutrient cycling, and provides sorption sites for pollutants such as herbicides, pesticides, soluble metals, and P (Altier et al., 1994; Alvord and Kadlec, 1996; Amador et al., 1997; Naiman and Decamps, 1997; Axt and Walbridge, 1999; Baker et al., 2000). One of the most important C-dependent functions in riparian wetlands is groundwater denitrification. The highest rates of groundwater denitrification in the subsurface occur where NO_3–laden groundwater interacts with supplies of labile organic C (Robertson et al., 1991; Jacinthe et al., 1998; Devito et al., 2000; Hill et al., 2000). To manage riparian zones for ecosystem services such as water quality protection, there is a need to estimate the locations of subsurface C in relation to groundwater flow.

Relationships between groundwater flow paths and soil C are often parent material dependent. Common soil parent materials in the glaciated Northeast are glacial tills, outwash, alluvium, and organic deposits (Schafer, 1981; Thorson and Schile, 1995). The majority of the soils in this region are Pleistocene age (Rector, 1981). Previous work in riparian zones in southern New England has suggested that riparian zones located in a glacial till geomorphic setting often contain groundwater surface seeps, thereby routing groundwater along paths that do not intersect subsurface C (Rosenblatt et al., 2001). Organic soils in the Northeast vary greatly with respect to groundwater flow. While some organic materials are underlain by highly permeable sands and gravels, others sit atop glacial tills, which can have low permeability. Parent materials such as outwash and alluvium typically contain stratified layers of permeable sands and gravels (Larson and Stone, 1982; Melvin et al., 1992; Benn and Evans, 1998). Thus, in these riparian zones there is probably significant groundwater flow in the subsurface (Kellogg et al., 2005). Alluvial soils typically contain buried C-enriched horizons, as well as a variety of other C forms in the subsurface (Blazejewski et al., 2005). Therefore, subsurface C in alluvial and outwash riparian wetlands will probably have a greater potential for fueling groundwater NO_3 removal than subsurface C located in till and in many organic riparian wetlands.

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The key to understanding the C distribution in the riparian subsurface may be to determine the factors driving streamside deposition, often referred to as *alluviation* (Fanning and Fanning, 1989). This analysis requires linking observations made at the reach scale in stream–riparian studies to features of the landscape that occur at scales from the stream reach to the whole watershed. Alluviation occurs as a result of two fluvial processes: lateral migration and overbank flow (Ritter, 1986). Landscape characteristics related to a specific location within a watershed (e.g., the floodplain width) and watershed characteristics (e.g., stream order and drainage area) can control alluviation by affecting overbank flow and lateral migration. Furthermore, biotic features of the landscape can influence stream and floodplain morphology. In North America, beavers (*Castor canadensis*) were abundant historically, and have probably promoted alluviation along most first- through fourth-order streams (Naiman et al., 1988); beaver dams cause streams to flood, and subsequently organic material and sediments are deposited adjacent to the streams. Many studies have investigated factors affecting post-settlement alluviation in agricultural watersheds of the Midwest (Magilligan, 1985; Beach, 1994; Lecce, 1997; Faulkner, 1998); factors identified as the best indicators of the volume of post-settlement alluvium include valley width (Magilligan, 1985; Lecce, 1997; Faulkner, 1998), watershed size (Magilligan, 1985; Faulkner, 1998), cross-sectional stream power (Lecce, 1997), and floodplain width (Beach, 1994). Characteristics such as these may be useful indicators of the extent of alluvial deposits and their associated C forms within riparian zones of other regions of North America.

Subsurface C can result from pedogenic, biologic, and geomorphic processes. These processes (i.e., podzolization, root growth and turnover, and alluviation) are in part controlled by specific watershed, landscape, and soil characteristics. Therefore, the spatial distributions of subsurface C forms may be related to characteristics such as these, which promote or inhibit their formation. In this study, we investigated the spatial distribution of the various C forms in the subsurface of alluvial and outwash riparian zones, and determined the watershed, landscape, and soil characteristics that govern the distribution of these forms.

MATERIALS AND METHODS

Soil organic C forms and distribution were examined at 22 sites along 14 first- through fourth-order streams of the Pawcatuck River watershed in southern Rhode Island (see Blazejewski et al., 2005). The soils ranged in drainage class from somewhat poorly drained to very poorly drained and were mapped as having alluvial or outwash parent materials (Soil Survey Staff, 1998). Of the 22 riparian sites, half were first or second order and the remainder third or fourth order (Table 1). First- and second-order riparian sites were chosen from a pool of 28 riparian sites identified by Rosenblatt et al. (2001) and mapped as having outwash soils. The sites chosen for study were representative of lower order riparian areas in southeastern New England with respect to vegetation, drainage class, and landscape characteristics. Representative higher order sites were chosen along the Wood and Beaver rivers, two of the larger tributaries of the Pawcatuck River. These sites were located at approximately equal intervals and spanned the entire length of the river. The five sites along the Beaver River and the uppermost site along the Wood River were along third-order riparian corridors and mapped as outwash soils. The other sites along the Wood River were in fourth-order settings and mapped as alluvial soils (Soil Survey Staff, 1998).

