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Soil Organic Carbon in a Mountainous, Forested Region: Relation to Site Characteristics

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ABSTRACT

Soil organic C content (SOC, kilograms C per square meter) and its relation to site characteristics are important in evaluating current regional, continental, and global soil C stores and projecting future changes. Data were compiled for 499 pedons in the largely forested, mountainous western Oregon region. The SOC of mineral soil ranged from 0.9 to 24 kg C m^{-2} (mean = 6.5) for 0- to 20-cm depth and 2.3 to 88 kg C m^{-2} (mean = 15.8) for 0- to 100-cm depth. Variability in each of the three terms that determine SOC – C concentration, bulk density, and rock volume – contributed substantially to SOC variation. Regression analysis of 134 forest pedons indicated that combinations of site characteristics explained up to 50% of the SOC variability. The SOC increased with annual temperature, annual precipitation, actual evapotranspiration, clay, and available water-holding capacity and decreased with slope. Relations for western Oregon differed qualitatively and quantitatively from those for other regions and contrasted with the decrease in SOC associated with increased temperature in Great Plains grasslands. Of the variability not explained by regression analysis, one-half may be due to the combined uncertainty associated with measurements of C concentrations, bulk density, and rock volume; natural within-site variability; and site-characteristic measurements. Other unexplained variability is probably due to potentially important but poorly documented site characteristics, such as recent vegetation composition, geomorphic disturbance regime, and fire history.

IMPROVED ESTIMATES of SOC, defined here as kilograms C per square meter to a specified depth, are important for calculating current regional, continental, and global soil C stores (Eswaran et al., 1993; Kern, 1994). Relating SOC to site characteristics may help in formulating and evaluating process models (Burke et al., 1989) and in assessing the effect of land use and climate change on soil C stores (Turner et al., 1993).

Relations between soil organic C and site characteristics have been studied extensively at local and regional scales (Jenny, 1941, 1980) and differ between forested regions. In tropical Australian rain forests, organic C concentration decreases with PCP and T (Spain, 1990). In temperate forests of Minnesota, Wisconsin, and Michigan, SOC increases with PCP, AET, available water storage, and clay content and varies among tree species (Grigal and Ohmann, 1992).

Relations also differ among grassland regions. In the southern Great Plains of the USA, organic C concentration is positively related to clay concentration and PCP and is not related to T (Nichols, 1984). In Wyoming and Montana, colder (cryic and frigid) soils have higher organic C concentrations than warmer (mesic) soils and organic C is related to texture only in the warmer soils (McDaniel and Munn, 1985). In cryic and frigid soils of Montana, organic C concentration increases with PCP and elevation, which is assumed to be negatively related to T (Sims and Nielsen, 1986). Across the entire Great Plains grasslands, SOC is positively related to PCP, clay, and silt and negatively related to T (Burke et al., 1989). In examining the north-central USA, Franzmeier et al. (1985) concluded that the effects of climate on SOC were expressed mainly through the vegetation, e.g., forest vs. prairie.

The objectives of our study were to determine (i) variability of SOC in the mountainous, forested region of western Oregon, as indicated by pedon data; (ii) relations between SOC and site characteristics; and (iii) the extent to which measurement errors and within-site variability affect these relations.

METHODS

The study area was the western portion of the state of Oregon, USA, bordered on the north by the Columbia River, on the south by 42°N lat, on the west by the Pacific Ocean, and on the east by the eastern slope of the Cascade Range. General land use, vegetation, and topography for this 90 000-km^2 area have been presented by Clarke et al. (1991).

We compiled pedon information, calculated SOC of the O horizon and of the mineral soil to depths of 20 and 100 cm, and used regression analysis to determine the relation of SOC to site variables, including those investigated in previous studies (Burke et al., 1989; Grigal and Ohmann, 1992). We chose the O horizon and mineral soil depths of 20 and 100 cm to facilitate comparison with other studies.

