

Macro- and Micromorphology of Subsurface Carbon in Riparian Zone Soils

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ABSTRACT

Soil organic matter (SOM) contains fractions that range from very active to passive, relative to microbial-driven ecosystem processes and functions. A classification system is needed that can test the hypothesis that SOM can be separated by morphology into functionally meaningful fractions. The objectives of this study were to use macro- and micromorphological techniques to classify the various C forms present in saturated (or seasonally saturated) subsurface horizons of hydric riparian soils, and to increase our understanding of their genesis. Nine soils formed in outwash or alluvium, located in Rhode Island riparian wetlands, were described and sampled up to depths of over 3 m. The majority of these soils had seasonally high water table levels at or above the soil surface. Thirty-four thin sections were constructed from undisturbed samples collected from subsurface horizons for micromorphological investigation. Six C forms (roots, fragmental organic matter [FOM], lenses, infillings, masses, and horizon C) and five root-decomposition classes were identified. All C forms were more abundant in the subsurface of alluvial soils than in the subsurface of outwash soils. Masses and roots were the most abundant C form identified. Most masses have likely formed from dispersion of C associated with decomposed roots. Alluvial deposition has resulted in considerable C in subsurface riparian zone soils in the form of buried A and O horizons, lenses, and FOM. Illuvial-horizon C was found primarily in sandy horizons having outwash parent materials. Carbon dating suggested that many of these C forms persist for thousands of years in the riparian subsurface. The variety of C forms that exist in riparian zone subsoils suggests that understanding C morphology, and how these forms are related, may prove useful for developing functionally different morphologic classes of soil C.

SOIL ORGANIC CARBON supplies govern a number of ecological processes operating within riparian wetlands. One such process is denitrification, the conversion of nitrate to nitrogen gases by primarily heterotrophic bacteria (Knowles, 1982). High rates of denitrification have been recorded in surface horizons of riparian soils (Pinay et al., 1993; Schipper et al., 1993). In many riparian settings, however, only a small portion of the groundwater moves through surface horizons (Hill et al., 2000; Gold et al., 2001). The highest rates of denitrification in the subsurface riparian soils have been observed where nitrate-laden groundwater interacts with supplies of oxidizable (i.e., active or labile) organic C (Robertson et al., 1991; Hedin et al., 1998; Devito et al., 2000; Hill et al., 2000). Thus, there is great interest in understanding the genesis, processing, and lability of organic matter in the subsurface of riparian wetlands.

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Soil organic matter contains fractions that range from very active to passive, relative to microbiological activity (Schimel et al., 1985), suggesting that classification of SOM forms may be helpful in understanding ecosystem processes. A number of systems have been devised to separate SOM into functionally equivalent categories based on their chemical, physical, and biological characteristics. Sollins et al. (1984) divided SOM into two broad categories: (i) mineral-free, partially decomposed plant debris (light fraction), and (ii) SOM sorbed on mineral surfaces or within organomineral aggregates (heavy fraction). The light fraction, defined originally by Greenland and Ford (1964), is more labile and decomposes more quickly than does SOM in the heavy fraction (Sollins et al., 1984). Organomineral fractions have been subdivided based on the size of the aggregates: macroaggregates (>250 μm) and microaggregates (<250 μm) (Edwards and Bremner, 1967). Elliot (1986) and Jastrow et al. (1996) found that the SOM associated with macroaggregates is more labile than the SOM associated with microaggregates. Other studies have used 53 μm as the size break between the larger, more labile fraction (particulate organic matter, POM) and the smaller, relatively inactive mineral associated SOM (Cambardella and Elliot, 1992; Six et al., 1998, 1999).

Although the depth and breadth of C research is rich, there still exists a need for detailed morphologic studies focused on C within saturated or seasonally saturated subsurface horizons. Most micromorphological approaches to classify SOM have focused on surface horizons (Heiberg and Chandler, 1941; Jongerius and Schelling, 1960; Barratt, 1964; Babel, 1975; Bullock et al., 1985). Although Bullock's system of classifying SOM into three main classes: plant residues, organic fine material, and organic pigment, can be applied to subsurface horizons, the system was not designed for macroscale studies. Additionally, in our focused studies on riparian zone soils (Gold et al., 2001; Rosenblatt et al., 2001; Blazewski, 2002), we have recognized many more C forms than those identified in previous studies. Thus, a morphological approach to classify soil C is needed. This classification system would provide the first step toward testing the hypothesis that SOM can be separated by morphology into functionally meaningful fractions. In this study, we (i) identified the forms of SOM present in the subsurface of riparian zone soils, (ii) classified the forms of SOM based on their macro- and micromorphology, and (iii) investigated the genesis of these forms.

Abbreviations: AMS, accelerator–mass spectrometer; BP, before present; c/f, coarse/fine ratio; $c/f_{100\mu\text{m}}$, coarse/fine ratio of the mineral component at a 100- μm limit; FOM, fragmental organic matter; PD, poorly drained; POM, particulate organic matter; SOM, soil organic matter; SWPD, somewhat poorly drained; VPD, very poorly drained.

MATERIALS AND METHODS

Seven riparian sites, representative of riparian wetlands in the Pawcatuck River watershed in southern Rhode Island in terms of vegetation, soils, and landscape characteristics, were chosen for detailed investigation (Fig. 1). Only sites with soils formed in outwash or alluvial deposits were considered because these soils have permeable subsurface media and transmit substantial groundwater to adjacent surface waters. All sites were forested wetlands (Cowardin et al., 1979) with trees at least 20 yr old, and dominated by red maple (*Acer rubrum* L.). The only exception was the Alder site, which was dominated by speckled alder [*Alnus rugosa* (Du Roi) Spreng.]. Common shrub species were sweet pepperbush (*Clethra alnifolia* L.) and highbush blueberry (*Vaccinium corymbosum* L.). Skunk cabbage (*Symplocarpus foetidus* (L.) Salisb. ex W.P.C. Barton), cinnamon fern (*Osmunda cinnamomea* L.), and tussock sedge (*Carex stricta* Lam.) were common in the herb layer.