All sites were forested wetlands dominated by red maple (*Acer rubrum* L.). Common shrub species were sweet pepperbush (*Clethra alnifolia* L.), highbush blueberry (*Vaccinium corymbosum* L.), spicebush [*Lindera benzoin* (L.) Blume], and winterberry [*Ilex verticillata* (L.) A. Gray]. Other common understory species were cinnamon fern [*Osmundastrum cinnamomeum* (L.) C. Presl], skunk cabbage [*Symplocarpus foetidus* (L.) Salisb. ex W.P.C. Barton], bullbriar (*Smilax rotundifolia* L.), and sphagnum moss.

To examine the distribution of alluvium and the various C forms across the riparian landscape, we described the soils and associated morphologic C forms along transects perpendicular to each of the 22 stream reaches (Soil Survey Staff 1993). Seven C forms were identified based on the morphometric definitions of Blazejewski et al. (2005): roots, fragmental organic matter (FOM, plant remains within the soil that do not appear root derived), lenses (thin layers of C-rich material, 2 cm thick or less), infillings (filled burrows or root channels), masses (dark patches of organic-rich soil material where the apparent genetic pathway could not be identified), illuvial C (C associated with Bh and Bhs horizons), and horizon C (A, O, and associated transition and combination horizons).

Transects were oriented perpendicular to a relatively straight portion of the stream and extended from the middle of the stream to the somewhat poorly drained soils on one side. We established each transect in an area representative of the riparian zone's hydric soil width, vegetation, soil drainage class, and landscape characteristics. Both sides of the stream were considered when locating each transect. Soils along the transects were described from soil pits (75–150 cm deep) and auger borings (up to 4 m deep). A total of eight soil pits were dug among all of the transects. We dug these pits before the auger sampling to develop a typology of C forms within riparian zones of southern New England (Blazejewski et al., 2005). Bulk samples of each horizon from the soil pits were collected, air dried, and passed through a 2-mm sieve. Roots and FOM that passed through the sieve were classified as fine, and those that did not were classified as coarse. We subsequently used the auger sampling to investigate the spatial distribution of C forms. A standard auger with a 7.5-cm-diameter bucket was used to collect soil samples, except for high-*n*-value mineral materials (low bearing capacity) and organic soils, where a Macaulay peat sampler was used.

The collection of soil descriptions along each transect represents a cross-sectional view of the extent of the alluvium, outwash, and C associated with these soils (Fig. 1). We sampled every 5 m where the transect was <50 m long, and every 10 m where the transect was 50 m or longer. In cases where subsurface C quantities and distribution differed between adjacent sampling locations, we described additional profiles to ensure a comprehensive picture of the C distribution along the transect. In addition, we used auger borings to sample soils beneath the stream channels. Alluvium was identified from outwash primarily by the presence of buried organic-rich horizons or lenses. From these cross-sectional areas, we quantified the amount of alluvium across the riparian landscape.

To identify drivers of alluvium cross-sectional area, we derived estimates of watershed or landscape variables hypothesized to explain the amount of alluvium accumulation (Table 2) and used regression analyses to evaluate these relationships. Digital raster graphic versions of USGS 7.5-min quadrangle maps, available through the

Table 1. Selected stream, watershed, and landscape characteristics at each study site. See Table 2 for descriptions of each characteristic.

Site	Stream order	First-order streams	Drainage area	Drainage relief	Wetlands	Wetlands within 450 m upstream	Stream gradient	Drainage density	Till	Δ6.2-m riparian width	Min.Δ6.2-m riparian width
		no.	km^2	m		%		km km^{-2}	%	m	
Rt 2/Rt 138	1	1	0.5	6	20	22	0.3	1.4	13	292	292
Laurel Lane	1	1	3.2	52	33	42	0.3	0.1	34	338	252
Yagoo Pond	1	1	1.1	43	17	2	0.4	0.6	42	168	71
Liberty Lane	1	1	0.9	52	16	8	0.9	1.6	80	1065	407
Carolina Fish	1	1	2.0	53	2	4	0.2	0.6	33	88	50
Blitzkrieg Road	1	1	1.5	63	19	23	0.4	1.6	64	148	75
Biscuit City	1	1	0.9	46	10	23	0.0	0.8	89	639	116
Burlingame	1	1	1.3	56	8	19	0.7	1.1	97	166	78
Peckham Farm	2	2	1.8	46	5	13	0.3	1.4	59	2107	450
Alton Jones	2	2	6.1	104	7	0	0.9	0.9	95	48	48
Meadow Brook	2	4	12.9	110	14	41	0.2	0.9	59	260	155
Parris Brook	3	6	19.1	133	16	19	0.3	0.7	87	736	179
Beaver River T1	3	4	12.6	98	13	16	0.2	0.7	89	44	44
Beaver River T2	3	7	21.6	134	14	16	0.2	0.9	82	124	107
Beaver River T3	3	7	23.3	140	14	30	0.6	0.9	79	89	69
Beaver River T4	3	8	27.5	143	14	16	0.1	0.9	71	143	143
Beaver River T5	3	9	31.1	145	14	18	0.1	0.8	71	61	55
Wood River T1	3	10	47.1	162	15	44	0.2	0.8	72	192	68
Wood River T2	4	19	90.8	168	12	19	0.1	0.8	75	705	196
Wood River T3	4	30	142.5	174	13	22	0.1	0.8	75	163	163
Wood River T4	4	46	190.5	184	14	30	0.1	0.8	73	98	69
Wood River T5	4	60	221.2	188	14	39	0.0	0.8	72	220	220

