Spatial Distribution of Soil Carbon in Southern New England Hardwood Forest Landscapes

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ABSTRACT

Understanding soil organic C (SOC) spatial variability is critical when developing C budgets, explaining the cause and effects of climate change, and for basic ecosystem characterization. We investigated delineations of four soil series to elucidate the factors that affect the size, distribution, and variability of SOC pools from horizon to landscape scales. These soils, classified as Udipsamments, Dystrudepts, Endoaquepts, and Haplosaprists, were sampled along random transects to a depth of 1 m. In very poorly and poorly drained soils 75 and 45% of total SOC was found below 30 cm, respectively. In contrast, only 30% of the total SOC could be accounted for below 30 cm in the well and excessively drained soils. Soils formed in outwash and young alluvium sequestered a greater portion of total SOC within the subsoil, while soils formed in loess held approximately 70% of the SOC within O and A horizons. Total SOC contents among the four soil types differed significantly ($p < 0.001$), with the wetter soils having greater accumulations of C. Soil C pools ranged from 110 Mg C ha^{-1} in the excessively drained Psamments (double the mean national value) to 586 Mg C ha^{-1} in the very poorly drained Saprists (30–60% lower than the mean national value). The two-fold differences between our data and the national averages support the need for regional assessments of soil C pools. Based on the coefficient of variation (CV) values, there appears to be nearly as much variability in the SOC pool within a delineation (CVs ranged 9 to 30%) as among delineations (CVs ranged from 15 to 31%) for the same soil type. Since significant differences were found for total SOC among delineations of the same soil type, we concluded that sampling from a significant number of delineations of the same series will provide a more accurate representation of SOC for scaling to the landscape or region than sampling at multiple locations within a single representative delineation.

Assessments of the distribution of C within and among soil types are critical to developing an understanding of the cause and effect relationships between climate or land use change, and release of CO_2 to the atmosphere (Schimel et al., 1994). Carbon distribution data are available from many sources at a variety of scales. Pedon data collected as a part of the USDA-NRCS Progressive Soil Survey have been used to estimate SOC pools in a number of studies (Franzmeier et al., 1985; Davidson and Lefebvre, 1993; Eswaran et al., 1993; Kern, 1994; Homann et al., 1995, 1998; Grossman et al., 1998). Similar conclusions and recommendations were drawn from each of these works and included: (i) taxonomic grouping is the best approach to estimate soil C pools; (ii) lower taxonomic categories (more detail) in Soil Taxonomy are more reliable predictors of C pools than are higher categories; and (iii) there is a strong need for estimates of C variability within and among pedons of the same soil type.

Although the national soil survey database is quite comprehensive, additional information would increase the usefulness of the database for predicting regional or national C pools. Of particular use would be data on the contribution of O horizons and subsoils of forest soils to the C pool (Eswaran et al., 1993; Stone et al., 1993; Grossman et al., 1998; Lal et al., 1998). In addition, a measurement of spatial variability in soil properties among taxonomically similar soils that are important in the calculation of C pools (i.e., percentage of C, rock fragment content, and bulk density), and an understanding of the confounding effects of climate, land use, species age and composition, and parent material on soil C pools would aid in the interpretation of the C estimates (Eswaran et al., 1993; Kern, 1994; Lathrop et al., 1995; Bouwman and Leemans, 1995; Batjes, 1996).

In this study, we examined the factors that influence soil C pools at the landscape scale. Landscape unit boundaries were defined based on soil survey delineations of four soil series typically found in southern New England. The objectives were to assess the size, variability, and distribution of the soil C pool in hardwood forests of this region. We addressed the following questions: (1) How does soil C content vary among soils with similar forest classification (hardwood forest) but varying soil properties? (2) Is there more variability in total soil C content within a delineation than among mapping units of the same series? (3) Is variability systematically related to soil characteristics such as drainage class or parent material?

MATERIALS AND METHODS

Study Area

This research was focused on forested areas within the Pawcatuck River watershed in southwestern Rhode Island (Fig. 1). This 64 000 ha watershed is dominated by glacial landforms composed of till and outwash materials of late Pleistocene age that are representative of southern New England (Schafer and Hartshorn, 1965; Quinn, 1971). Outwash covers most of the valley landscape in which the present day streams have shifted or meandered across depositing alluvial materials. In addition, portions of outwash landscapes are covered with a silt mantle (Flint, 1930; Schafer, 1981; Rector, 1981; Lawson, 1995), considered to be loess (Wright and Sautter, 1988; Stolt, 1998).

Potential research sites were identified by overlaying geographic information systems (GIS) land use/land cover and soils coverages (August et al., 1995) across the Pawcatuck

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Abbreviations: CV, coefficient of variation; SOC, soil organic C.

