SPATIAL DISTRIBUTION OF CARBON IN THE SUBSURFACE OF RIPARIAN ZONES

Abstract

Soil carbon supplies vary spatially within and among riparian wetlands. Understanding this variability is essential to assessments of carbon-dependent riparian wetland functions such as water quality enhancement and carbon storage. In this study, we examined the distribution of carbon with depth across the riparian landscape. Our objectives were to describe the spatial distribution of various carbon 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 carbon in the subsurface representing an important source of carbon for riparian zones functions.

Buried A horizons and carbon-rich lenses, which define the distribution 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. In order to assess the best predictors of alluvium distribution within riparian zones, eleven watershed characteristics were examined. A forward stepwise regression found that watershed size and floodplain width are two of the most important indicators of the quantity, width, and depth of alluvium, and subsequently subsurface carbon, within glaciated riparian zones.
Soil carbon stocks are variable within and among riparian zones. The quantities and forms of carbon vary spatially, especially in the subsurface. Recent studies have documented the presence of carbon rich layers at depths greater than one meter in riparian zones (Hill et al., 2000; Blazejewski et al., 2005). In addition, numerous carbon forms have been identified in riparian soils (Blazejewski et al., 2005). Understanding the spatial distribution of these carbon forms is essential for scientists and regulators to accurately assess carbon-dependent functions of different areas of a riparian wetland.

Groundwater denitrification is one common carbon-dependent function in riparian wetlands. Studies have shown that the highest rates of groundwater denitrification in the subsurface occur where nitrate-laden groundwater interacts with supplies of labile organic carbon (Robertson et al., 1991; Jacinthe et al., 1998; Devito et al., 2000; Hill et al., 2000). In order to manage riparian zones for water quality protection, scientists must be able to identify the locations of subsurface carbon in relation to groundwater flow.

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 allowing groundwater to avoid contact with subsurface carbon (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, other organic materials are underlain by glacial tills which can have very slow permeability. Parent materials such as outwash and alluvium typically contain stratified and or sorted layers of sands and gravels (Larson and Stone, 1982; Melvin et al, 1992; Benn and Evans, 1998). Thus, in these types of riparian zones there is likely significant groundwater flow in the
subsurface (Kellogg et al., 2005). As such, subsurface carbon in alluvial and outwash riparian
wetlands will likely have a greater potential for fueling groundwater nitrate removal than
subsurface carbon located in till and in many organic riparian wetlands.

The key to understanding carbon distribution in the riparian subsurface may be to
determine the factors driving streamside deposition (which is often referred to as alluviation,
Fanning and Fanning, 1989). Alluvial soils typically contain buried carbon enriched horizons, as
well as a variety of other carbon forms in the subsurface (Blazejewski et al., 2005). 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., floodplain
width) and watershed characteristics (e.g., stream order, drainage area) can also control
alluviation by affecting overbank flow and lateral migration. In North America, beavers (Castor
canadensis) were very abundant historically, and have likely 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 carbon
forms within riparian zones of other regions of North America.

Subsurface carbon can result from numerous pedogenic, biologic, and geomorphic
processes. Similar to alluviation, many of these processes are controlled by specific watershed,
landscape, and soil characteristics. Therefore, the probability exists that the spatial distributions
of the various subsurface carbon forms are related to characteristics such as these, which essentially promote or inhibit their formation. In this study, we investigated the spatial distribution of the various carbon 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 carbon form and distribution were examined at 22 sites along fourteen first through fourth order streams of the Pawcatuck River watershed in southern Rhode Island. Soils ranged in drainage class from somewhat poorly drained (SWPD) to very poorly drained (VPD) and were mapped as having alluvial or outwash parent materials (USDA, 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. 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 fairly equal intervals apart while spanning 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 (USDA, 1998).

All sites were forested wetlands dominated by red maple (*Acer rubrum*). Common shrub species were sweet pepperbush (*Clethra alnifolia*), highbush blueberry (*Vaccinium corymbosum*), spicebush (*Lindera benzoin*), and winterberry (*Ilex verticillata*). Other common
understory species were cinnamon fern (*Osmunda cinnamomea*), skunk cabbage (*Symplocarpus foetidus*), bullbriar (*Smilax rotundifolia*) and *Sphagnum* moss.