The Entisols, Inceptisols, and Histosols at these sites ranged in drainage class from somewhat poorly drained (SWPD) to very poorly drained (VPD) (Table 1). Soils at Pendar Road, Peckham, and the SWPD portion of the Liberty Lane site have formed in outwash deposits (Table 1). The other sites contained alluvial soils overlying outwash or glaciolacustrine deposits (Table 1). Alluvial soils were distinguished from outwash soils by the presence of buried organic-rich horizons or layers. In southern New England, buried horizons are characteristic of Holocene age alluvial soils, and are not typically found in outwash soils.

Nine soil pits were excavated at the seven riparian sites. Seven of the soil pits were deep (+ 1.5 m) and two were shallow (+ 0.75 m). The pits were dug as deep as possible and inflowing groundwater was removed when necessary with a pump. A soil auger was used to sample below the bottom of the pits. Macroscopic descriptions of the soils were made following standard procedures (Soil Survey Staff, 1993). In the field, roots were described irrespective of whether they were alive or dead. Each C form, defined as a zone of C enrichment, was identified and described at the macroscale. In general, C forms larger than 2 mm in size were considered macroscopic features. A 10× hand lens was occasionally used to aid in the macroscopic observations in the field to assist in the identification of the various C forms.

Undisturbed samples of selected horizons containing various C forms were collected for micromorphological analysis from each soil pit. A total of 34 soil samples from 21 horizons were collected in Kubiena tins, air-dried, impregnated under vacuum with an epoxy resin, and constructed into thin sections. These soils contain <5% clay, and thus, no artifact voids as a result of shrinking on drying were observed. Most (21) of the thin sections were 60 × 45 mm in size; 13 were 25 × 45 mm. Subsurface horizons that had a relatively high abundance of C forms were generally selected for thin section sampling and analysis. One to seven samples were collected for preparation of thin sections from each soil pit. Most samples were taken from B, AC, and A/C horizons. Other samples were collected from Ap, AB, BC, and C horizons (Table 1). Thin sections were examined with dissecting and petrographic microscopes. Micromorphological descriptions were made using the terminology of Bullock et al. (1985). These descriptions focused on the related distribution pattern, orientation, boundary, and color of the C form. If roots were observed, the decomposition class of the root was noted. Three hundred point counts at 100× magnification were made along transects of each thin section. These data were used to estimate percentages of the various C forms, to determine porosity, and the coarse/fine (c/f) ratio of the mineral component at a 100- μm limit ($c/f_{100\mu\text{m}}$).

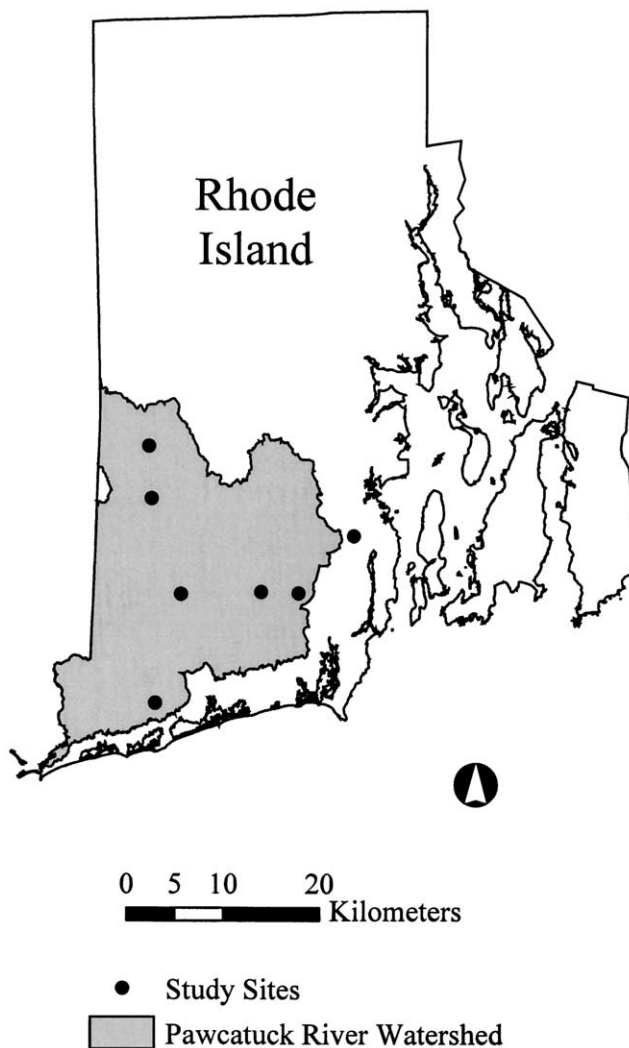


Fig. 1. Location of the seven sites in relation to the Pawcatuck River Watershed in Rhode Island, USA.

In cases where multiple thin sections were constructed for a horizon, point counts were averaged across the slides.

Three samples from two buried horizons were C dated. In one of the horizons (an A^b horizon 83–93 cm from the soil surface), the roots and soil matrix were separated and dated separately. In the other horizon, leaf fragments from a lens 300 to 350 cm from the soil surface were collected and dated. The roots and leaf fragments were dated using the accelerator–mass spectrometer (AMS) technique (Donahue et al., 1983; Linick et al., 1986). The soil matrix from the A^b horizon was dated with the standard radiometric technique.

RESULTS AND DISCUSSION

Six C forms were identified: roots, FOM, lenses, infillings, masses, and horizon C (Table 2).

Roots

Roots were the C form most commonly identified. In the field, we identified two root macrosubclasses: fibrous roots and root traces (Table 2). Fibrous roots ranged in form from live roots to partially decomposed roots where cellular materials were still clearly visible. Root

Table 1. Horizon characteristics, point count results, and macroscopic C descriptions of the 21 horizons examined microscopically.