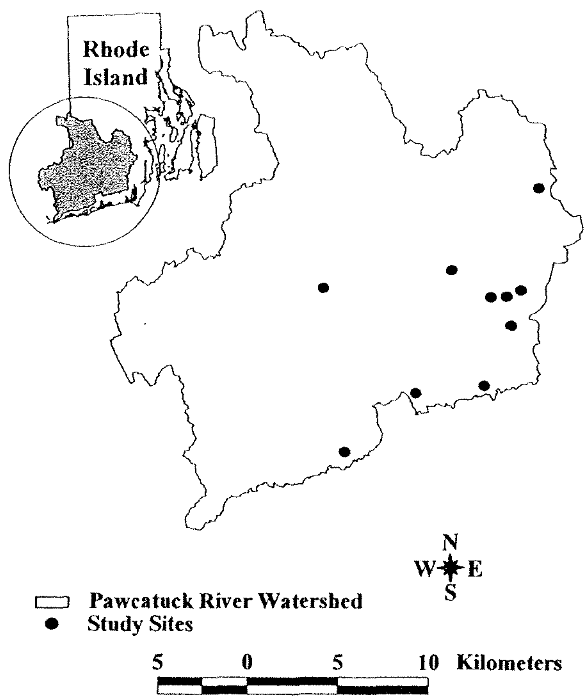

Fig. 1. Location of the 10 study sites in the Pawcatuck River watershed in Rhode Island.

River watershed to identify mapping units of soils formed in outwash, aeolian, alluvial, and organic parent materials that were dominated by hardwood forests. Soil GIS coverages were developed from the 1:15 840 soil survey of Rhode Island (Rector, 1981). Over 70 delineations (mapping units), identified as Windsor, Enfield, Raypol, and Carlisle (see Table 1 for family classifications) and mapped as consociations, were examined in a field reconnaissance survey. These four soil types were chosen because they are commonly mapped in southern New England and provide a diverse range of drainage classes and parent materials (Table 1).

Three delineations representative of the Enfield and Carlisle series, and two units of the Raypol and Windsor series were chosen for detailed study. These sites were chosen because the soils within each delineation met the range of characteristics established for each soil series, the landscapes were dominated by hardwood forests, and the age of the trees was relatively uniform within the delineation. The largest trees (based on diameter at breast height) within 25 m of the soil transects (see below) of each of the dominant species were cored to determine the age of the stand. A minimum of 10 increment cores was collected from trees at each site and stand age was determined by averaging the four oldest trees of those selected (Table 1). We avoided unusually large trees because they might represent a period before the majority of the stand developed.

Sampling Design

Soils were collected along two randomly chosen transects within each of the 10 delineations (Young et al., 1991). Sampling locations were spaced at 25-m intervals for a total of five sampling points (0, 25, 50, 75, and 100 m) per transect (10 per delineation). Samples at each location were collected by horizon to a depth of 1 m (except in a few cases). Organic horizons of the mineral series were collected from a 15 by 15 cm area intact and separated into fibric (Oi), hemic (Oe), and sapric (Oa) horizons when possible. Mineral samples were collected using a 4.7-cm diam. split-core sampler. Fibric and hemic horizons of the organic series (Carlisle) were collected from a 15 by 15 cm area intact and separated into the two horizon materials. Sapric materials were collected by horizon using a Macauley peat sampler.

All samples were analyzed for bulk density and organic matter content. Bulk density calculations were corrected for coarse fragment (>2 mm) mass and volume (Blake and Hartge, 1986). Organic matter contents were determined for all of the soil samples via loss on ignition (Nelson and Sommers, 1996). Samples from four of the mapping units (one for each series) were analyzed for total C using an automated C and N analyzer (Carlo-Erba, Milan, Italy) (Nelson and Sommers, 1996). These

Table 1. Soil and site characteristics for the 10 Windsor, Enfield, Raypol, and Carlisle soils.

Site	Parent material	Stand age†	Delineation size	Basal area
			ha	m^2 ha^{-1}
		Windsor—Excessively drained; mixed, mesic Typic Udipsamments; §*Quercus rubra*, *Q. coccinea*, *Q. velutina*, and *Pinus rigida*		
Bg	Outwash	64 (67)	12	23 (1.8)‡
Sp	Outwash	95 (97)	5	25 (1.9)
		Enfield—Well-drained; coarse-silty over sandy or sandy-skeletal, mixed, mesic Typic Dystrudepts; §*Acer rubrum*, *Quercus rubra*, *Q. coccinea*, *Q. velutina*, *Q. alba*, and *P. rigida*		
GS1	Loess/Outwash	81 (82)	3	27 (2.3)
GS2	Loess/Outwash	84 (93)	8	17 (2.0)
Rt95	Loess/Outwash	86 (91)	8	24 (1.9)
		Raypol—Poorly drained; coarse-loamy over sandy or sandy-skeletal, mixed, mesic Aeric Endoaquepts; §*Acer rubrum*, *Quercus bicolor*, *Q. rubra*, *Q. alba*, and *Carya glabra*		
Rt2	Loess/Outwash	105 (119)	32	26 (2.2)
Rt138	Alluvium	58 (63)	15	37 (1.6)
		Carlisle—Very poorly drained, euic, mesic Typic Haplosaprists; §*Acer rubrum* and *Chamaecyparis thyoides*		
URI	Organic	105 (116)	15	19 (1.1)
Rt110	Organic	77 (80)	97	20 (2.2)
CHTH	Organic	101 (105)	49	25 (1.8)