Pedon Carbon

Field descriptions of pedons and laboratory analyses conducted between 1955 and 1991 were compiled from a variety of studies (Table 1). Pedons were included in our analysis if they met all of the following criteria: (i) known location, (ii) pedon depth of at least 50 cm or to a rock horizon (designated by R, Cr, bedrock, or rock) if that horizon was within the upper 50 cm, (iii) organic C concentration and rock content (either volumetric or gravimetric) measured for the surface mineral-soil horizon, and (iv) measurements of organic C concentration and rock content missing for no more than 20% of the pedon depth. For example, a 70-cm-deep pedon would be included if organic C concentration or rock content data were missing for a subsurface horizon up to 14 cm thick (20% of 70 cm), but excluded if data were missing for a thicker subsurface horizon. A horizon with missing data was assigned values from an adjoining, genetically similar horizon in the pedon, or assigned the average of values from the adjoining,

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Abbreviations: SOC, soil organic carbon; T, mean annual temperature; AET, actual evapotranspiration; PET, potential evapotranspiration; PCP, mean annual precipitation; AWC, available water-holding capacity to 100-cm depth; GIS, geographic information system; SD, standard deviation; CV, coefficient of variation.

Table 1. Sources of western Oregon pedon data used for soil organic C content analysis.

Source or study	Total	C concentration method		Bulk density method			Rock content	
		Walkley-Black	Combustion	Clod	Core	Calculated	Field	Laboratory
	no. of pedons							
National Soil Survey Center, Lincoln, NE	40	40	0	18	0	22	18	22
National Soil Survey Center, Lincoln, NE with supplementary information from Soil Conservation Service, Portland, OR	137	137	0	75	0	62	92	45
Soil Conservation Service, Portland, OR	79	79	0	5	0	74	49	30
Soil surveys (Soil Conservation Service, 1964, 1970, 1973a,b; Soil Survey Staff, 1975)	35	35	0	2	0	33	31	4
Stand Management Cooperative, Univ. of Washington, Seattle	69	0	69	0	69	0	69	0
Zinke-Stangenberger soil C database, Univ. of California, Berkeley (Zinke et al., 1984), with supplementary information from Tidball (1965)	18	9	9	0	18	0	0	18
Other (Badayos, 1983; D. Binkley, 1993, unpublished data, summarized in Binkley et al., 1992; J. Bockheim and S.L. Turnbaugh, Univ. of Wisconsin, unpublished data; Brown, 1975; Brown and Parsons, n.d.; Ezenwa, 1977; Franklin, 1971; Gelderman, 1970; Harris, 1973; Hoppe, 1989; Laurent, 1979; Marshall, 1991; J.E. Means, 1993, unpublished data, summarized in Means et al., 1992; Meurisse, 1972)	121	113	8	16	76	29	103	18

genetically similar horizons above and below it. Of the pedons included in the analyses, 17% had missing data.

Organic C concentration had been measured on the <2-mm fraction for all pedons. Therefore, we calculated SOC of the <2-mm material as

$$
\begin{aligned}
&\text{SOC (kg m}^{-2}\text{ to 20- or 100-cm depth)} = \\
&\quad \Sigma[\text{organic C concentration of} <\text{2-mm material (g kg}^{-1}) \\
&\quad \times \text{bulk density of} <\text{2-mm material (g cm}^{-3}) \\
&\quad \times \text{horizon depth (cm)} \\
&\quad \times (1 - \text{rock volume [\%]}/100\%) \\
&\quad \times 10^4\,\text{cm}^2\,\text{m}^{-2} \times 10^{-6}\,\text{kg}^2\,\text{g}^{-2}]
\end{aligned}
$$

where the summation is across portions of horizons within the specified depth. The SOC was calculated only for pedons with relevant information, including supplemental missing values, to the specified depth, or for pedons with rock horizons within the specified depth. Various methods had been used to measure the variables in the equation (Table 1). Although the different methods can yield different values, there are no universally applicable conversion factors between the different methods (e.g., for organic C concentration, see Nelson and Sommers, 1982). Therefore, we made no attempt to convert or correct values to a common methodology.