Horizon†	Depth cm	Texture‡	Micromorphological analysis							Macroscopic description		
			Voids %	C/F _{100µm} ratio	Dominant root class§	Roots¶ #	Horizon C#	Lenses†† %	FOM‡‡ %	Masses§§	Macrocarbon forms	Roots¶¶
Alder VPD—coarse-loamy, mesic Humaqueptic Fluvaquent (alluvium over outwash); SHWT††† = surface												
Bhb (1)	55–82	ls	31.3	6.1	0, 2	1.3	16.3 (c)	0.0	0.0	1.3	m-10YR 2/1 root traces	m-VF, F, M
C (1)	82–136	s	24.0	4.2	2	1.7	24.0 (e), 7.0 (c)	0.0	0.3	0.0	c-10YR 3/2 root traces	c-F, M
Alton Jones PD—coarse-loamy over sandy or sandy-skeletal mesic Fluvaquent Dystrudepts (alluvium over outwash); SHWT = surface												
A/C (3)	38–60	sl	20.6	4.4	2	0.0‡‡‡	2.9 (c)	9.0 (e)	0.0‡‡‡	0.0	c-F-C 10YR 2/1 & 10YR 3/1 masses, root derived? Lenses 1–5 cm thick of 10YR 2/1 & 10YR 3/1	f-VF, F
Liberty Lane A VPD—sandy, mesic Terric Haplosaprists (alluvium over outwash); SHWT = surface												
A/C (3)	67–76	sil	3.3	0.0	3	2.8	0.0	47.1 (p)	0.9	0.0‡‡‡	m-10YR 3/1, 10YR 2/1 lenses	f-F
Liberty Lane B VPD—sandy, mesic Terric Haplosaprists (alluvium over outwash); SHWT = surface												
A and Bg1 (3)	45–51	sil	6.9	0.0	3	6.0	31.6 (p)	0.0	0.0	0.0‡‡‡	In Bg, m-10YR 3/3, 2.5Y 3/2 masses, c-M 10YR 3/3 root traces	m-F, M, c-C
Bg1 (4)	47–59	sil	5.4	0.1	3, 4	7.4	0.0	0.0	0.0‡‡‡	2.1	m-10YR 3/3, 2.5Y 3/2 masses, c-M 10YR 3/3 root traces	m-F, M, c-C
BC (1)	74–99	fsl/lcos	26.3	1.2	1, 2	0.0‡‡‡	0.0	0.0	0.0	0.0	c-F 2.5Y 5/6 masses	c-VF, F, M
Liberty Lane C SWPD—coarse-loamy, mesic Oxyaquic Dystrudepts (outwash); SHWT = 35 cm												
Bw2 (1)	35–45	sl	15.3	0.5	3, 4	0.0‡‡‡	0.0	0.0	0.0	0.0	m-M 10YR 3/3 root traces	c-F, M
BC1 (1)	45–66	sl	9.3	0.9	0, 2	0.0	0.0	0.0	0.0	0.0	c-C 10YR 4/3 masses, c-M 10YR 3/3 root traces	c-F, M
BC2 (1)	66–77	sl	19.3	3.2	1	0.3	0.0	0.0	0.0	0.0	c-C 10YR 4/3 masses, c-M 10YR 3/3 root traces	–
BC3 (2)	77–92	Gr ls/lc	24.8	0.6	2	0.0	0.0	0.0	0.0	0.0	–	–
Meadow Brook PD—sandy-skeletal over loamy, mesic Fluvaquent Humaquepts (alluvium over glaciolacustrine deposits); SHWT = surface												
Bg (1)	20–42	sil	5.0	0.0	4	5.7	33.7 (p)	0.0	2.3	0.0‡‡‡	m-M, C 10YR 2/1 masses, m-C 10YR 4/3 masses, f-M 10YR 2/1 root traces	m-F
2ACb2 (1)	62–86	Gr ls	36.3	8.4	1, 2	1.7	16.3 (e)	0.0	1.7	0.0	m 10YR 2/1 lenses 2–10 mm thick, A ^b 10YR 2/2 at 75 cm	m-F
3ACb1 (1)	103–115	X Gr ls	36.7	1.2	2	2.0	20.0 (e)	0.0	2.0	0.0	m-C 10YR 2/1 masses	m-F
4C (1)	140–280	vfs	17.7	0.3	2	0.0‡‡‡	0.0	0.0	6.3	0.0	2–5 mm lenses of 10YR 3/2 leaf material	–
Peckham Farm PD—coarse-loamy, mesic Typic Humaquepts (outwash); SHWT = surface												
Bg1 (3)	40–56	ls	13.3	1.4	2	2.4	0.0‡‡‡(c)	0.0	0.0	0.0‡‡‡	c-F, M 10YR 3/2 & 10YR 4/2 masses, f-F, M, C 10YR 3/3 root traces	–
Parris Brook PD—coarse-loamy, mesic Fluvaquent Humaquepts (alluvium over glaciolacustrine deposits); SHWT = surface												
C1 (2)	61–67	lfs	25.2	5.5	2	0.8	6.3 (c)	4.8 (e)	0.3	0.0	3cm 2.5Y 4/2 lens, f-F 10YR 2/1 masses	–
Pendar Road SWPD—coarse-loamy, mesic Typic Humaquepts (outwash); SHWT = 10 cm												
Ap (1)	0–18	fsl	30.3	1.7	0	0.3	25.0 (e)	0.0	0.0	0.0	–	c-F, M, f-C
AB (1)	30–36	fsl	27.0	1.5	2	0.0‡‡‡	37.7 (e)	0.0	0.0	0.0	–	c-F, M
Bw1 (1)	36–49	ls	31.0	3.4	–	0.0	10.3 (c)	0.0	0.0	0.0	c (5–10%) 5YR 3/2, 7.5YR 4/4 illuvial patches	f-F
Bw2 (1)	49–63	ls	22.7	18.8	–	0.0	11.3 (c)	0.0	0.0	0.0	c (10–20%) 5YR 3/2, 7.5YR 4/4 illuvial patches	–

† The number in parentheses indicates the number of thin sections that were examined for that horizon. For horizons with >1 thin section, the values represent the means of all thin sections.