Rhode Island Geographic Information Systems, were used to quantify all 11 variables examined in our analyses. Two variables, Δ6.2-m riparian width and minimum Δ6.2-m width, were examined to provide an estimate of local topography at the study sites (Table 2). The Δ6.2-m riparian width variable was defined as the distance between the stream channel and a 6.2-m (20-foot or two contour lines) gain in elevation along a line normal to the stream channel.

A forward stepwise regression (Zar, 1984) was applied to elucidate the relationships between the landscape or watershed characteristics and the cross-sectional area of alluvium at each site. Initial probability values for entry into and removal from the model were 0.10 and 0.15, respectively. In the event that no variables were significant at this level, the significance levels were decreased to 0.20 and 0.25 for entry and removal, respectively. We took this approach to increase the likelihood that several variables would be selected for the model. One-way analysis of variance was used to identify significant differences in alluvial deposition among the various order streams. A Tukey test was applied to identify means that were significantly different at the 0.05 level (Zar, 1984).

We examined the distribution of roots (live and dead) among drainage classes, between outwash and alluvial soils, with distance from the stream, and in relation to depth. To examine how root distributions differed among drainage classes, we selected one representative profile (based on soil morphology and site characteristics) from each drainage class at each site; not all drainage classes were found at all sites. A total of 342 horizons from 47 different profile descriptions was included in this analysis. The profiles were grouped into either alluvium or outwash deposits based on field identification. For each parent material, root abundance was plotted in relation to the distance from the stream and the depth from the soil surface to the middle of the horizon (midpoint depth; Fig. 2). For this analysis, horizons that had common or many roots (Soil Survey Staff, 1993) of any size class were classified together as having common/many roots. If all of the various root size classes identified within a horizon had an abundance class of few or very few (Soil Survey Staff, 1993), the horizon was considered to have few roots.

Variations in root distribution between outwash and alluvial soils were examined by comparing the range of maximum depths at which roots were observed in these landscape settings. Comparisons were made based on all 82 transect points from the 11 sites that contained both alluvial and outwash soils. Root distribution data for each transect point were placed in a group based on parent material and distance from the alluvial–outwash boundary (Fig. 3). Alluvial parent materials were located between the alluvial–outwash boundary and the stream at all sites containing both parent materials.

RESULTS AND DISCUSSION

Abundance of Carbon Forms in Riparian Settings

Roots, lenses, masses, and buried A horizons were observed to depths of >230 cm (Table 3). Of all the morphologic C forms observed, roots were the most common (identified to a depth of 4 m, the maximum depth at which any other forms were observed). Horizon C (most often as a buried A or A-transitional horizon) was the second most common C form. Although A horizons originally form at or near the soil surface, 72 of the 404 (18%) A horizons observed had a midpoint depth >100 cm (Table 3), demonstrating that buried C is commonly found in the deeper regolith of these riparian wetlands.

The distribution of C-rich lenses carries important information about landscape history. Lenses are indicative of relatively brief periods of stability at the soil surface (Blazejewski et al., 2005), and glacial deposits rarely show considerable organic C. Thus, we interpret the depth of the deepest C-rich lens as the depth to the top of glacial materials, and the depth of the uppermost lens or buried A horizon as coincident with the last episodic addition to the alluvial soils. Lenses were scarce beneath 200 cm; 65 of the 80 (81%) observations of lenses occurred 50 to 200 cm from the present soil surface. This observation suggests that alluvial deposits in first- through fourth-order riparian zones of this region tend to be <2 m thick. The presence of relatively thick O and A horizons at the present soil surface for most of the alluvial sites, and the general lack of lenses within 50 cm of the soil surface, suggests that riparian zone soils of forested lower order subwatersheds in southern New England are not currently locations of rapid deposition.