In order to examine the distribution of alluvium and the various carbon forms across the riparian landscape, we described the soils and associated carbon forms along a transect perpendicular to each of the 22 stream reaches. Soils were described according to Soil Survey Staff (1993), paying close attention to the various carbon forms. Six carbon 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 carbon 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), and horizon carbon (A, O, Bh or Bhs, and associated transition and combination horizons). Carbon associated with Bh and Bhs horizons was termed illuvial carbon.

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. Each transect was established in an area representative of the riparian zone in terms of 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 to 150 cm deep) and auger borings (up to 4 m deep). A standard bucket auger 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. We sampled every 5 m if the transect was less than 50 m long, and every 10 m if the transect was 50 m or longer. In cases where adjacent sampling locations differed considerably in terms of subsurface carbon quantities and distribution, we described additional profiles in order to develop a greater understanding of the carbon distribution along the transect. In addition to examining the terrestrial settings, we used
auger borings to sample soils beneath the stream channels. A total of eight soil pits were dug along the transects. Bulk samples of each horizon from these pits were collected, air dried, and passed through a 2-mm sieve. Roots and FOM were classified as coarse (the portions that do not pass through a 2-mm sieve) and fine.

The collection of soil descriptions along each transect represents a cross-sectional view of the extent of the alluvium, outwash, and carbon associated with these soils (Fig. 1). Alluvial soils were recognized based on the presence of buried organic rich horizons or lenses. From these cross-sectional areas, we quantified the amount of alluvium across the riparian landscape. We compared these measures with other riparian zone and watershed characteristics to assess relationships between the amount of alluvium and watershed/landscape characteristics (Table 2).

Digital versions of USGS 7.5 minute quadrangle maps, available through the Rhode Island Geographic Information Systems (RIGIS), were used to quantify all eleven 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 feet; two contour lines) gain in elevation along a line normal to the stream channel.

A forward stepwise regression (Zar, 1984) was applied to elucidate relationships between the landscape/watershed characteristics and the cross-sectional area of alluvium at each site. 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. This approach was taken in order to increase the likelihood that several variables would be selected for the model. Our purpose was to determine which factors might be most useful at explaining the variation in alluvial cross-sectional area among sites, not necessarily which factors were
highly significant. One-way Analysis of Variance was used to identify significant
differences in alluvial deposition among the various order streams. A Tukeys 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) both among drainage classes
and between outwash and alluvial soils. To examine how root distributions differed among
drainage classes, we selected one representative profile 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 were 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 stream and the depth from the soil
surface to the middle of the horizon (“mid-point depth”). Ordinal scale root abundance
classes (few, common, and many; Soil Survey Staff, 1993) were used to quantify root
abundance.

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.
Abundance of Carbon Forms in Riparian Settings

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

Carbon-rich lenses were only observed in alluvial soils and most were located 50 to 200 cm from the present soil surface. Lenses are indicative of relatively brief periods of stability at the soil surface (Blazejewski et al., 2005). Glacial deposits rarely show considerable organic carbon. Thus, our interpretations of the soil morphology are that the depth of the deepest carbon-rich lens represents the depth to top of the glacial materials; and that the depth of the uppermost lens or buried A horizon represents the last rapid or episodic addition to the alluvial soils. The scarcity of lenses beneath 200 cm suggests that alluvial deposits in first through fourth order riparian zones of this region tend to be less than two meters 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 locations of rapid deposition at the present time.

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), indicating that these carbon forms are intimately associated with surface or
near-surface soil environments. Masses are difficult to observe in dark carbon-rich surface and
buried surface horizons, thus it is very probable that a greater percentage of masses occur within
these horizons than is suggested by these data.

Of the 150 soils described in the field, FOM (mostly wood chips) was identified in only
twenty horizons (Table 3). This is in stark contrast to the observations made on samples
collected from the soil pits and treated in the lab. Of the 8 soils sampled from pits and treated in
the lab, FOM was identified in twenty-two of the horizons. The greater frequency of FOM
observations in the lab likely 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 surface (buried
A or O) horizons (Table 3). If pedoturbation were actively moving FOM to the soil subsurface,
more observations of FOM would have likely been recorded in the deeper adjacent horizons.
This suggests that alluvial deposition is the main process responsible for incorporating FOM into
the subsurface.