‡ Abbreviations for texture: Gr = gravelly, X = extremely, fsl = fine sandy loam, lcos = loamy coarse sand, lfs = loamy fine sand, ls = loamy sand, s = sand, sil = silt loam, sl = sandy loam, vfs = very fine sand.

§ Dominant root class refers to the decompositional root class most frequently identified in the point counts. (Two numbers indicates codominants.)

¶ Root traces were counted as roots in the point counts.

Horizon C refers to the carbon associated with C-rich horizons. The letter in parentheses indicates the observed horizon C microsubclass. Abbreviations for microsubclasses: c = chitonic, e = enaulic, p = porphyric.

†† Lenses were defined as thin layers of C-rich material. The letter in parentheses indicates the observed lens microsubclass. Abbreviations for microsubclasses: c = chitonic, e = enaulic, p = porphyric.

‡‡ Fragmental organic matter (FOM) was defined as plant remains within the soil that do not appear to be root-derived.

§§ The term mass refers to a dark patch of organic-rich soil material with no apparent genetic pathway.

¶¶ Abbreviations for abundance classes: f = few, c = common, m = many. Abbreviations for size classes: VF = very fine, F = fine, M = medium, C = coarse.

Abbreviations for drainage classes: SWPD = somewhat poorly drained, PD = poorly drained, VPD = very poorly drained.

††† Seasonal high water table (SHWT) values are based on direct observation and morphology.

‡‡‡ Indicates that the C form was observed in the thin section(s) but not detected in the point counts.

Table 2. Carbon forms identified in riparian zones and appropriate subclasses at the macro- and microscale.

Class	Macros subclass	Micro subclass
Roots	fibrous roots root traces	decomposition Classes 0–4†
Fragmental organic matter	fragmental organic matter	fragmental organic matter
Lenses	organomineral lenses detrital lenses	enaulic lenses
Infillings	infillings	porphyric lenses detrital lenses
Masses	masses	infillings
Horizon	A horizon O horizon Bh horizon/illuvial Patch	masses enaulic C porphyric C chitonic C

† See Table 3 for root decomposition classes.

traces were defined as roots that have decomposed to such an extent as to stain the surrounding mineral material and all evidence of cellular structure has been destroyed. Root traces generally had low Munsell color chromas and values. Common colors were 10YR 3/3 (dark brown), 10YR 2/2 (very dark brown), 10YR 3/2 (very dark grayish brown), 10YR 3/1 (very dark gray), and 10YR 2/1 (black). Color and shape helped distinguished root traces from the soil matrix.

Under the microscope, roots were divided into 1 of 5 microsubclasses based on the amount of observable decomposition (Table 3, Fig. 2). Criteria used to classify roots in the relatively early stages of decomposition were the amount of breaks in the sheath and the completeness of the inner portion. The amount of cellular structure still visible, the orientation of the remaining tissue fragments, and the degree of mixing of the root-derived organic matter with the surrounding soil were the criteria used to classify roots in the later stages of decomposition. On the basis of these criteria, Class 0, 1, and 2 roots would be considered fibrous in the field, while most of the Class 3 and all Class 4 roots would have been classified as root traces in the field. Macroscopic observations of roots in the field normally suggested very little, if any, decomposition. Microscopic observation, however, suggested that the majority of roots were partially decomposed, suggesting that most of the roots observed in the subsurface horizons were dead.

Only five of the 21 horizons examined microscopically had >2% coverage by roots (Table 1). Four of these horizons had a silt loam texture and a $c/f_{100\mu\text{m}}$ ratio of <0.2 (Table 1). The Peckham Farm Bg1 horizon was the exception (Tables 1 and 4). This horizon had a loamy sand texture, a $c/f_{100\mu\text{m}}$ ratio of 1.4, and on average, 2.4% of the thin section area was occupied by roots: a relatively high percentage of roots, considering the coarse texture and high c/f ratio of this horizon. One of the three thin sections used to average root percentages from this horizon contained a large decaying root. This large root weighted the point counts such that this horizon appears to contain more roots than are representative of the soil horizon. Horizons with a silt loam texture also had the lowest porosity and represented four of the five horizons with a dominant microroot subclass of 3 or 4 (Table 1). There are several possible reasons

Table 3. Criteria for root decomposition class determinations.

Root decomposition class	Characteristics
0	very little or no decomposition very few or no breaks in sheath inner portion is complete
1	few or no breaks in sheath inner portion is not complete
2	fragments are still oriented in original root shape common to many breaks in root sheath tissues are still common as fragments, but the fragments are becoming disoriented from original root shape
3	carbon is starting to disperse to surrounding soil visible cells/tissues are uncommon or absent mineral material is mixing in feature is not dominantly matrix colored original root shape is discernible
4	visible cells/tissues are absent staining of mineral material is the only evidence of root remains feature is dominantly matrix colored original root shape is indefinite but inferred

why roots were more common in the silt loam textured horizons. Silt loam soils likely provide more favorable conditions for root growth in regard to nutrient and moisture status than sandy soils. In addition, decomposition is likely slower in silt loam textured horizons due to increased levels of physical protection in these finer-textured horizons (Verberne et al., 1990; Van Veen and Kuikman, 1990), and because there is less water flow in these horizons, leading to less exchange of nutrients and oxygen.

Fragmental Organic Matter

Fragmental organic matter was defined as plant remains within the soil that do not appear to be root-derived, such as wood chips, leaf remains, and other plant detritus (Fig. 3). This definition most closely approximates the mineral free, partially decomposed, plant debris described by Sollins et al. (1984) and is solely based on morphology. Fragmental organic matter is not to be used synonymously with POM, which is defined by laboratory fractionation as SOM that does not pass through a 53- μm sieve after complete dispersion of the soil (Cambardella and Elliot, 1992). Fragmental organic matter was observed in nine out of the 21 horizons examined under the microscope and to a depth of 280 cm (Table 1). At 100 \times magnification, cellular structure of the FOM was often visible. These plant remains were deposited on the soil surface and subsequently incorporated into the subsoil via burial (flooding) or pedoturbation. We only observed FOM within alluvial soils, suggesting that burial by flood deposits is more important than pedoturbation in incorporating surface plant remains into the subsoils of riparian zones.