† The largest trees (based on diameter at breast height) within 25 m of the soil transects (see below) of each of the dominant species were cored to determine the age of the stand. A minimum of 10 increment cores were collected from trees at each site and stand age was determined by averaging the four oldest trees of those selected. Age of the oldest tree is in parentheses.
‡ Mean of 10 prism measurements with standard errors in parentheses.
§ Dominant overstory vegetation.

acid soils are free of carbonates. Organic C data from these four mapping units (550 samples) were used to establish horizon-specific and soil-series specific C/OM regression equations, which were used to determine C concentrations in samples from the remaining six units (Davis, 2001). To calculate total SOC (Mg C ha^{-1}), C data were pooled by Oi and Oe (Oie), Oa, A, B, and C horizons in the mineral soils. In the Carlisle soils, data were pooled by Oie horizons, and upper (0–50 cm) and lower (50–100 cm) Oa horizons. When calculating means of the pooled data we weighted the subhorizon data that collectively forms the pooled master horizon by the thickness of each subhorizon. In certain pedons particularly loose or dense materials, or an abundance of coarse fragments, prevented us from sampling the C horizons. We estimated the C horizon portion of the total SOC stored in these pedons by using the average bulk density and percentage of C values from the C horizons of the pedons within the mapping unit that could be sampled.

Descriptive statistics such as means and coefficients of variation (standard deviation/mean) and comparative (ANOVA, and Tukey's multiple comparison) analyses were performed in SPSS version 10 (SPSS Inc., 1999). A nested ANOVA (with mapping unit effects nested within soil type) was used to compare total SOC contents in the upper 1 m of the soils. Four one-way ANOVAs were run to determine if there were significant differences in total SOC content among delineations of the same series. The Bonferonni adjustment was used to correct *p*-values for the increased probability of Type I errors associated with comparing the results of multiple comparisons.

RESULTS AND DISCUSSION

Site, Pedon, and Horizon Characteristics

Acer rubrum and mixed *Quercus* species were the dominant vegetation at the study sites (Table 1). Silt loam, deposited as loess or alluvium, was the predominant texture of the Raypol and Enfield sola. In these soils, sandy or sandy skeletal outwash occurred at the base of the solum such that these soils had strongly contrasting family particle-size classes (Table 1). Windsor soils developed in outwash and were dominated by loamy sand and sand textures.

The average solum thickness of the mineral soils ranged from 66 to 88 cm (Table 2). The combined Oi and Oe horizons (Oie) ranged in thickness from 2 to 11 cm and had similar bulk density values (0.07–0.12 g cm^{-3}) and SOC concentrations (400–500 g kg^{-1}) regardless of the soil or site (Table 2). Windsor soils lacked Oa horizons and less than half of the Enfield pedons (13 of 29) contained Oa horizons. The Raypol soils had the thickest Oa horizons of the mineral soils (mean: 9 cm). Carlisle soils were dominated by thick (>1 m) accumulations of sapric (Oa) materials. The SOC concentrations of the Carlisle Oa horizons were significantly higher, and the bulk density values significantly lower, than the Oa horizons of the mineral soils (Table 3). The mineral soil Oa horizons are thin by nature and there is a greater likelihood that denser mineral material will be mixed in with the organic materials as a result of pedoturbation. Therefore, these horizons tend to have higher bulk density and the lower SOC concentrations. Overall, the wetter soils had greater SOC storage in O horizons, and this difference is a function of the C contents in Oa horizons. By comparison, C contents in O horizons in Oregon (10 Mg C ha^{-1}, Homann et al., 1995), the Great Lakes Region (17 Mg C ha^{-1}, Grigal and Ohmann, 1992), and on average for temperate forests (21 Mg C ha^{-1}, Vogt et al., 1995) are lower than the average C contents in the O horizons of the mineral soils we studied (21–42 Mg C ha^{-1}).

Soil organic C concentrations for A and B horizons ranged from 25 to 63 and 3 to 14 g kg^{-1}, respectively (Table 2). Carbon concentrations in the A horizons increased as drainage class became wetter such that the Enfield (well) and Raypol (poorly drained) A horizons had significantly higher SOC levels than the excessively drained Windsor (Table 3). Raypol soils had significantly higher SOC concentrations in the B horizons, suggesting that drainage class affects SOC content throughout the solum. The higher SOC concentrations in the Raypol B horizons resulted in significantly lower bulk density values compared with B horizons in the Windsor soils. The thickness of the A and B horizons or the solum the three mineral soils were not significantly different, however, the total SOC held in these horizons and the solum increased as the drainage class became wetter.