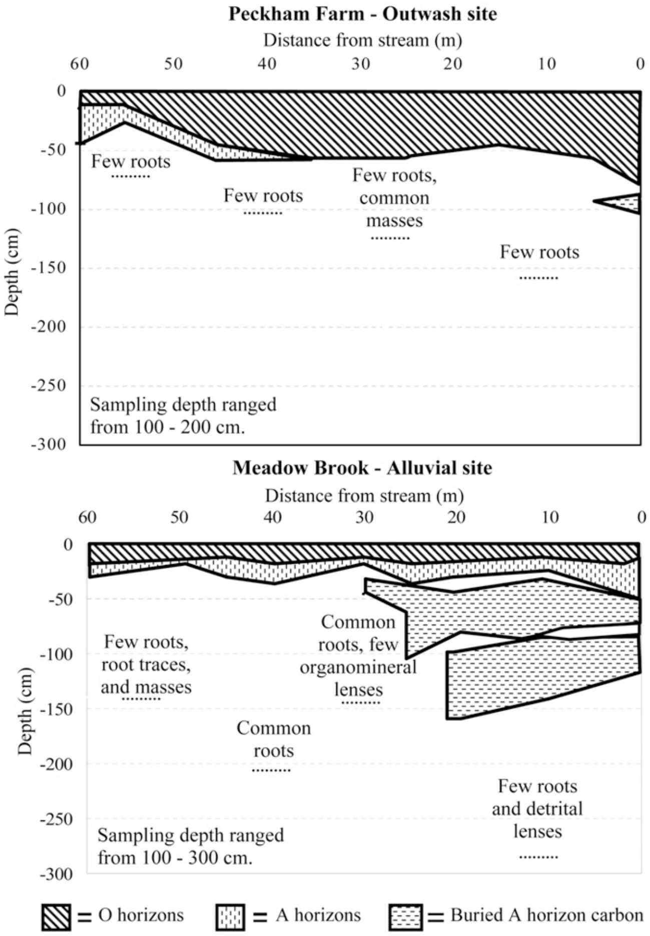


Fig. 1. Cross-sections of representative outwash (top) and alluvial (bottom) riparian zones. The alluvial geomorphic setting has greater supplies of subsurface C, and the various C forms extend to greater depths than in the outwash setting. The buried A horizon C includes Ab and buried transitional (AC or CA) horizons. The dotted lines indicate the maximum depths of the various C forms.

Carbon-rich masses were most often observed within 100 cm of the soil surface. Seventy-six percent of all masses were located within or directly underneath surface or former surface horizons (Table 3), suggesting that these C forms are intimately associated with surface or near-surface soil environments. Masses are difficult to observe in dark C-rich surface and buried surface horizons, thus it is probable that a greater percentage of masses occur within these horizons than suggested by these data.

Of the 150 soils described in the field, FOM (mostly wood chips) was identified in only 20 horizons (Table 3). This is in stark contrast to the observations made on samples collected from the soil pits and sieved in the lab. Of the eight soils sampled from pits and sieved in the lab, FOM was identified in 22 of the horizons. The greater frequency of FOM observations in the lab probably reflects the fact that FOM was much easier to observe after the soil samples were dried and sieved. Seventy-five percent of all FOM observations were made within 50 cm of the surface, and 90% of all observations were within surface or buried C-rich (buried A or O) horizons (Table 3). If pedoturbation were actively moving FOM to the soil subsurface, more observations of FOM would probably have been recorded in the deeper adjacent horizons. This suggests that alluvial deposition is mainly responsible for incorporating FOM into the subsurface.

Although illuvial C was identified in a range of drainage classes (somewhat poorly, poorly, and very poorly drained), all of these soils developed in the coarser textured outwash parent materials. The limitation of illuvial C to coarse-textured outwash

Table 2. Variables examined to assess the relationship between the cross-sectional area of alluvium and watershed characteristics. The sources of the variables were digital versions of USGS 7.5-min quadrangle maps, the Rhode Island soils coverage, and the Rhode Island wetlands coverage, all available through the Rhode Island Geographic Information System (RIGIS).

Variable	Description
Stream order	Stream order based on the Strahler (1952) stream network classification system
First-order streams	Number of first-order streams within the watershed
Drainage area	Area of watershed, delineated on digital versions of USGS 7.5-min quadrangle maps using ArcView 3.2
Drainage relief	Difference in elevation between the highest and lowest points of the watershed
Wetlands	Percentage of the watershed mapped as wetland
Wetlands within 450 m	Percentage of the area identified as wetland in the Rhode Island wetlands coverage within 450 m immediately upgradient of the study site within the watershed
Stream gradient	Gradient of the stream at the location of each study site
Drainage density	Total stream length of each watershed divided by the drainage area
Till	Percentage of the watershed mapped as having soils formed in glacial till
Δ6.2-m riparian width	Average distance between the stream channel and a 6.2-m (20-foot; two contour lines on a USGS quadrangle map) gain in elevation along a line normal to the stream channel. The side of the stream on which the transect was located was the side used to determine this variable. The distance was measured three times for each site: once at the transect location and at the locations 150 m upstream and downstream from the site location. This variable was the average of these three measurements.
Min. Δ6.2-m riparian width	Minimum average distance between the stream channel and a 6.2-m gain in elevation along a line normal to the stream channel. The side of the stream that had a lesser perpendicular distance to a 6.2-m gain in elevation was used, regardless of the transect location. The distance was measured three times 150 m apart and averaged.