Most measurements (Table 1) of organic C concentration had been made by the Walkley-Black method (Soil Survey Laboratory Staff, 1992). We converted Walkley-Black values reported as organic matter percentage to organic C concentration (grams C per kilogram) by multiplying by 5.8. For some pedons, measurements of total C had been made by high-temperature combustion (Nelson and Sommers, 1982). Because the soils of western Oregon are acidic, carbonates were not expected in the soils and organic C was assumed to be equal to total C.

Bulk density was measured by the clod method at 33 kPa moisture tension (Soil Survey Laboratory Staff, 1992) for some pedons and by the core method (Blake and Hartge, 1986) for others (Table 1). For pedons where bulk density was not reported for A and B horizons, it was calculated (Table 1) from linear functions of organic C concentration derived by regression analysis from those western Oregon pedons where bulk density had been measured by the clod method (Table 2). The functions for the pumice-ash and andic soils differed considerably from those developed by Manrique and Jones (1991) for soils from throughout the USA (Table 2). Although other studies have used data transformations and nonlinear equations to relate bulk density to organic C or organic matter (Grigal et al., 1989; Huntington et al., 1989; Manrique and Jones, 1991), neither visual inspection nor statistical analysis of our data showed a substantial advantage of these methods over linear relations. The bulk density of C horizons was poorly related to organic C. Therefore, when bulk density was missing for the C horizon, we used 1.01 g cm^{-3} for pumice-ash or andic soils, based on 28 measurements and 1.56 g cm^{-3} for other soils, based on 14 measurements. Data analyses (described below) based on pedons that had either measured or calculated bulk densities yielded conclusions similar to data analyses that used only pedons with measured bulk densities. We present results from the former analyses, because they cover broader ranges of site characteristics.

Rock volume was often reported in field descriptions as a percentage of total volume (Table 1). Rock mass (percentage of total mass) was reported in some laboratory results (Table 1) and includes rocks of all sizes, based on statements of Soil Survey Laboratory Staff (1992). Rock mass was converted to rock volume by Method 3B2 of the Soil Survey Laboratory Staff (1992). The rock density used in the calculation was 1 g cm^{-3} for pedons with parent material of volcanic ash or pumice and 2 g cm^{-3} for other parent material, based on data of Flint and Childs (1984). Because rock horizons (indicated in field descriptions by a descriptive term or designation of Cr or R horizon) are not necessarily solid rock but can be saprolite and have fracture planes, based on values from two pedons we assigned 10% soil volume and 90% rock volume to the upper 10 cm of the rock horizons and 100% rock volume at greater depth.

Table 2. Linear regression equations† of bulk density to organic C from this study and from Manrique and Jones (1991).

Horizon, soil category	Intercept	Slope	n	r^2	Range of organic C
					g kg^{-1}
	This study				
A, pumice-ash or andic	0.92	−0.0028	103	0.48	3–215
B, pumice-ash or andic	1.09	−0.0074	68	0.39	2–78
A, other	1.39	−0.0092	59	0.62	3–115
Ap, other	1.53	−0.0086	19	0.66	<1–61
B, other	1.42	−0.0122	153	0.22	<1–61
	Manrique and Jones (1991)				
A horizon	1.51	−0.0113	19 651	0.36	NA‡
B horizon	1.52	−0.0153	10 349	0.38	NA

† Bulk density (g cm^{-3}) = intercept + slope × organic C (g kg^{-1}).

‡ NA = not available.