Total C storage is a function of horizon thickness, bulk density, and SOC concentration. Of these parameters, the one that showed the most variability depended upon the soil, horizon, and whether the comparisons were made within sites (Table 2) or among sites of the same series (Table 3). For example, CV for horizon thickness for the Oie horizons ranged from 3 to 25% within individual sites (Table 2) and between 19 and 79% when means were calculated based on all of the data for each series (Table 3). By comparison, CVs for SOC concentration of the Oie horizons were all <20% and for means calculated within a site the CVs were all <10%. Much greater variability (CVs of 27–57%) was reported for SOC concentrations in the top 20 cm of forests soils in Oregon (Homann et al., 1995) and Wisconsin (Kabrick et al., 1997), respectively, suggesting that a number of factors such as soil type, forest type, management history, stand age, or climate are also important in explaining SOC variability. Average CVs for the parameters used to calculate total SOC for a horizon or profile were highest (41–55%) for the poorly drained Raypol soils (Table 3). This variability is a reflection of the two types of parent materials of these soils (alluvium and loess). Loess tends to have minimal variability associated with the depositional process (Mausbach et al., 1980). In contrast, alluvial materials are deposited as layers in response to repeated flooding which can result in considerable variability with respect to depth-related properties.

Distribution of Soil Organic Carbon within Profiles

We examined the average proportion of total SOC stored within each master horizon among delineations and soil parent materials (Fig. 2 and 3). The O horizons

Table 2. Weighted means (Mean) and coefficients of variation (CV) for thickness, bulk density, soil organic C (SOC) content, and total SOC storage for the master horizons, sola, and upper 1 m of the 10 study sites. Means were weighted based on the thickness of the subhorizons that together form the master horizon.

Site	Horizon	n	Thickness		Bulk density		SOC concentration		Total SOC content	
			Mean	CV	Mean	CV	Mean	CV	Mean†	CV
			cm	%	g cm^{-3}	%	g kg^{-1}	%	Mg ha^{-1}	%
Windsor										
Bg	Oie	10	9	3	0.12	31	403	7	40	6
	A	10	6	10	1.04	7	26	18	14	13
	B	10	58	9	1.37	2	6	12	40	7
	Solum	10	73	24	–	–	–	–	94	14
	Upper 1 m	10	100	–	–	–	–	–	104a	13
Sp	Oie	10	9	8	0.11	9	424	4	34	7
	A	10	12	21	0.95	6	25	6	29	23
	B	10	46	46	6	1.30	3	8	11	42
	Solum	10	66	19	–	–	–	–	105	19
	Upper 1 m	10	100	–	–	–	–	–	117a	15
Enfield										
GS1	Oie	9	8	9	0.12	7	450	3	41	11
	Oa	9	4	22	0.30	15	299	8	29	23
	A	9	16	7	0.88	4	42	10	55	16
	B	9	51	15	1.26	2	6	9	36	16
	Solum	9	78	29	–	–	–	–	161	32
	Upper 1 m	9	100	–	–	–	–	–	168a	27
GS2	Oie	10	7	11	0.12	16	421	5	29	8
	A	10	15	8	0.92	5	39	16	43	10
	B	10	53	7	1.35	4	5	12	32	12
	Solum	10	75	14	–	–	–	–	104	27
	Upper 1 m	10	100	–	–	–	–	–	113b	24
Rt95	Oie	9	8	10	0.09	7	443	2	29	6
	Oa	4	3	25	0.33	10	246	2	20	13
	A	10	18	7	0.84	4	35	11	50	10
	B	7	61	7	1.33	2	6	9	45	6
	Solum	10	70	47	–	–	–	–	118	22
	Upper 1 m	10	100	–	–	–	–	–	129b	15
Raypol										
Rt138	Oie	10	2	13	0.07	16	402	4	6	18
	Oa	10	6	7	0.17	11	232	4	22	9
	A	10	7	47	0.65	51	47	56	30	88
	B	6	56	18	1.37	9	9	20	63	24
	Ab	7	28	68	1.56	60	29	65	67	51
	Solum	10	88	25	–	–	–	–	145	34
	Upper 1 m	10	100	–	–	–	–	–	149a	30
Rt2	Oie	9	11	6	0.08	11	433	2	38	15
	Oa	8	12	27	0.34	14	208	17	67	27
	A	10	14	15	0.73	5	63	7	62	16
	B	10	39	11	1.20	6	14	16	60	18
	Solum	10	73	14	–	–	–	–	209	21
	Upper 1 m	10	100	–	–	–	–	–	223b	19
Carlisle										
URI	Oie	9	4	25	0.08	18	415	9	16	38
	Upper Oa	10	50	–	0.12	18	469	6	259	7
	Lower Oa	10	50	–	0.13	32	485	5	227	14
	Upper 1 m	10	100	–	–	–	–	–	494a	29
Rt110	Oie	10	8	10	0.08	5	490	1	31	11
	Upper Oa	10	50	–	0.11	5	524	1	292	4
	Lower Oa	10	50	–	0.13	5	498	2	323	4
	Upper 1 m	10	100	–	–	–	–	–	645b	9
CHTH	Oie	10	3	14	0.09	8	503	1	12	11
	Upper Oa	10	50	–	0.11	7	529	1	289	7
	Lower Oa	10	50	–	0.12	2	534	1	317	4
	Upper 1 m	10	100	–	–	–	–	–	618b	10

† Means for total SOC storage with different letters are significantly different at the 0.05 alpha level within each soil type.