Lenses

Lenses were defined as thin layers of C-rich material located between layers of C-poor material (Fig. 3). Lenses ranged in thickness from a few millimeters to 2 cm, and generally contained more FOM and roots than the adjacent soil. In a number of soils, multiple lenses were present, oriented parallel to one another. In the field,

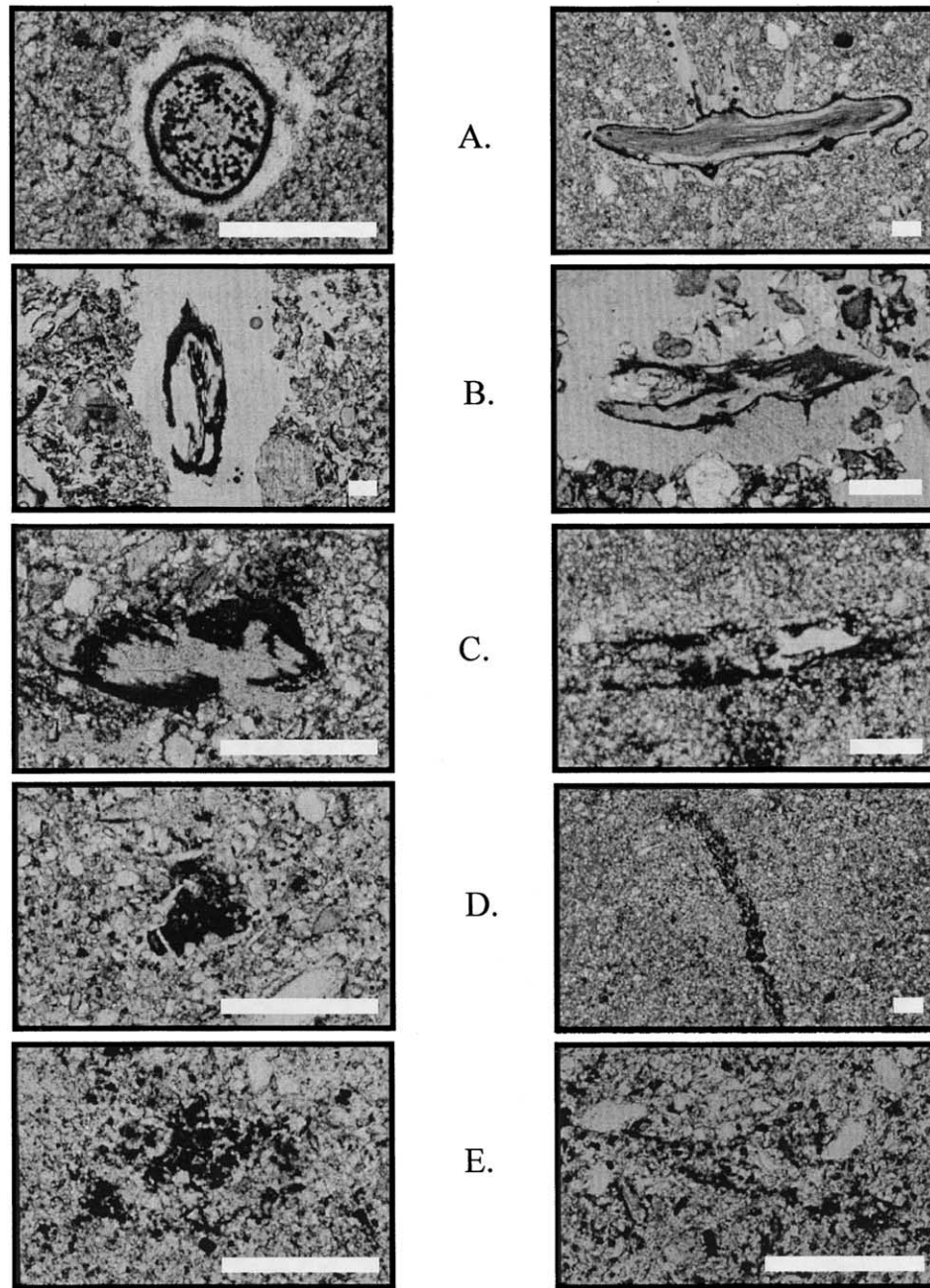


Fig. 2. Cross-sectional and longitudinal views of the different root decomposition classes. (A) Class 0 root, inner portion and sheath are complete. (B) Class 1 root, inner portion and sheath are incomplete. (C) Class 2 root, C is dispersing into surrounding soil, tissue fragments are still present. (D) Class 3 root, visible tissues are absent, root shape is discernible. (E) Class 4 root, visible tissues are absent, original root shape is indefinite. The bar in the lower corner = 0.5 mm.

boundaries between lenses and the underlying and overlying matrix were generally abrupt. Under the microscope, these boundaries were typically described as having prominent contrast and clear sharpness (Bullock et al., 1985). Their thin nature, abrupt boundaries, and abundance of roots and FOM suggest that lenses formed during short periods of land surface stability. During these periods, the landscape was stable long enough for organic matter to accumulate at the surface; however, before a complete A or O horizon had time to develop, mineral material was deposited on the surface as a result of flooding and surface aggradation.

There were two different types of lenses observed in the field: organomineral and detrital. Organomineral materials form when decomposing organic residues and root exudates chemically interact with mineral grains, binding soil particles together (Brady and Weil, 1996). The majority of lenses we observed were comprised of organomineral material. Microscopic observations revealed that the C in the sandy-textured lenses was primarily related to finer-textured organomineral aggregates that occurred between coarse grains. In our C classification scheme, we refer to organomineral aggregates found within the void spaces between coarse grains as *enaulic*

Table 4. Soil profile description of the Peckham Farm Poorly Drained site, a representative outwash soil.