The O horizon data for 25% of the forest pedons was reported as O horizon mass (kilograms per square meter) and C concentration (grams C per kilogram), which we multiplied together to determine SOC. For 58% of the forest pedons, we multiplied the O horizon thickness reported in the field descriptions by 0.51 kg C m^{-2} cm^{-1} of depth. This conversion factor is an average value based on pedons used in this synthesis (Tidball, 1965) and other Pacific Northwest studies (Gessel and Balci, 1965; Little and Ohmann, 1988; Homann et al., 1992; Cole et al., 1995). Although subhorizons of the O horizon can have different conversion factors (Alexander et al., 1989), subhorizon thicknesses were reported for only 19% of the O horizons reporting thickness; therefore, a single conversion factor for the entire O horizon thickness was used. Based on stated sampling procedures, these O horizon values did not include coarse woody debris. No O horizon data were reported for 18% of the forest pedons.

Ancillary Information

Quality and quantity of site information varied considerably among pedons. Some field descriptions and laboratory analyses had very specific location information, complete profile descriptions, land use, vegetation, site history, geomorphic position, slope, aspect, elevation, parent material, soil classification, and laboratory texture analyses. Other pedons had more limited information.

Locations were translated to latitude and longitude by examining 7.5-min quadrangle topographic maps produced by the U.S. Geological Survey (Denver, CO). Average monthly precipitation and temperature were obtained by overlaying pedon locations onto 10 by 10 km grid cell climate layers in a GIS, based on the 1948 to 1987 data from 35 weather stations within and surrounding the study area (Karl et al., 1990). The precipitation layers were developed by methods described by Daly et al. (1994). The temperature layers were developed by converting weather station temperatures to sea level equivalent temperature, interpolating between stations based on linear inverse distance and reconverting to grid cell elevations (D. Marks, 1993, personal communication). The adequacy of these GIS layers was tested by comparing 1951 to 1980 average values (National Oceanic and Atmospheric Administration, 1990) for western Oregon weather stations that were not used to develop the GIS data layers with values from the GIS data layers for the weather station locations. There was good agreement between GIS and observed annual precipitation (r = 0.88, n = 39). There was poor agreement between uncorrected GIS and observed annual temperature (r = 0.45, n = 29), but agreement improved substantially (r = 0.92, n = 29) after lapse-rate correction of the GIS value for the elevation differences between GIS grid cells and weather stations. Therefore, for the pedon locations, temperature was corrected for the difference between grid cell and pedon elevations; month-specific lapse rates ranged from 5.9 to 7.6°C per 1000-m difference. Average difference between grid cell and pedon elevations was 195 m.

Elevations were reported on pedon descriptions for 79% of the pedons and were used in our analysis. For the other pedons, we took elevations from a digital-elevation model with cell size of 65 m (east–west) by 92 m (north–south; U.S. Geological Survey, 1987). The adequacy of this process was indicated by the excellent agreement (r = 0.98, n = 392) between reported pedon elevations and elevations from the digital elevation model for these pedon locations. Elevations ranged from 0 to 2040 m for all pedons, 15 to 1550 m for pedons used in the regression analysis with site characteristics, 43 to 1250 m for weather stations used in development of GIS temperature and precipitation layers, and 2 to 1970 m for weather stations used to test adequacy of those layers.

The AET was calculated from monthly water balance using PET (Thornthwaite and Mather, 1955), monthly temperature and precipitation from the GIS layers, and AWC. The latter was calculated as the difference between volumetric water content at 10 and 1500 kPa matric pressures, as used by Grigal and Ohmann (1992) in the 0- to 100-cm depth of mineral soil. Volumetric water content was calculated from texture (using equations of Rawls et al., 1982), bulk density, and rock content. In the use of Rawls' equations, the assumption of no organic matter was made; therefore AWC and AET represent indicators rather than actual values. This assumption was made because for the regression analyses of SOC as functions of site characteristics, we did not want AWC and AET to be dependent on organic C, a situation which would have resulted in C content being a function of itself.