soils restricted the distribution so that only seven of the 150 soils examined contained this C form. The rather limited distribution of soils with illuvial C should not suggest, however, that illuvial C is irrelevant to subsurface ecological processes in riparian zones of this region. Illuvial C dominates an entire horizon (i.e., spodic or Bhs horizons), is often separated from surface horizons, and may be particularly important in outwash settings that otherwise generally do not contain abundant subsurface C. In addition, spodic horizons often contain high concentrations of sesquioxides, which may be important sites for P sorption in riparian settings. Therefore, illuvial C may play an important role in ecosystem processes in certain riparian zones.

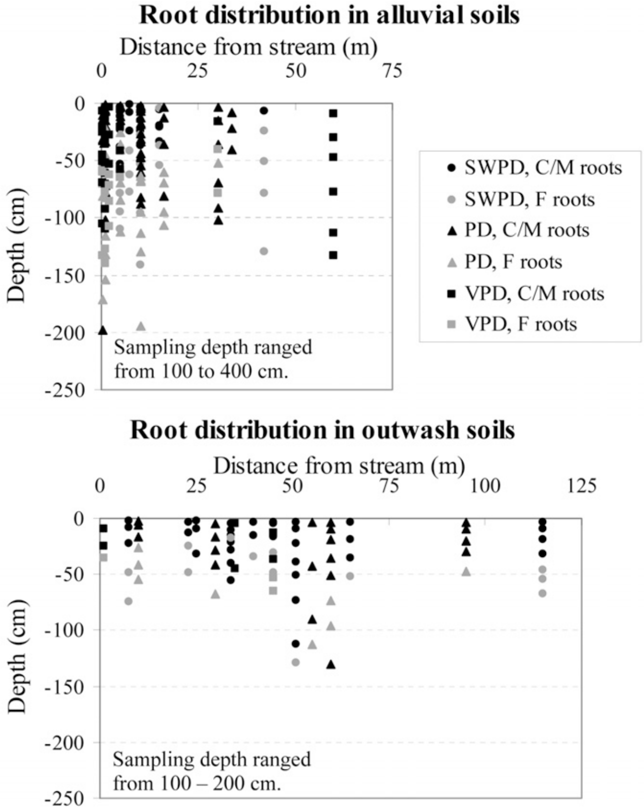
Of the 21 stream channels sampled, 17 had C-rich material buried beneath the sands and gravels on the stream bottom (Table 4). Cobbles and stones prevented sampling deeper than 30 or 40 cm in the stream channels of the four sites that lacked C-rich material, so there is the possibility of C-rich material buried beneath these rocks. Many of the C-rich horizons beneath the stream bed were designated A/C or C/A (Table 4), as there appeared to be substantial mixing of surface horizon soils with sands and gravels.

Carbon beneath the stream channel could potentially be very important for groundwater NO_3 removal. Groundwater that flows beneath the biologically active zone of the soil can be discharged into the stream via the stream bottom (Hill, 1996; Gold et al., 2001). If the C below the stream channel is sufficiently labile, associated microbial activity may create anoxic microsites; where these conditions coincide with hydraulic conductivity sufficient to attract significant amounts of flow, these areas could remove large amounts of groundwater NO_3 via groundwater denitrification. These pools of C could be especially important in the summer when water tables are low and groundwater interaction with the surface soil is at a minimum.

Alluvial Deposits and Carbon Distribution

Roots and buried A horizons (buried by alluvial deposition) represent the majority of C observed in the subsurface of riparian zones. These buried horizons and C-rich lenses, which we used to identify the distribution of alluvial soils (see the first 30 m in the alluvial setting depicted in Fig. 1), were identified in the field in 21 out of the 22 sites (Table 5). Alluvial deposits were most common and thickest immediately next to the stream. These buried C-rich layers, with their associated underlying C forms, represent an important source of C for riparian zone processes and functions (Gurwick, 2007; Gurwick et al., 2008a).

Unfortunately, identifying the extent of alluvium in lower order riparian corridors using off-site tools is not always possible. Soil surveys are often used to identify the extent of alluvial deposits. The 1:15,840-scale soil survey of our study area indicated that all 18 of the first- through third-order sites were composed entirely of outwash soils. Our field investigations, however, found that 12 of them had predominantly alluvial soils and five others contained areas of alluvial soils. These observations suggest that alluvial soils should be expected in lower order riparian zones of the glaciated Northeast. How extensive these alluvial materials are within the riparian zone, however, is unknown. Thus, we



Drainage Class Abbreviation: VPD-very poorly drained; PD-poorly drained; SWPD-somewhat poorly drained.
Root Abundance Abbreviations: C/M- common/many; F- few.