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

Of the 21 stream channels that were sampled, 17 had carbon-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 carbon-rich material, so there is the possibility that there may be carbon-rich material buried beneath these rocks. Many of the carbon-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 nitrate 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 carbon below the stream channel is labile, anaerobic conditions exist (possibly in microsites), and the hydraulic conductivity of these layers is sufficient to attract significant amounts of flow, these areas could potentially remove high amounts of groundwater nitrate via groundwater denitrification. These pools of carbon could be especially important in the summer when water tables are very 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 carbon in the subsurface of riparian zones. These buried horizons and carbon-rich lenses, which essentially define 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 4). Alluvial deposits were most common and thickest immediately next to the stream. These
buried carbon-rich layers, with their associated underlying carbon forms, represent an
important source of carbon for riparian zones processes and functions (Gurwick, 2007).

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, however, indicated
that all 18 of the first through third order sites were composed entirely of outwash soils,
when our field investigations found that 12 of them had predominantly alluvial soils, and 5
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 analyzed a
number of watershed and landscape variables to determine if certain variables could be used
as a predictor of the extent of alluvium in lower order streams in outwash landscapes.

Although there is a great deal of variability among sites (coefficients of variation ranged
from 17 to 127%), the higher order streams tend to have a greater distribution of alluvium than
lower order streams (Table 4). Significant differences (0.05 level) 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 carbon rich materials (i.e. buried surface
horizons or lenses) ranged from 110 to 199 cm, with no apparent systematic explanation based
on stream order for the depth of buried layers (Table 4).

Our regression modeling showed that the best predictor of alluvium for higher (3rd and 4th)
order riparian zones was the minimum Δ6.2-m riparian width (P<0.05; R² = 0.37; Fig. 4).
Minimum Δ6.2-m riparian width reflects the overall flatness of landscape and width of the
floodplain at the location of the riparian zone. In the Midwest, valley bottom width and
floodplain width were also identified as dominant factors affecting post-settlement alluviation.
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 all of 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.

To determine if the same relationships established for third and fourth order also held for first and second order streams, a stepwise regression analysis was performed on just the first and second order streams. In this analysis, drainage area (P<0.001) and percent wetlands within 450 m upstream (P<0.10) were the variables meeting probability criteria for the model (Fig. 5). Both variables were positively related to increasing alluvial deposition (R² = 0.87). We hypothesized that the percent wetlands within 450 m variable reflects 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 less than 20 km². All eleven of our first and second order sites had a drainage area less than 20 km², further suggesting that alluviation is controlled by similar factors in comparably sized watersheds in various regions of North America.

**Distribution of Roots**

Alluviation appears to be the dominant soil process affecting root distribution in the riparian zones. Of the 22 riparian sites, 11 sites contained areas of outwash soils adjacent to alluvial soils (i.e. Fig. 1, alluvial setting). At these sites, 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). This occurs because flooding and deposition are more common closer to the
streams, and subsequently alluvial deposits are thickest closer to the streams. Thus, roots that
were once located close to or at the soil surface become buried deeper and deeper over time.
Most roots in the deep subsurface of riparian zones in this region appear to be hundreds to
thousands of years old (Gurwick, 2007), suggesting that roots are not simply growing deeper
closer to the streams, but geomorphic process (alluviation) is responsible for their presence at
great depths.

Implications

Although biologic, pedologic, and geomorphic processes govern the spatial distribution of
carbon within riparian landscapes, distinctly different patterns in the extent of the various carbon
forms were observed between alluvial and outwash soils. These observations suggest that
geomorphic processes, particularly flooding and deposition, impart a substantial effect on soil
carbon distribution in riparian corridors along the first through fourth order streams. These
processes result in the burial of substantial carbon in the form of roots and organic rich layers
(up to 4 meters below the present soil surface). Roots buried nearly a meter below the present
soil surface were dated to over 4000 years old, and leaf fragments from three meters deep dated
to over 13000 years 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. The
fact that these plant materials are still observable in the field suggests that decomposition is far
from complete. How effective these thousands of year old plant remains are at fueling riparian
functions such as denitrification is unknown and demonstrate a need to determine whether these
carbon forms support present-day microbial activity.