Statistical Methods

Differences in SOC, C concentration, rock content, and bulk density among land use classes were evaluated with the Kruskal–Wallis nonparametric test (Woolson, 1987) carried out by SAS Institute (1985) software, followed by the Dunn nonparametric multiple comparison test (Woolson, 1987).

Relations between SOC and site characteristics were determined with stepwise regression (SAS Institute, 1985). Independent variables were entered into and retained in the regression models at $P < 0.01$.

RESULTS AND DISCUSSION

Mineral Soil Organic Carbon

For individual pedons, SOC of mineral soil ranged from 0.9 to 24.3 kg C m^{-2} in the 0- to 20-cm layer and from 2.3 to 88.2 kg C m^{-2} in the 0- to 100-cm layer. Based on field descriptions, pedons were classified into four land use categories: cultivated (13% of pedons), pasture–orchard (13%), forest (70%), and undesignated (5%). Variability of SOC was high in all categories (Table 3). On average, pasture–orchard had higher SOC than cultivated and forest, but there was no substantial difference between the latter two.

There was considerable variation in the three variables used to calculate SOC: C concentration, bulk density of the <2-mm fraction, and rock volume (Table 3). Pasture–orchard soil had lower rock volume and higher bulk density than forest; both factors contributed to higher SOC in pasture–orchard. Pasture–orchard soil had higher C concentration than cultivated; this was offset partially by lower bulk density, ultimately yielding higher SOC in the pasture–orchard. Cultivated soil had lower C concentration but higher bulk density and lower rock volume than forest; cumulatively, this resulted in similar SOC in cultivated and forest soils.

Forest soils were further divided into the following groups: (i) pumice–ash, soils whose parent material was reported as pumice or volanic ash; (ii) andic, soils whose parent material was not reported as volcanic ash or pumice but whose soil classification indicated andic characteristics; (iii) other, soils whose parent material was not reported as volcanic ash or pumice and whose soil classification did not indicate andic characteristics; and

Table 3. Mineral-soil organic C content, C concentration, bulk density, and rock volume ($\bar{x}$ [standard deviation]) for 0- to 20- and 0- to 100-cm depths in western Oregon pedons.

	n		C content		C concentration		Bulk density		Rock volume	
Soil category	0–20	0–100	0–20	0–100	0–20	0–100	0–20	0–100	0–20	0–100
			kg C m^{-2}		g kg^{-1}		g cm^{-3}		%	
All	499	462	6.5 (3.7)	15.8 (10.8)	45 (33)	20 (18)	0.95 (0.27)	1.10 (0.25)	13 (16)	17 (20)
Undesignated	25	18	5.6 (2.3)	13.2 (4.6)	32 (18)	12 (5)	1.05 (0.21)	1.20 (0.14)	8 (12)	8 (9)
Cultivated	63	60	6.1 (3.1) B**†	14.8 (11.6) B**	27 (23) B	13 (16) B	1.28 (0.18) A	1.34 (0.16) A	3 (5) B	2 (4) C*
Pasture-orchard	63	54	8.8 (4.9) A**	22.9 (15.3) A**	52 (36) A	27 (24) A	1.02 (0.23) B	1.15 (0.23) B*	5 (11) B	11 (19) B*
Forest	348	330	6.3 (3.5) B	15.0 (9.5) B	49 (34) A	21 (17) A	0.87 (0.24) C	1.04 (0.25) C*	17 (17) A	22 (21) A
Pumice-ash	64	63	3.8 (2.2) c	8.3 (6.2) c	36 (23) b	16 (12) b	0.78 (0.12)b*	0.87 (0.13) b	27 (17) a	36 (19) a
Andic	57	53	9.8 (4.1) a	25.0 (11.0) a	91 (36) a	44 (24) a	0.62 (0.16) c*	0.77 (0.20) b	9 (12) b	16 (18) b
Other	181	173	6.1 (2.6) b	14.4 (7.5) b	38 (19) b	16 (8) b	0.99 (0.22) a	1.19 (0.19) a	14 (16) b	18 (20) b
Unspecified	46	41	6.1 (3.9)	14.8 (8.6)	55 (48)	22 (17)	0.81 (0.19)	1.03 (0.18)	24 (18)	24 (18)

Within each column, two values identified by different letters differ at $P < 0.001$ if at least one of the letters has no * or **, $P < 0.01$ if both letters have **, and $P < 0.05$ if both letters have *.