in mineral soils accounted for 20 to 40% of the total soil C pool. Based on the ages of the forests, the O horizons of these mineral soils are probably only 60 to 100 yr old. We did not track the land-use history of these sites. However, based on soil properties we can suggest some likely uses. All of the mineral soils contained Ap horizons indicating that these soils were used for agriculture purposes in the past. Enfield and Windsor soils have minimal amounts of coarse fragments, have good drainage throughout the solum, and are presently used for crops and turfgrass in southern New England. Raypol soils were also cultivated at some point, however, because of periodic saturation in the upper solum and possible flooding, these sites were likely used

Table 3. Average weighted means (Mean) and coefficients of variation (CV) for thickness, bulk density, SOC content, and total soil organic C (SOC) storage for the master horizons, sola, and upper 1 m of the four soil types. Data represent an average of the data from each site within a soil type.

		Thickness		Bulk density		SOC concentration		Total SOC Content	
Horizon	n	Mean	CV	Mean	CV	Mean	CV	Mean	CV
		cm	%	g cm^{-3}	%	g kg^{-1}	%	Mg ha^{-1}	%
				Windsor					
Oie	20	9a	19	0.11a	7	413a	17	37a	23
A	20	9a	74	1.00a	21	26a	42	21a	81
B	20	52a	28	1.34a	8	7a	38	41a	27
Solum	20	70a	22	–	–	–	–	100	17
Upper 1 m	20	100	–	–	–	–	–	110a	15
				Enfield					
Oie	28	7ab	30	0.11ab	38	438a	11	33a	32
Oa	13	3a	63	0.31a	37	283a	23	26a	65
A	29	16a	23	0.88ab	14	38b	40	49b	29
B	26	54a	29	1.31a	9	6a	31	37a	38
Solum	29	74a	32	–	–	–	–	127	34
Upper 1 m	29	100	–	–	–	–	–	136a	29
				Raypol					
Oie	19	6bc	79	0.08b	41	417a	10	21b	97
Oa	18	9a	75	0.24a	54	222a	32	42a	97
A	20	13a	62	0.66b	38	53b	42	43b	73
B	16	45a	43	1.26a	20	12b	55	61b	55
Ab	7	28	19	1.56	60	29	65	67	51
Solum	20	80a	23	–	–	–	–	177	31
Upper 1 m	20	100	–	–	–	–	–	187b	31
				Carlisle					
Oie	29	5	68	0.08ab	34	471a	15	20b	73
Upper Oa	30	50	–	0.11b	37	507b	11	280b	19
Lower Oa	30	50	–	0.13b	60	506b	11	289b	27
Upper 1 m	30	100	–	–	–	–	–	586c	20

† Means with different letters are significantly different at the 0.05 alpha level among soil types for the same horizon.

more often for pasture than cultivation. Therefore, our C storage data suggest that within the first 60 to 100 yr of forest regrowth, following a land use change from agriculture, the development of O horizons may lead to a substantial increase in SOC.

The A horizons generally contained a similar proportion of the total SOC as the O horizons (Fig. 2 and 3). Only at the drier Windsor Bg site does the proportion of SOC contained in the A horizon appear considerably less than in the O horizons. Subsurface horizons (B and C horizons) contained between 26 and 55% of the SOC within the mineral soils (Fig. 2 and 3). Nearly 40% of the total SOC stored in the Windsor soils was stored in the B horizons. Torn et al. (1997) found similar amounts of SOC (33–70% of the total pool) in subsurface horizons. These studies emphasize the importance of including SOC in the subsoil horizons to the total SOC.

Drainage class influences the distribution of SOC throughout the profile, with wetter soils storing a greater portion of SOC deeper in the profile (Zdruli et al., 1995; Rapalee et al., 1998). The effect of drainage class on the distribution of C with depth can be clearly observed when comparing the excessively well-drained Windsor and well-drained Enfield soils to the poorly drained Raypol and very poorly drained Carlisle soils (Fig. 4). Over 75% of the C stored in the upper meter of the Carlisle soil is below 30 cm. In comparison, Raypol soils store about 45% of the total SOC pool below this depth, and in the better drained Windsor and Enfield soils approximately 30% of the total SOC is present below 30 cm. The similarity in the distributions of total SOC with depth for the Windsor and Enfield soils (Fig. 4) contrasts to how SOC is proportioned among horizons (Fig. 2). Windsor soils (Psamments) store the largest proportion of the SOC pool in the B horizons (Fig. 2), whereas in the Enfield soils (coarse-silty over sandy) the A or O horizons contain the largest proportion of the SOC pool. These data suggest that parent material affects the distribution of SOC among horizons and that the effects of drainage class on the proportions of the SOC pool with depth are more important on the wetter end of the spectrum.