In order to develop an understanding of the patterns of ecosystem processes such as
denitrification and carbon 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 1:15840-scale soil surveys consistently misrepresented the extent of alluvial soils along lower order streams mapped as outwash. As such, soil survey users should expect to find greater quantities of alluvium, especially along lower order streams, than indicated by county scale soil surveys.

Statistical analysis of a variety of watershed characteristics suggested that watershed size and floodplain width are the best predictors of the extent of alluvial deposits within a 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 strengthen and 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 continue to show that riparian zones of different geomorphic settings are also 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.
REFERENCES


USDA. 1998. SSURGO: Soil survey geographic database for State of Rhode Island. USDA, NRCS, NCSS National Cartography and Geospatial Center, Fort Worth, TX.

List of Figures.

Figure 1. Cross sections of representative outwash and alluvial riparian zones. The alluvial geomorphic setting has greater supplies of subsurface carbon, and the various carbon forms extend to greater depths than in the outwash setting. The buried A horizon carbon includes Ab and buried transitional horizons (AC or CA horizons).

Figure 2. Root abundance in relation to drainage class, depth and distance from stream within alluvial and outwash soils.

Figure 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.

Figure 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.

Figure 5. Predicted value of cross-sectional area of alluvium vs. actual value for first and second order sites (N = 11). Drainage area (P<0.001) and percent wetlands within 450 m upstream (P<0.1) were the two significant variables selected by a stepwise regression analysis.
Figure 1. Cross sections of representative outwash and alluvial riparian zones. The alluvial geomorphic setting has greater supplies of subsurface carbon, and the various carbon forms extend to greater depths than in the outwash setting. The buried A horizon carbon includes Ab and buried transitional horizons (AC or CA horizons).
Root distribution in alluvial soils

Sampling depth ranged from 100 to 400 cm.

Root distribution in outwash soils

Sampling depth ranged from 100 – 200 cm.

**Drainage Class Abbreviation:** VPD-very poorly drained; PD-poorly drained; SWPD-somewhat poorly drained.

**Root Abundance Abbreviations:** F-few; C/M- common/many.

**Figure 2.** Root abundance in relation to drainage class, depth, and distance from stream within alluvial and outwash soils.
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.
**Figure 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.

\[ y = 4.77 + 0.25(\text{min. Δ6.2-m riparian width}) \]

\[ R^2 = 0.37 \]
Figure 5. Predicted value of cross-sectional area of alluvium vs. actual value for first and second order sites (N = 11). Drainage area (P<0.001) and percent wetlands within 450 m upstream (P<0.1) were the two significant variables selected by a stepwise regression analysis.

\[ y = -2.66 + 3.08(\text{drainage area in km}^2) + 0.32 \times (\% \text{ wetlands within 450 m upstream}) \]

\[ R^2 = 0.87 \]
Table 1. Selected stream, watershed, and landscape characteristics at each study site. See Table 2 for descriptions of the each characteristic.