† Statistical analyses were performed with the Kruskal-Wallis test using SAS (SAS Institute, 1985), followed by the Dunn nonparametric multiple-comparison test (Woolson, 1987). Uppercase letters pertain only to comparison among cultivated, pasture-orchard, and forest land uses. Lowercase letters pertain only to comparison among pumice-ash, andic, and other forest soils.

(iv) unspecified, soils whose parent material or soil classification were not reported. The SOC was in the order andic > other > pumice-ash. On average, the andic pedons were both warmer and exposed to higher precipitation than pumice-ash pedons, as indicated by annual temperature and precipitation (mean [SD]): 64 andic pedons 229 (65) cm, 9.0 (1.9)°C; 57 pumice-ash pedons, 144 (78) cm, 6.8 (1.7)°C; and 181 other pedons, 170 (65) cm, 9.9 (1.5)°C.

Average SOC of forest mineral soils in this study (6.3 kg C m^{-2} to 20-cm depth and 15 kg C m^{-2} to 100-cm depth) was higher than in several other regional studies. Averages for 169 forest sites in Minnesota, Wisconsin, and Michigan were 4.0 kg C m^{-2} to 20 cm and 10.5 kg C m^{-2} to 100 cm (Grigal and Ohmann, 1992). In the north-central USA, including forests, grasslands, and cultivated lands, averages for mineral soils were 4.7 kg C m^{-2} to 20 cm and 10.7 kg C m^{-2} to 100 cm (Franzmeier et al., 1985). The average for Florida Spodosols, including natural forests, pine plantations, cultivated crops, and pasture, was 10.4 kg C m^{-2} to 100 cm; however, Stone et al. (1993) emphasized that considerable C occurs in those soils at >100-cm depth and concluded that complete profiles, some to >200-cm depth, averaged 18.3 kg C m^{-2}. The average for 149 forest profiles in southeast Alaska was 18.5 kg C m^{-2} per profile, with some profiles extending to 150-cm depth (Alexander et al., 1989). Differences in all soil forming factors, including climate, parent material, topography, vegetation, and disturbance, may contribute to the differences between SOC of western Oregon forests and other regions. The world average for all soils is 11.7 kg C m^{-2} to 100-cm depth, based on the data of Eswaran (1993).

O Horizon Organic Carbon

For O horizons, those with measured SOC averaged 1.0 kg C m^{-2} (range 0.1–4.5, $n = 86$) and those with thickness-based SOC averaged 2.4 kg C m^{-2} (range 0.5–11, $n = 201$). Measured SOCs were largely from young (16–64-yr-old) second-growth forests of the Stand Management Cooperative (Table 1; Edmonds and Hsiang, 1987), for which O horizons may have been reduced by prescribed burning during site preparation prior to stand establishment (Little and Ohmann, 1988). Average of both measured and thickness-based SOC was 2 kg C m^{-2}. This is similar to the average of 1.7 kg C m^{-2} in Minnesota, Wisconsin, and Michigan forests (Grigal and Ohmann, 1992). The forest floor data compiled by Vogt et al. (1986) indicate average values of 0.7 kg C m^{-2} for tropical forest, 1.4 kg C m^{-2} for temperate forest, and 1.7 kg C m^{-2} for boreal forest; and the data of Vogt et al. (1995) yield averages of 0.5 kg C m^{-2} for tropical forest, 1.7 kg C m^{-2} for temperate forest, and 3.3 kg C m^{-2} for boreal forest. All these are much lower than the average of 8.3 kg C m^{-2} for O horizons overlying forest mineral soils in southeast Alaska (Alexander et al., 1989).