Total Soil Organic Carbon Content Within and Among Soil Types

Total SOC content, defined on the upper 1 m of the soil including the organic horizons, ranged from 104 to 223 Mg C ha^{-1} in the mineral soils and between 494 and 645 Mg C ha^{-1} in the organic Carlisle soils (Tables 2 and 3). Analysis of variance showed a significant difference in total SOC among both soil types and sites (Table 4). The size of the total SOC pool followed a drainage class trend with Carlisle soils containing significantly greater ($p < 0.001$) amounts of total SOC than the three mineral soils and the Raypol soils also having significantly higher total SOC than the better drained Enfield and Windsor soils (Table 3). The SOC pools reported for forest soils in New Hampshire (160 Mg C ha^{-1}; Huntington et al., 1988) fall within the range of SOC in the mineral soils of this study. Total SOC in the Enfield series (136 Mg C ha^{-1}) was similar to SOC

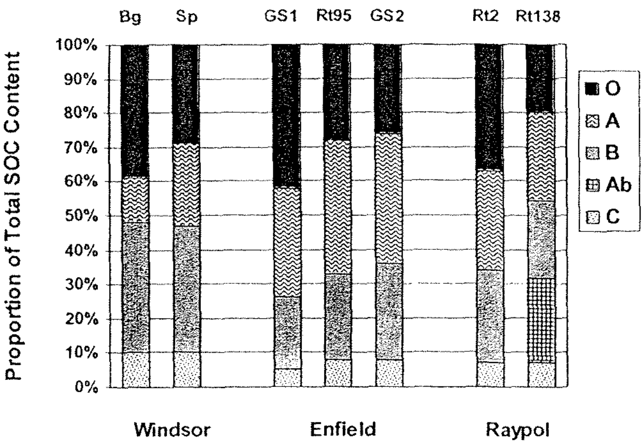

Fig. 2. Proportion of the total soil organic C (SOC) pool stored in upper 1 m by master horizon of the three mineral soil sites. Windsor soils have formed in outwash and are excessively drained; Enfield soils have formed in loess over outwash and are well drained; and Raypol soils are poorly drained having formed in loess (Rt2) and alluvium (Rt138).

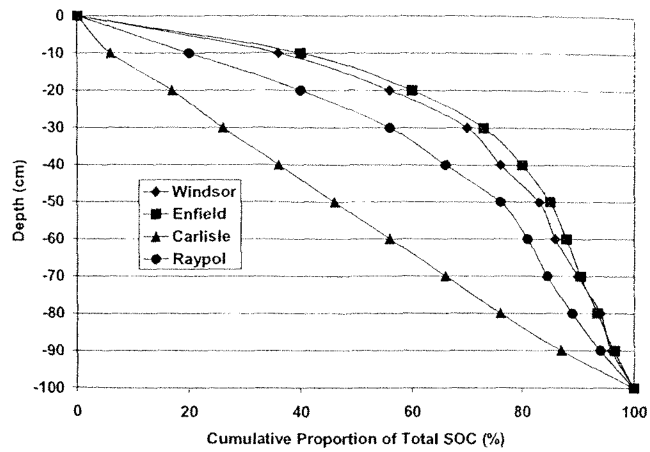

Fig. 4. Cumulative proportion of the total soil organic C (SOC) content with depth for upper 1 m of the four soil types studied. Data were averaged at 5-cm intervals for all of the pedons for each soil type.

content in well-drained till-derived soils (115–130 Mg C ha^{-1}) in Rhode Island (Hooker and Compton, 2003). Soil C content in the Carlisle series was approximately 20% lower than estimated pools of SOC in the upper meter of organic soils in the north central USA (740 Mg C ha^{-1}; Franzmeier et al., 1985) and the estimated global mean for wetlands (720 Mg C ha^{-1}; United States Department of Energy, 1999).

There was no significant difference at the 0.05 probability level in SOC content between the two Windsor mapping units (Table 5). Total SOC stored varied significantly within mapping units of the Enfield ($p = 0.003$), Raypol ($p = 0.001$), and Carlisle ($p = 0.004$) soils, suggesting that soil and site conditions, such as basal area or geomorphic setting affects the amount of SOC in these soils. In Enfield sites, the differences in SOC content among sites could be attributed to lower SOC concentrations (3% lower) in the Oie horizon and the absence of an Oa horizon in the GS2 site, and lower SOC concentrations (ranging from 0.5–5% lower) throughout the Oie and Oa horizons of the Rt95 site (Table 2). Thus, seemingly minor differences in O horizon characteristics

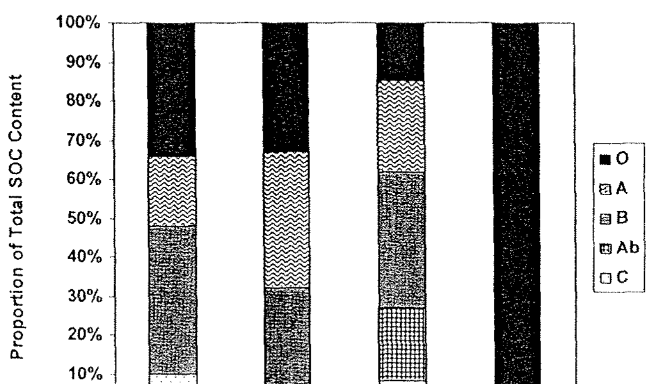

Fig. 3. Proportion of the total soil organic C (SOC) pool stored in the upper 1 m by master horizon based on soil parent materials.

can have a significant effect on SOC pools at the landscape scale. Each of the forest stands occupying the Enfield landscapes are approximately 80 to 85 yr old (Table 1), thus stand age cannot explain differences in SOC storage in the Enfield soils. Basal area for the GS1 site, which has significantly higher SOC content than the other two Enfield sites, is nearly 60% greater (10 m^2 ha^{-1}) than the GS2 site. A greater basal area may equate to higher yearly C additions to the soil through litterfall and root turnover, and thus a larger C pool in the O and A horizons.