Horizon	Depth cm	Texture	Munsell color	Roots†	Other carbon features†
Oi	0–4		5YR 3/3	m-VF, F	–
Oa	4–14		10YR 2/1	c-VF, F, f-M	–
A	14–30	sl	10YR 3/1	c-F, f-M, C	–
AB	30–40	ls	10YR 2/2 & 10YR 4/2	c-VF, F, f-M	–
Bg1	40–56	ls	10YR 6/1		c-F, M 10YR 3/2 and 10YR 4/2 organic masses
Bg2	56–63	s	2.5Y 4/2	f-F	c-F, M 10YR 4/3 organic masses
BC	63–83	fs	2.5Y 5/1	–	–
C1	83–110	s	2.5Y 5/1	–	–
C2	110–150+	s	2.5Y 5/1	–	–

† Abbreviations for abundance include: f = few; c = common; m = many. Abbreviations for size include: VF = very fine; F = fine; M = medium; C = coarse.

C. The term is derived from a specific type of c/f-related distribution pattern (enaulic) in which there is a skeleton of coarser particles with aggregates of finer material in the intergranular spaces (Fig. 3; Stoops and Jongerius, 1975; Bullock et al., 1985).

Organic matter in silt loam lenses appeared to be evenly dispersed throughout the matrix; separate aggregates of organic material bound to finer mineral particles were not observable in thin sections. The void space between coarse particles is essentially completely filled with organic matter closely associated with particles of silt and clay. Carbon having this morphology was considered porphyric, after the porphyric-related distribution pattern described by Stoops and Jongerius, (1975) where coarser grains are totally enveloped in finer materials (Fig. 3). Common colors of enaulic and porphyric C were 10YR 3/3 (dark brown), 10YR 2/2 (very dark brown), 10YR 3/1 (very dark gray), and 10YR 2/1 (black).

The other type of lenses were made up of detritus such as leaf fragments. At the Meadow Brook poorly drained (PD) and Parris Brook PD sites (Table 5), detrital lenses only a few millimeters thick, and generally separated by 1 to 5 cm of sediment, were found at least 1 m below the water table and at depths ranging from 150 to 350 cm. The leaf fragments were 7.5YR 2.5/2 (very dark brown), but changed to 10YR 2/1 (black) after being exposed to air for a few minutes, suggesting rapid oxidation. The soil matrix surrounding these lenses was well sorted, and had textures of fine sand, very fine sand, and fine sandy loam. This soil morphology is indicative of a low-energy environment, such as a glacial pond or lake.

Infillings

Surface horizons are the primary locations for biological activity. Within these horizons, pore space is formed by root and animal activity. In cases where large pores are formed and filled by this activity, the term *krotovina* is applied. At the microscale, these filled burrows or filled root channels are termed *infillings*. Bullock et al. (1985) defined infillings as pedofeatures that form when soil material completely or partially fills in a void. An

infilling can be considered a C form when C-rich soil material has filled in the void. Infillings were the least common C form observed in the subsurface horizons addressed in this study. The few observed infillings were directly below A horizons, approximately 1 to 2 cm in diam., only a few centimeters long, and 10YR 2/2 (very dark brown) and 10YR 2/1 (black).

Masses

The term *mass* was used to refer to a dark patch of organic-rich soil material where the apparent genetic process could not be identified (Fig. 3). All the soils, spanning a range of texture and drainage classes, contained masses, appearing as dark-stained, irregularly shaped, mineral material ranging from 1 mm to >5 cm in size. Common colors of masses were 10YR 3/2 (very dark grayish brown), 10YR 2/2 (very dark brown), 10YR 3/1 (very dark gray), and 10YR 2/1 (black). Masses were more common closer to or within organic-rich horizons than deeper in the profile.

The occurrence of masses in the same horizons as the other C forms suggests the possibility of multiple genetic pathways for their formation. Within riparian zone soils, some of these pathways include pedoturbation (i.e., faunalpedoturbation, floralpedoturbation) (Hole, 1961; Johnson et al., 1987; Peacock and Fant, 2002), transformation, erosion, eluviation, and alluviation (Fanning and Fanning, 1989). Because masses and roots were the most abundant C form identified in the field, the likelihood that masses formed primarily from roots is very high. With time, roots break down and root-derived C disperses into the surrounding soil to form root traces (Fig. 2). Eventually, the C associated with root traces can become partially consumed by soil microbes, or mixed with the surrounding mineral material by pedoturbation. This series of steps can transform a fibrous root, root trace, or FOM into a barely recognizable C form, and finally into a form with no apparent genetic derivation in the field or under a microscope (a mass) (Fig. 3).

Horizon Carbon

In our classification scheme, all C-rich horizons (A, O, and Bh) were classified as having horizon C (Table 2). Buried A horizons were the most common subclass of horizon C observed in the subsurface of riparian soils. Although A horizons contain many other C forms, they are predominantly comprised of enaulic or porphyric C (Table 1). Buried O horizons were not sampled in this study; however, we expect these horizons to contain substantial amounts of enaulic and or porphyric C, depending on the nature of the mineral materials.

Illuvial C appears as dark coatings on sand or silt grains (Daniels et al., 1975) in either Bh horizons or as patches (Fig. 4). Although illuvial patches are not a horizon, they were classified with illuvial horizons since they are similar in terms of genesis. Buol et al. (1997) reviewed the processes that result in the accumulation of illuvial C. Although most of these processes fell under the process termed *podzolization*, where organometallic complexes migrate into the subsoil (DeConinck, 1980;