Fig. 2. Root abundance in relation to drainage class, depth, and distance from the stream within alluvial and outwash soils. Horizons that had common or many roots of any size class were classified as having common/many (C/M) roots. If all of the various root size classes identified within a horizon had an abundance class of few or very few, the horizon was classified as having few (F) roots.

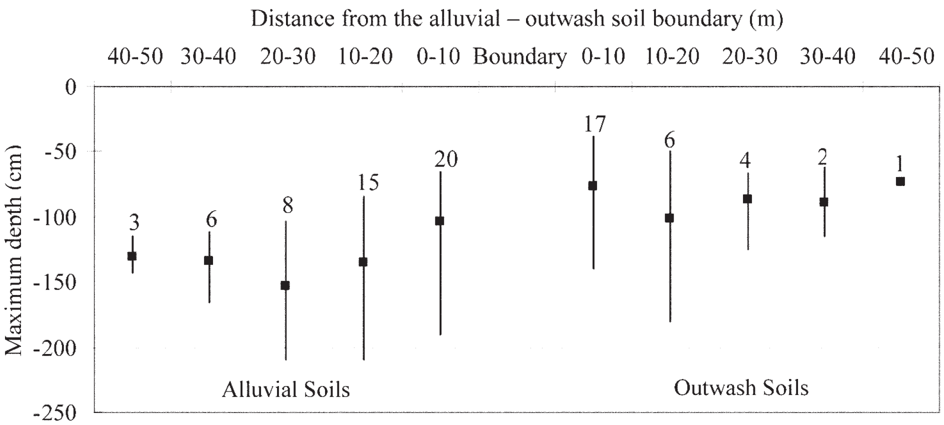


Fig. 3. Means and range of maximum depths of roots for 82 soil profiles from 11 sites, plotted against distance from the alluvial–outwash soil boundary. All observed roots (live and dead) were included in this analysis. The soil profiles were divided into 10 groups, based on their parent material and distance from the alluvial–outwash soil boundary. The lines indicate the shallowest and deepest maximum depths at which roots were observed for each group. The squares indicate the mean maximum depth of roots for that group. The number above each line indicates the number of soil profiles within that group.

Table 3. Maximum depth at which the various C forms were observed, and the number of observations of each form in relation to horizon midpoint depth and the above-surface horizon† in the riparian soils of this study.

C form	Maximum depth	Horizon midpoint depth				Total field observations	Relation to above-surface horizon		
		<50 cm	50–100 cm	100–200 cm	>200 cm		Within a surface horizon	One horizon below	Two or more horizons below
	cm	no.							
Roots	400	534	249	101	10	894	648	130	116
Fragmental organic matter	170	15	3	2	0	45	18	1	1
Lenses	350	8	34	31	7	80	48	16	16
Infillings	43	3	1	0	0	4	0	4	0
Masses	280	40	31	6	1	78	27	32	19
A horizon C	235	284	48	66	6	404	404	0	0
Bh horizon C	82	6	1	0	0	7	0	1	6
O horizon C	114	107	7	1	0	115	115	0	0

† A horizons, O horizons, and A or O transitional horizons were considered to be surface horizons, even if they are not at or near the soil surface today.

analyzed a number of watershed and landscape variables to determine if certain variables could be used to predict the extent of alluvium in lower order streams in outwash landscapes.

Although there is considerable variability among sites (CVs of 17–127%), the higher order streams tend to have a greater width of alluvium, cross-sectional area of alluvium within 10 m of the stream, and total cross-sectional area of alluvium than lower order streams (Table 5). Significant differences ($P < 0.05$) among stream orders were observed for the cross-sectional area of alluvium and the width of the alluvium across the riparian zone. The mean maximum depth of buried C-rich materials (i.e., buried surface horizons or lenses) ranged from 110 to 199 cm, with no apparent relationship to stream order (Table 5).

Our regression modeling showed that the best predictor of the cross-sectional area of alluvium for higher (third and fourth) order riparian zones was the minimum Δ6.2-m riparian width ($P < 0.05$, $R^2 = 0.37$; Fig. 4). Minimum Δ6.2-m riparian width reflects the overall flatness of the landscape and the width of the floodplain at that location. In the Midwest, valley bottom width and floodplain width were also identified as dominant factors affecting post-settlement alluviation (Magilligan, 1985; Beach, 1994; Lecce, 1997; Faulkner, 1998). Flow velocity and depth typically increase through narrow valleys, promoting transport rather than deposition of sediments (Magilligan, 1985; Lecce, 1997). Conversely, flatter and wider floodplains have the potential for greater vertical accretion across the landscape. In addition, the widest floodplains provide the greatest opportunity for lateral migration of the stream channels, further promoting the accumulation of alluvial deposits.