The large difference in SOC content between the two Raypol units was attributed to a thinner O horizon and lower SOC concentrations throughout the solum of the alluvial Raypol site (Rt138; Table 2). The Rt138 site is located on a floodplain geomorphic setting and by far has the lowest SOC content within the Oie horizons of the mineral soils. Soils on floodplains are not as stable as the upland areas, and flooding events may remove some of the lighter organic fractions while depositing organic matter–poor silty mineral material, resulting in a lower SOC pool. The Rt2 site in the present land use appears to be nearly twice as old as the Rt138 site. The additional 50 yr of continued forested conditions may account for some of the additional C in the soil pool.

The reasons for the 150 Mg C ha^{-1} difference among the Carlisle sites are not apparent. Trees at the Rt110 site are the youngest of the three sites and the Rt110 site has the largest SOC pool (Table 2), suggesting that stand age is not a factor. Likewise, even though the Carlisle mapping unit with the lowest SOC pool also had the smallest basal area (18.6 m^2 ha^{-1}), this trend did not follow for the other two sites, suggesting that

Table 4. Summary of nested analysis of variance with site nested within soil type for total soil organic C (SOC) (Mg ha^{-1}) within the upper meter.

Source	Sum of squares	Degrees of freedom	Mean square	F value	P value
Soil type	4 149 517	3	1 383 172	383.39	< 0.001
Site (soil type)	174 557	6	29 093	8.06	< 0.001
Error	321 090	89	3 608		

Table 5. Summary of one-way analysis of variance comparing total SOC (Mg ha^{-1}) in the upper meter means within soil types.

Source	Sum of squares	Degrees of freedom	Mean square	F value	P value
		Windsor			
Model	788	1	788	3.17	0.092
Error	4 476	18	249		
Total	5 264	19			
		Enfield			
Model	15 312	2	7 656	7.42	0.003
Error	26 845	26	1 032		
Total	42 157	28			
		Raypol			
Model	27 723	1	27 723	14.61	0.001
Error	34 163	18	1 898		
Total	61 886	19			
		Carlisle			
Model	130 666	2	65 333	6.91	0.004
Error	255 289	27	9 455		
Total	385 955	29			

differences in basal area could not be used to account for variability in SOC content. Observations of change in the peat morphology with depth suggest that over time a number of different plant communities may have occupied these landscapes. For example, at the University of Rhode Island site reddish brown (2.5YR 3/3) Oa horizons occur interdispersed within the more typical black sapric materials. Reddish brown sapric materials in southern New England wetlands are indicative of vegetation dominated by white cedar (*Chamaecyparis thyoides*). These differences in plant communities likely reflect changes in hydrologic conditions, which may affect C concentrations and total SOC contents.

Measures of variability for SOC (Mg ha^{-1}) content in the solum and upper meter of these soils were similar or lower than for individual horizons (Tables 2 and 3). Variation in SOC content in the upper 1 m within individual mapping units ranged from 9 to 30% (Table 2). Average measures of variability for the four soil types were similar to the individual sites and ranged from 15 to 31% (Table 3). Windsor soils had the lowest average CV for SOC content in the upper 1 m (15%), followed by the Carlisle (20%), with the Enfield and Raypol having similar amounts of variability (29 and 31%, respectively). Huntington et al. (1988) reported slightly higher CVs (38%) for SOC content within mixed hardwood forest soils in New Hampshire. Lower within-site variability in SOC content (CVs of 0–16%) was observed in forest soils throughout the Northwest (Homann et al., 1995).

Comparison with National and Global Mean Values

A number of studies at regional, national, and global scales have used soil taxonomic groupings and soil survey data to estimate area-wide SOC pools (Table 6).

Table 6. Total soil organic C (SOC) (Mg ha^{-1}) in the upper 1 m of the Windsor, Enfield, Raypol, and Carlisle soils compared with total SOC values from the literature for soils of similar taxonomic classification. Locations in parentheses under the Criteria heading indicate whether data are reported as local, regional, national, or global averages.