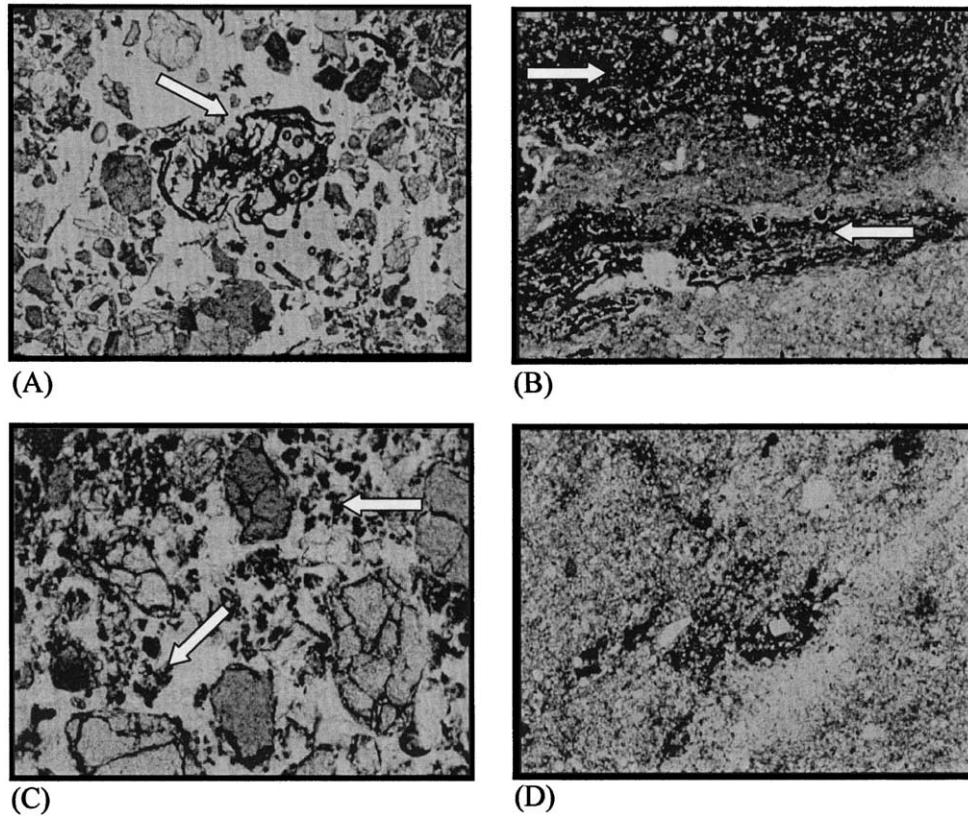


Fig. 3. Micrograph showing examples of various C forms in riparian zone subsoils. (A) Example of fragmental organic matter. Frame width is approximately 6 mm. (B) Examples of lenses in an A/C horizon with a silt loam texture. The C associated with the lenses has a porphyric related distribution pattern. Frame width is approximately 6 mm. (C) Example of enaulic C in an A horizon with a sandy loam texture. The C associated with the dark aggregates is termed enaulic C. Frame width is approximately 1.2 mm. (D) Example of a mass. Frame width is approximately 6 mm.

Lundström et al., 2000), Buol et al. (1997) cited many other related mechanisms important in the accumulation of illuvial C in the subsoil.

Several characteristics are very useful in distinguishing illuvial C. The presence of an albic horizon (Soil Survey Staff, 1999) directly above a C-enriched horizon

Table 5. Soil profile description of the Parris Brook Poorly Drained site, a representative alluvial soil underlain by glaciolacustrine deposits.

Horizon	Depth	Texture [†]	Munsell color	Roots [‡]	Other features [†]
	cm				
Oi	0–4		10YR 3/3	m-VF, F, M	
A	4–22	sil	10YR 2/2	m-VF, F, M, c-C	
Bg	22–31	sil	10YR 4/1	m-VF, F, c-M	c-F 10YR 3/2 root traces & m-M 10YR 2/2 organic masses
A ^u b	31–39	sil	10YR 2/1	c-VF, F	
Bgb	39–45	sil	10YR 5/2	c-F, M	c-M 10YR 2/1 organic masses & one 10YR 2/1 organomineral lens 3 mm thick at 43 cm
C	45–50	lfs	2.5Y 5/2	c-VF, F	m-M 10YR 3/2 root traces
A ^u b	50–57	sil	10YR 2/1	f-F	
B ^u gb	57–61	sil	2.5Y 6/2	f-F	One 10YR 2/1 organomineral lens 3 mm thick
C1	61–67	lfs	2.5Y 5/2	c-VF, F	f-F 10YR 2/1 organic masses & one 2.5Y 4/2 organomineral lens 3 cm thick at 64 cm
C2	67–83	ls	2.5Y 4/2	c-VF, F	m-F, M 10YR 2/1 root traces
A ^u b	83–93	sil	10YR 3/2	m-VF, F, M	
2C	93–106	xgr lcos	10YR 3/2	m-F, M sheaths	
3A ^u b	106–114	sil	10YR 3/2	m-VF, F, M	
4C1	114–137	xgr lcos	2.5Y 4/2	m-VF, F, M sheaths	
4C2	137–176	xgr vcoss	2.5Y 4/2	m-VF, F, M sheaths	
5C	176–300	fs	5Y 5/1		m 10YR 2/1 & 10YR 3/2 lenses 2–5 mm thick of leaf material

[†] Abbreviations for texture: fs = fine sand, lcos = loamy coarse sand, lfs = loamy fine sand, ls = loamy sand, s = sand, sil = silt loam, sl = sandy loam, vcoss = very coarse sand; vfs = very fine sand, xgr = extremely gravelly.

[‡] Abbreviations for abundance include: f = few; c = common; m = many. Abbreviations for size include: F = fine; M = medium; C = coarse.

strongly suggests that the C in the B horizon is illuvial. Another useful indicator is the characteristic coffee grounds color generally associated with spodic materials; where hues are usually redder than 10YR (Bullock and Clayden, 1980; Rourke et al., 1988; Soil Survey Staff, 1999), and chromas and values are usually 4 or less. The Bh horizons we observed were often 7.5YR 3/2 (dark brown) or 7.5YR 2.5/2 (very dark brown). The illuvial patches were 7.5YR 4/4 (brown) and 7.5YR 3/2 (dark brown).