Table 4. Description of the C-rich material observed underneath the stream channel at each site. The numbers in parentheses indicate the total thickness of the listed horizons (cm), where applicable.

Site	Description
Rt 2/Rt 138	A/C horizon (24)
Laurel Lane	A horizon (7)
Yagoo Pond	A and AC horizons (40)
Liberty Lane	A and A/C horizons (25)
Carolina Fish	C/A horizon (16)
Blitzkrieg Road	Ab and A/C horizons (40)
Biscuit City	A/C horizon (47)
Burlingame	Multiple Ab horizons up to 135 cm
Peckham Farm	A horizon (30)
Alton Jones	None
Meadow Brook	Ab horizon (7)
Parris Brook	Ab and A/C horizons (40)
Beaver River T1	A and A/C horizons (20)
Beaver River T2	None
Beaver River T3	A/C horizon (30)
Beaver River T4	Lens of wood chips at 35 cm
Beaver River T5	A/C horizon (20)
Wood River T1	None
Wood River T2	None
Wood River T3	A and A/C horizons (40)
Wood River T4	A horizon (15)
Wood River T5	Not accessible

To determine if the same relationships established for third- and fourth-order riparian zones held for lower order streams of the watershed, a stepwise regression analysis was performed on the first- and second-order streams. In this analysis, drainage area ($P \leq 0.001$) and wetland percentage within 450 m upstream ($P < 0.10$) were the variables meeting the probability criteria for the model (Fig. 5). Both variables were positively related to alluvial deposition ($R^2 = 0.87$). We hypothesized that the large values of the wetland percentage within 450 m variable reflect an extensive low-lying floodplain, similar to the minimum Δ6.2-m riparian width variable, which provides a greater opportunity for alluvial deposition than a narrow riparian zone with steep slopes to the upland. Faulkner (1998) found drainage area to be the only significant factor affecting alluvial deposition in watersheds <20 km^2. All 11 of our first- and second-order sites had a drainage area <20 km^2, further suggesting that alluviation is controlled by similar factors in comparably sized watersheds across North America.

Distribution of Roots

Alluviation appears to be the dominant soil process affecting the root distribution in riparian zones. Of the 22 riparian sites, 11 contained areas of outwash soils adjacent to alluvial soils (i.e., Fig. 1, alluvial setting). At these sites, the vertical root distribution tended to be greater within the alluvial soils portion of the landscape, and the maximum depth at which roots were observed generally increased closer to the stream (i.e., further from the outwash alluvium boundary; Fig. 3). Most roots in the deep subsurface of the riparian zones in this region appear to be relics hundreds to thousands of years old (Gurwick, 2007), suggesting that roots are not simply growing deeper closer to the streams, but that as surface soils, which contain roots, are buried rapidly during episodic events, some of the root tissue associated with that soil is buried and preserved. The distribution of roots in the

Table 5. Cross-sectional area of alluvium, cross-sectional area of alluvium within 10 m of the stream, width of alluvium, and maximum depth of buried C-rich material at each site.

Site	Stream order	Cross-sectional area of alluvium	Cross-sectional area of alluvium within 10 m of the stream	Width of alluvium	Maximum depth of buried C-rich material†
		m^2		m	cm
Rt 2/Rt 138	1	0	0	0	0
Laurel Lane	1	15	7	30	138
Yagoo Pond	1	4	4	5	123
Liberty Lane	1	4	4	7	76
Carolina Fish	1	6	6	5	120
Blitzkrieg Road	1	9	6	15	85
Biscuit City	1	11	8	15	76
Burlingame	1	19	18	10	265
First-order means‡		9 a (74%)	7 a (79%)	11 a (85%)	110 a (69%)
Peckham Farm	2	1	1	1	96
Alton Jones	2	11	7	15	80
Meadow Brook	2	53	12	40	350
Second-order means		22 ab (127%)	7 a (83%)	19 ab (106%)	175 a (86%)
Parris Brook	3	43	11	46	300
Beaver River T1	3	35	12	40	120
Beaver River T2	3	3	3	5	70
Beaver River T3	3	12	12	10	150
Beaver River T4	3	15	8	20	95
Beaver River T5	3	48	20	42	290
Wood River T1	3	12	7	20	86
Third-order means		24 ab (74%)	10 a (51%)	26 ab (63%)	159 a (61%)
Wood River T2	4	43	14	40	142
Wood River T3	4	56	18	35	210
Wood River T4	4	19	12	20	208
Wood River T5	4	90	15	70	235
Fourth-order means		52 b (57%)	15 a (17%)	41 b (51%)	199 a (20%)

† Buried C-rich material was considered to be surface horizons or lenses buried beneath alluvial deposits.

‡ Means with different letters are significantly different at the 0.05 level. Coefficients of variation are indicated in parentheses.

subsurface may simply reflect the spatial distribution of buried horizons, which appears related to distance from the stream.