Relation of Organic Carbon to Site Characteristics

We used linear regression analysis to relate the SOC in O horizon, 0- to 20-cm depth of mineral soil, and 0- to 100-cm depth to forest site characteristics. In one approach, stepwise regression analysis was used; SOC was the dependent variable and regressed against sets of (i) independent variables plus their squares or (ii) independent variables plus their squares and cross-products. A set consisted of T, PET, or AET plus AWC, PCP, slope (percentage), and contents (kilograms per square meter to 20- or 100-cm depth) of sand, silt, and clay individually or summed together. The T, PET, and AET were not used in the same set because they were highly correlated ($r > 0.7$). In general, other variables were more poorly correlated with T, PET, and AET and among themselves; e.g., for T vs. PCP, $r = 0.08$. Those few that were correlated at $r > 0.7$ (AWC and silt content to 20 cm and AWC and silt content to 100 cm) were not allowed to enter the same equation. In the second approach, the form of the regression model of Burke et al. (1989) was fit to our data. Our analysis was restricted to the 134 forest pedons for mineral soil for which all of the above variables were known. Of these, 31 were excluded from the O horizon analysis because of missing information.

The O horizon SOC related poorly to site characteristics, with a maximum adjusted R^2 of 0.12. In contrast,

Table 4. Coefficients for regression equations† of mineral-soil organic C content (kg C m^{-2}) in 0- to 20- and 0- to 100-cm depths as functions of actual evapotranspiration (AET) and other site variables for well-drained, forested sites with known slope and texture (*n* = 134).

	0- to 20-cm depth						0- to 100-cm depth					
	Without cross products			With cross products			Without cross products			With cross products		
Variable‡	Coefficient	SRC§	*P*	Coefficient	SRC	*P*	Coefficient	SRC	*P*	Coefficient	SRC	*P*
Constant	1.1		0.02	1.7		0.0006	−0.5		0.7	−0.2		0.9
AET^2	1.3×10^{-3}	0.46	0.0001	1.3×10^{-3}	0.46	0.0001	5.2×10^{-3}	0.65	0.0001	3.5×10^{-3}	0.44	0.0001
Clay20	3.2×10^{-2}	0.31	0.0001									
AET × Clay20				6.8×10^{-4}	0.36	0.0001						
Slope × Silt20				-2.9×10^{-4}	−0.19	0.003						
PCP^2										-8.0×10^{-5}	−0.32	0.0005
PCP × AWC										2.6×10^{-3}	0.52	0.0001
Adjusted R^2	0.44			0.47			0.42			0.50		

† Regression equations are of the form C content = constant + coefficient1 × variable1 + coefficient2 × variable2 + . . .

‡ AET = calculated actual evapotransporation (cm yr^{-1}), range = 20 to 64; Clay20 = mass of clay to 20-cm depth (kg m^{-2}), range = 0 to 100; Slope = slope (%), range = 0 to 80; Silt20 = mass of silt to 20-cm depth (kg m^{-2}), range = 11 to 170; PCP = mean annual precipitation (cm yr^{-1}), range = 28 to 458; AWC = available water-holding capacity to 100-cm depth (cm), range = 5 to 28.

§ SRC = standardized regression coefficient = coefficient × (standard deviation of variable)/(standard deviation of soil organic C content).

the forest floor SOC model of Grigal and Ohmann (1992) was able to explain much more variability (R^2 = 0.40), because the model included stand age and tree species, neither of which were available in our data set.

The AET explained more variation in SOC in both the 0- to 20-cm (R^2 = 0.36) and the 0- to 100-cm (R^2 = 0.42) mineral soil than any other single variable. Clay content explained additional variation in the 0- to 20-cm soil, but no other individual variables were significant for the 0- to 100-cm layer (Table 4). When cross-products were allowed to enter the equation, slope × silt was significant for the 0- to 20-cm layer, and PCP × AWC for the 0- to 100-cm layer (Table 4). Although PET and T were individually more poorly correlated than AET with SOC in the 0- to 100-cm layer, models (not shown) with either PET or T, plus PCP and AWC, explained about the same amount of variability as the AET-with-cross-products model.