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<th>Site</th>
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<th>Drainage density (km/km²)</th>
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<td>4</td>
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<td>Beaver River T1</td>
<td>3</td>
<td>4</td>
<td>12.6</td>
<td>98</td>
<td>13</td>
<td>16</td>
<td>0.2</td>
<td>0.7</td>
<td>89</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
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<td>134</td>
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<td>0.9</td>
<td>82</td>
<td>124</td>
<td>107</td>
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<tr>
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<td>7</td>
<td>23.3</td>
<td>140</td>
<td>14</td>
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<td>0.9</td>
<td>79</td>
<td>89</td>
<td>69</td>
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<tr>
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<td>143</td>
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<td>0.9</td>
<td>71</td>
<td>143</td>
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<td>31.1</td>
<td>145</td>
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<td>61</td>
<td>55</td>
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<tr>
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<td>10</td>
<td>47.1</td>
<td>162</td>
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<td>44</td>
<td>0.2</td>
<td>0.8</td>
<td>72</td>
<td>192</td>
<td>68</td>
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<td>19</td>
<td>90.8</td>
<td>168</td>
<td>12</td>
<td>19</td>
<td>0.1</td>
<td>0.8</td>
<td>75</td>
<td>705</td>
<td>196</td>
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<td>Wood River T3</td>
<td>4</td>
<td>30</td>
<td>142.5</td>
<td>174</td>
<td>13</td>
<td>22</td>
<td>0.1</td>
<td>0.8</td>
<td>75</td>
<td>163</td>
<td>163</td>
</tr>
<tr>
<td>Wood River T4</td>
<td>4</td>
<td>46</td>
<td>190.5</td>
<td>184</td>
<td>14</td>
<td>30</td>
<td>0.1</td>
<td>0.8</td>
<td>73</td>
<td>98</td>
<td>69</td>
</tr>
<tr>
<td>Wood River T5</td>
<td>4</td>
<td>60</td>
<td>221.2</td>
<td>188</td>
<td>14</td>
<td>39</td>
<td>0.0</td>
<td>0.8</td>
<td>72</td>
<td>220</td>
<td>220</td>
</tr>
</tbody>
</table>
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 minute quadrangle maps, the Rhode Island soils coverage, and the Rhode Island wetlands coverage, all available through the Rhode Island Geographic Information System (RIGIS).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream order</td>
<td>Stream order based on the Strahler (1952) stream network classification system</td>
</tr>
<tr>
<td>Number of first order streams</td>
<td>Number of first order streams within the watershed</td>
</tr>
<tr>
<td>Drainage area</td>
<td>Area of watershed</td>
</tr>
<tr>
<td>Drainage relief</td>
<td>Difference in elevation between the highest and lowest points of the watershed</td>
</tr>
<tr>
<td>Percent wetlands</td>
<td>Percent of the watershed mapped as wetland</td>
</tr>
<tr>
<td>Percent wetlands within 450 m</td>
<td>Percentage of the area identified as wetland in the Rhode Island wetlands coverage within 450 m immediately up-gradient of the study site within the watershed</td>
</tr>
<tr>
<td>Stream gradient</td>
<td>Gradient of the stream at the location of each study site</td>
</tr>
<tr>
<td>Drainage density</td>
<td>Total stream length of each watershed divided by the drainage area</td>
</tr>
<tr>
<td>Percent till</td>
<td>Percent of the watershed mapped as having soils formed in glacial till</td>
</tr>
<tr>
<td>Δ6.2 m-riparian width</td>
<td>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 on which the transect was located was the side used to determine this variable. The distance was measured 3 times for each site, once at the transect location, and at the locations 150 m upstream and downstream from the site location. The average of these 3 measurements represented this variable.</td>
</tr>
<tr>
<td>Minimum Δ6.2 m-riparian width</td>
<td>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 3 times 150 m apart and averaged.</td>
</tr>
</tbody>
</table>
Table 3. Maximum depth at which the various carbon forms were observed, and the number of observations of each form (excluding roots) in relation to horizon mid-point depth and the above surface horizon† in the riparian soils of this study.

<table>
<thead>
<tr>
<th>Carbon Form</th>
<th>Maximum depth (cm)</th>
<th>&lt;50</th>
<th>50-100</th>
<th>100-200</th>
<th>&gt;200</th>
<th>Total Field Observations</th>
<th>Within a surface horizon</th>
<th>One horizon below</th>
<th>Two or more horizons below</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roots</td>
<td>400</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Fragmental organic matter</td>
<td>170</td>
<td>15</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>45</td>
<td>18</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Lenses</td>
<td>350</td>
<td>8</td>
<td>34</td>
<td>31</td>
<td>7</td>
<td>80</td>
<td>48</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Infillings</td>
<td>43</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Masses</td>
<td>280</td>
<td>40</td>
<td>31</td>
<td>6</td>
<td>1</td>
<td>78</td>
<td>27</td>
<td>32</td>
<td>19</td>
</tr>
<tr>
<td>Horizon Carbon (A)</td>
<td>235</td>
<td>284</td>
<td>48</td>
<td>66</td>
<td>6</td>
<td>404</td>
<td>404</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Horizon Carbon (Bh)</td>
<td>82</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Horizon Carbon (O)</td>
<td>114</td>
<td>107</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>115</td>
<td>115</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