Implications

Although biologic, pedologic, and geomorphic processes govern the spatial distribution of C within riparian landscapes, distinctly different patterns in the extent of the various C forms were observed between alluvial and outwash soils. These observations suggest that geomorphic processes, particularly flooding and deposition, impart a substantial effect on the soil C distribution in riparian corridors along first- through fourth-order streams. These processes result in the burial of substantial C in the form of roots and organic-rich layers (up to 4 m below the present soil surface). Roots buried nearly 1 m below the present soil surface were dated to >4000 yr old, and leaf fragments from 3 m deep dated to >13,000 yr old (Blazejewski et al., 2005; Gurwick, 2007). These data indicate that in the saturated riparian soils, dead plant material may require thousands of years to decompose. How effective these plant remains are at fueling riparian functions such as denitrification is unknown, but laboratory studies on numerous buried horizons coupled with in situ studies using natural abundance ^{14}C have shown that ancient C supports present-day microbial activity in the riparian subsurface (Gurwick et al., 2008b).

To develop an understanding of the patterns of ecosystem processes such as denitrification and C storage at a regional scale, modelers depend on offsite tools such as soil surveys to identify functionally significant areas of the landscape. Our study found that 1:15,840-scale soil surveys were ineffective at mapping the extent of alluvial soils along lower order streams mapped as outwash. These omissions are probably a consequence of mapping at scales too small to illustrate narrow bands of alluvium. As such, soil survey users should expect to find greater quantities of alluvium than indicated by county-scale soil surveys, especially along lower order streams.

Statistical analysis of a variety of watershed characteristics suggested that watershed size and floodplain width are the best predictors of the cross-sectional area of alluvial deposits within a

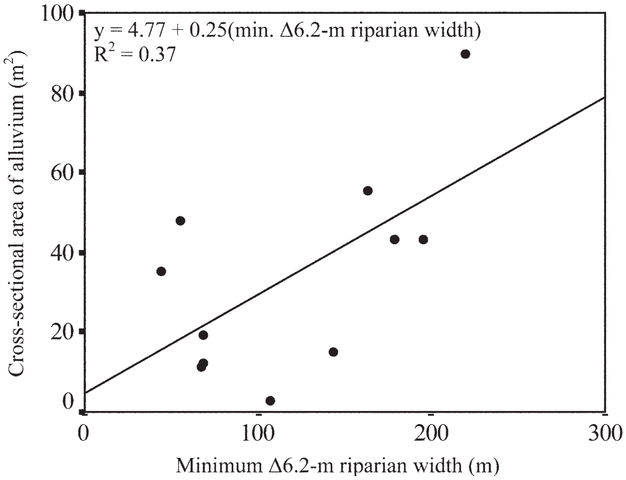


Fig. 4. Correlation between the cross-sectional area of alluvium and the minimum Δ6.2-m riparian width for third- and fourth-order sites (n = 11). The minimum Δ6.2-m riparian width was the only significant ($P < 0.05$) variable selected by a stepwise regression analysis.

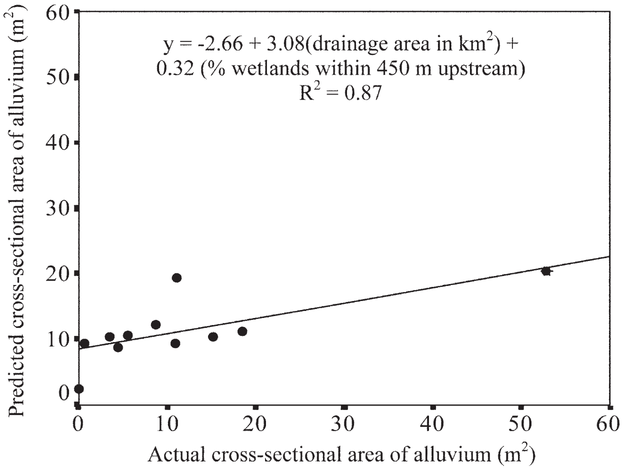


Fig. 5. Predicted value of cross-sectional area of alluvium vs. the actual value for first- and second-order sites (*n* = 11). Drainage area (*P* < 0.001) and wetland percentage within 450 m upstream (*P* < 0.1) were the two significant variables selected by a stepwise regression analysis.

riparian zone. Flat, wide floodplains appear to provide a greater opportunity for alluvial deposition than narrow floodplains. Although statistically significant relationships were identified, additional research is needed to confirm the accuracy of the models. Kellogg et al. (2005) examined in situ groundwater denitrification rates at four riparian zones of this study, and found that the one site that showed a significant decline in denitrification rates with depth lacked buried organically enriched layers. If future studies also show that riparian zones of different geomorphic settings are different functionally, having an offsite tool to identify specific types of riparian zones would be extremely useful. One approach may be to develop high-intensity soil survey procedures, on the order of wetland delineations, to map specific types of riparian zones. These maps would assist scientists and regulators to accurately assess and manage riparian zones for the various functions that these ecosystems provide.

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