Under the microscope, illuvial C was observed to have a chitonic *c/f*-related distribution pattern (Stoops and Jongerijs, 1975), where coarse particles are surrounded by a coating of finer particles. Thus, in our system, chitonic C refers to a microsubclass used to identify coatings of C on coarse grains in Bh or Bhs horizons or patches (Fig. 4). Illuvial C was observed in the field as Bh horizons (Table 1) or as chitonic C in thin sections collected from A/C, Bg, Bw, and C horizons in six of the nine soils we studied. The three soils that lacked illuvial C were the two Liberty Lane VPD alluvial soils, and the Meadow Brook PD alluvial soil. Mineral horizons in the upper portions of these three soils have a silt loam texture. Illuvial C was present within horizons with textures of sand, loamy sand, loamy fine sand, and sandy loam, but not in any horizons with a texture of silt loam, fine sandy loam, or very fine sand. Chitonic C was observed in seven out of the 11 horizons with a $c/f_{100\mu\text{m}}$ ratio > 1.25 , but not in any of the 10 horizons with a $c/f_{100\mu\text{m}}$ ratio < 1.25 (Table 1). These observations agree with the literature, which suggests that the processes that result in illuvial C are generally restricted to medium- to coarse-textured horizons (Buol et al., 1997; Lundström et al., 2000).

APPLICATION TO SOIL CARBON DYNAMICS

Six C forms and five different root decomposition classes were identified in the riparian soils. With time, decomposition and various pedological processes can transform C from one form to another. Thus, many of the C forms observed in the subsoils of riparian zones are genetically related. As SOM decomposes, the labile fractions become depleted and the more passive fractions remain. Therefore, the end products of decompositional sequences will likely be less labile than the initial C forms.

To further our understanding of the genesis and stability of subsurface C, three samples were radiocarbon dated. These horizons were well below the water table and had likely rarely been out of a saturated environment. The matrix material of the A^b horizon, 83 cm below the soil surface, at the Parris Brook study site had a conventional age of 9400 ± 70 radiocarbon years BP (before present), by the standard radiometric technique. Roots sampled from this horizon had a conventional age of 4090 ± 40 radiocarbon years BP by the AMS technique. These results suggest that this A horizon was buried approximately 10 000 yr ago, but roots continued to grow in the horizon. The date of the roots

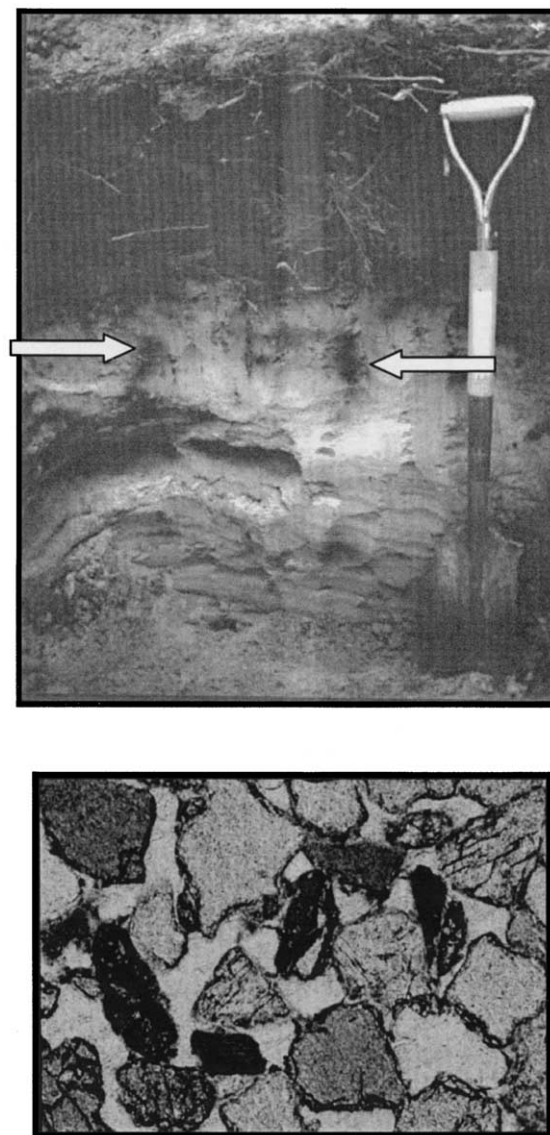


Fig. 4. Illuvial C at the macroscopic and microscopic scale. (Top) illuvial patches observed at the Pendar Road study site; (bottom) example of chitonic C on sand grains. Frame width is approximately 1.2 mm.

should be interpreted cautiously because roots of many different ages may be present within this horizon. The third radiocarbon sample was a series of lenses comprised of leaf fragments collected from a depth of 300 to 350 cm at the Meadow Brook study site. These lenses had a conventional radiocarbon age of $13\,890 \pm 70$ yr BP by the AMS technique, and a calibrated date circa 16 260 to 17 060 yr BP. Calibration is based on ^{14}C dating materials, such as tree rings and varves, for which the absolute date is known, and adjusting the conventional radiocarbon date accordingly (Stuiver et al., 1993; Sewell, 1998). The calibrated dates are consistent with the estimated time of glacial ice retreat in this region (Boothroyd et al., 1998), supporting the possibility that these lenses were deposited in a glaciolacustrine environment.

The C dating results indicate that C forms can persist for thousands of years in saturated riparian soils, and

that many of the roots, lenses, and other C forms within the subsurface of riparian zones are relict from hundreds to thousands of years ago. Given that leaf fragments are still recognizable without magnification after 16 000+ years, many of the C forms observed in this study appear capable of persisting in riparian zone soils. The stability of the C during such a time frame is likely a result of low oxygen and/or anaerobic conditions within the soil due to prolonged periods of saturation.

Our results suggest that soil classification and morphology data may be useful for categorizing C forms into functionally different classes. Although most of the forms were observed more than 1 m below the surface, all six forms appeared to be more commonly found closer to or within surface horizons or former surface horizons than deeper in the profile. Illuvial C appears to be restricted to coarser-textured soils. More labile forms, such as roots and root traces, appear more common in the finer-textured silt loam horizons. Alluvial deposition was identified as the dominant process incorporating C forms such as lenses, A and O horizons, and FOM into the subsurface of riparian zones, and these forms were more common in the subsurface of alluvial soils than in outwash soils. These results provide a basis for making predictions about the nature and extent of labile C distributions in different riparian zones, which should help to assess their capacity to function as denitrification sinks for nitrate in the landscape.

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