Criteria	Windsor (Typic Udipsamment)	Enfield (Typic Dystrudept)	Raypol (Aeric Endoaqeupt)	Carlisle (Typic Haplosaprist)
	Mg C^{-1} ha^{-1}			
SOIL SERIES				
Rhode Island (USA)	110 (94–127)†	136 (96–175)†	187 (129–245)†	586 (469–703)†
WORLD SOIL ORDERS				
(global)	85 Regosols in secondary forest (Bouwman, 1990)	215 Cambisols in secondary forest (Bouwman, 1990)	215 Cambisols in secondary forest (Bouwman, 1990)	–
(global)	52 Dystric Regosol (Kern, 1994)	141 Dystric Cambisol (Kern, 1994)	188 Gleyic Cambisol (Kern, 1994)	820-992 Histosols (Kern, 1994)
CANADIAN TAXONOMY				
(Canada)	118‡ Regosols (Tarnocai, 1998)	93‡ Brunisols (Tarnocai, 1998)	93‡ Brunisols (Tarnocai, 1998)	1091‡ Organic (Humisols) (Tarnocai, 1998)
USA SOIL TAXONOMY				
Order (USA)	69 Entisols (Kern, 1994)	117 Inceptisols (Kern, 1994)	117 Inceptisols (Kern, 1994)	843 Histosols (Kern, 1994)
Suborder (USA)	49 Psamments (Kern, 1994)	90 Ochrepts (Kern, 1994)	135 Aquepts (Kern, 1994)	869 Saprists (Kern, 1994)
(Maine, USA)	49 Psamments (Davidson and Lefebvre, 1993)	158 Ochrepts (Davidson and Lefebvre, 1993)	–	1270 Saprists (Davidson and Lefebvre, 1993)
Great group (USA)	53 Udipsamments (Kern et al., 1998)	167 Dystrochrepts (in the Northwest) (Kern et al., 1998)	124 Endoaquepts (Kern et al., 1998)	–

† Means for each soil series with range in parentheses.
‡ No depth specified.

Total SOC content within the Windsor units (110 Mg C ha^{-1}) was approximately double the global and national values predicted for soils with the same classification (soil order, suborder, and great group), but were similar to estimated SOC contents in Regosols (Entisols) in Canada. Soil C content in the Enfield series was slightly lower than mean values estimated for Udepts (Ochrepts) in Maine (Davidson and Lefebvre, 1993) and Dystrudepts in the Pacific Northwest (Kern et al., 1998). Both the Enfield and Raypol total SOC estimates were similar to global values for their corresponding World Taxonomy suborders, Dystric and Gleyic Cambisols, respectively. Raypol soils had higher SOC contents than would have been predicted based on their USDA taxonomic classification. Soil C content in the Carlisle series (586 Mg C ha^{-1}) was 30 to 60% lower than national and global values for Histosols. Similar disagreements between national averages and regional estimates were reported for Spodosols in Maine (Davidson and Lefebvre, 1993) and Florida (Stone et al., 1993). These findings suggest national and global aggregations of soils data, based on soil taxonomic classification, may not accurately reflect regional or local SOC pools.

Implications for Scaling-up Carbon Estimates

At the landscape scale we found that C pools varied from 100 to 650 Mg ha^{-1}. Considering that the vegetation was hardwood forest at each site, and that there were significant differences in SOC pools among the various soil types, the use of coarse vegetation classes to group landscapes is not adequate for estimating SOC pools. Therefore, any comprehensive approach to inventory SOC pools will likely involve national soil survey data. How these soils data are to be grouped remains in question. Our comparisons with global and national averages suggest that grouping by taxonomic order is not an acceptable approach. For example, the Histosols that we examined stored 30 to 60% less SOC than the global or national averages. Similar discrepancies were observed for the mineral soils. One of the core problems with using the order approach is exemplified by the 50 Mg ha^{-1} (or 27–36%) difference in SOC between the poorly drained (187 Mg ha^{-1}) and well-drained (136 Mg ha^{-1}) Inceptisols. To reduce the effect of this coarse-scaling problem, Kern (1994) suggested that SOC data be averaged by great group because at this level specific information regarding soil properties believed to affect C storage such as drainage, climate, and coarse textures are incorporated in the classification. Region-wide, the great group approach may be useful in grouping soils, but even at this level we still found substantial differences between national averages and our SOC pools for the same great groups.

Soils examined in this study were chosen based on series level criteria since this level of classification provides the most detailed information about a soil. Most map units within second-order (county-wide) soil surveys are consociations. With the digitizing of most of the soil surveys in process or completed, and the additional SSURGO certification of many surveys in the works, estimating C pools using a GIS with series level attribute pedon data appears to be a possibility. The spatial variability data collected in this study provide some insight into how the soil survey data can be best used to estimate SOC pools within a region. Three of the four soil series we examined were found to have significantly different pools of C among delineations of the same series. These differences suggest that data from a single typical pedon may not provide the true mean SOC pool stored in these soils. We sampled 10 pedons within each of two or three delineations for each series. Based on the CV values, there appears to be nearly as much variability in the SOC pool within (CV's ranged 9–30%) as among delineations (CV's ranged from 15–31%) for the same land cover and soil type. These spatial variability data suggest that, instead of sampling at multiple locations within a single delineation to obtain the average SOC for a map unit, a more useful approach may be to sample from a significant number of delineations of the same series. This map unit SOC pool could then be applied to each of the map unit delineations in the soil survey area, recognizing that land use differences may result in additional variability to the overall C content estimate.

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