† 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.
Table 4. Cross-sectional area of alluvium, cross-sectional area of alluvium within 10 m of the stream, width of alluvium, maximum depth of buried carbon-rich material, and a summary of the carbon-rich material observed underneath the stream channel at each site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Stream order</th>
<th>Cross-sectional area of alluvium (m²)</th>
<th>Cross-sectional area of alluvium within 10 m of the stream (m²)</th>
<th>Width of alluvium (m)</th>
<th>Maximum depth of buried carbon-rich material† (cm)</th>
<th>Summary of carbon-rich material observed underneath the stream channel‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rt 2 / Rt 138</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>A/C horizon (24)</td>
</tr>
<tr>
<td>Laurel Lane</td>
<td>1</td>
<td>15</td>
<td>7</td>
<td>30</td>
<td>138</td>
<td>A horizon (7)</td>
</tr>
<tr>
<td>Yagoo Pond</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>123</td>
<td>A and AC horizons (40)</td>
</tr>
<tr>
<td>Liberty Lane</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>76</td>
<td>A and A/C horizons (25)</td>
</tr>
<tr>
<td>Carolina Fish</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>120</td>
<td>C/A horizon (16)</td>
</tr>
<tr>
<td>Blitzkrieg Road</td>
<td>1</td>
<td>9</td>
<td>6</td>
<td>15</td>
<td>85</td>
<td>Ab and A/C horizons (40)</td>
</tr>
<tr>
<td>Biscuit City</td>
<td>1</td>
<td>11</td>
<td>8</td>
<td>15</td>
<td>76</td>
<td>A/C horizon (47)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Multiple Ab horizons up to 135 cm</td>
</tr>
<tr>
<td>Buntingame</td>
<td>1</td>
<td>19</td>
<td>18</td>
<td>10</td>
<td>265</td>
<td>A/C horizon (24)</td>
</tr>
<tr>
<td>1st order means§</td>
<td>9a (74%)</td>
<td>7a (79%)</td>
<td>11a (85%)</td>
<td>110a (69%)</td>
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<td></td>
</tr>
<tr>
<td>Peckham Farm</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>96</td>
<td>A horizon (30)</td>
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<tr>
<td>Alton Jones</td>
<td>2</td>
<td>11</td>
<td>7</td>
<td>15</td>
<td>80</td>
<td>None</td>
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<tr>
<td>Meadow Brook</td>
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<td>53</td>
<td>12</td>
<td>40</td>
<td>350</td>
<td>Ab horizon (7)</td>
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<tr>
<td>2nd order means</td>
<td>22ab (127%)</td>
<td>7a (83%)</td>
<td>19ab (106%)</td>
<td>175a (86%)</td>
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<td>Parris Brook</td>
<td>3</td>
<td>43</td>
<td>11</td>
<td>46</td>
<td>300</td>
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<td>35</td>
<td>12</td>
<td>40</td>
<td>120</td>
<td>A and A/C horizons (20)</td>
</tr>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>70</td>
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<td>Beaver River T3</td>
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<td>12</td>
<td>10</td>
<td>150</td>
<td>A/C horizon (30)</td>
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<td>Beaver River T4</td>
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<td>15</td>
<td>8</td>
<td>20</td>
<td>95</td>
<td>Lens of wood chips at 35 cm</td>
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<td>Beaver River T5</td>
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<td>48</td>
<td>20</td>
<td>42</td>
<td>290</td>
<td>A/C horizon (20)</td>
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<td>12</td>
<td>7</td>
<td>20</td>
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<tr>
<td>3rd order means</td>
<td>24ab (74%)</td>
<td>10a (51%)</td>
<td>26ab (63%)</td>
<td>159a (61%)</td>
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<td></td>
</tr>
<tr>
<td>Wood River T2</td>
<td>4</td>
<td>43</td>
<td>14</td>
<td>40</td>
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<td>12</td>
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<td>Wood River T5</td>
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<td>90</td>
<td>15</td>
<td>70</td>
<td>235</td>
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<td>4th order means</td>
<td>52b (57%)</td>
<td>15a (17%)</td>
<td>41b (51%)</td>
<td>199a (20%)</td>
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</tr>
</tbody>
</table>

† Buried carbon rich material was considered to be surface horizons or lenses buried beneath alluvial deposits.
‡ The number in parentheses indicates the total thickness of the listed horizon(s) in cm, where applicable.
§ Means with different letters are significantly different at the 0.05 level. Coefficients of variation are indicated in parentheses.

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