Our model without cross-products for 0- to 20-cm depth (Table 4) is qualitatively similar to the one derived for the Lake States forests by Grigal and Ohmann (1992), although they used a soil depth of 0 to 25 cm and also included tree species in their model. Both models indicate similar trends for clay content and AET. A 10 kg m^{-2} increase in clay content is associated with a 0.3 kg C m^{-2} increase in our model and with a 0.4 kg C m^{-2} increase in the original Grigal–Ohmann model. A shift of AET from 30 to 40 cm yr^{-1} is related to a 0.9 kg C m^{-2} increase in our model and to a 0.5 kg C m^{-2} increase in the original Grigal–Ohmann model.

Table 5. Coefficients for regression equations† of mineral-soil organic C content (kg C m^{-2}) in 0- to 20-cm depth as a function of temperature and other site variables for well-drained, forested sites with known slope and texture (*n* = 134). Equations were modified from the form presented in Burke et al. (1989).

	Modified Burke			Modified Burke with slope		
Variable‡	Coefficient	SRC§	*P*	Coefficient	SRC	*P*
Constant	7.6×10^{-1}		0.3	9.7×10^{-1}		0.2
T^2	1.9×10^{-2}	0.27	0.0001	1.8×10^{-2}	0.26	0.0001
PCP	2.3×10^{-2}	0.68	0.002	2.6×10^{-2}	0.77	0.0003
PCP^2	-7.1×10^{-5}	−0.79	0.0001	-7.5×10^{-5}	−0.84	0.0001
PCP × Clay	5.1×10^{-4}	0.53	0.0001	5.0×10^{-4}	0.52	0.0001
Slope				-2.0×10^{-2}	−0.18	0.008
Adjusted R^2	0.43			0.46		

† Regression equations are of the form C content = constant + coefficient1 × variable1 + coefficient2 × variable2 + . . .

‡ T = mean annual temperature (°C), range = 2.8 to 12.8; PCP = mean annual precipitation (cm yr^{-1}), range = 28 to 458; Clay = clay (%), range = 0 to 54; Slope = slope (%), range = 0 to 80.

§ SRC = standardized regression coefficient = coefficient × (standard deviation of variable)/(standard deviation of soil organic C content).

Results of fitting the model of Burke et al. (1989) to our forest data are presented in Table 5. Two terms in the original model were not significant (T [$P > 0.5$] and PCP × silt content [$P > 0.05$]) and, therefore, were not included in our modified model. The original Burke et al. (1989) model and our model are qualitatively similar with respect to PCP and clay in that both models indicate that SOC increases with those variables. In contrast, the models differ with respect to temperature. An increase in T from 3 to 13°C, the range for our study, is associated with a 3 kg C m^{-2} increase in our model but an 8 kg C m^{-2} decrease in the original Burke et al. (1989) model. This discrepancy might be due to the differences in seasonal temperature patterns; ranges of T and PCP (3–13°C and 28–458 cm in our study vs. 4–23°C and 30–120 cm in Burke et al., 1989); and vegetation type, which affects both microclimate and the quantity, quality, and distribution of detrital inputs into mineral soil. Grigal and Ohmann (1992) also found disagreement between their observations for forests and the Burke et al. (1989) grassland model.

The SOC in the 0- to 20-cm layer decreased with increased slope. In the model with cross-products (Table 4), when silt content is set at our data set average (60 kg m^{-2} in 0–20 cm layer), an increase in slope from 0 to 50% yields a decrease in SOC of 0.9 kg C m^{-2}. A similar increase in slope in the modified Burke model (Table 5) yields a decrease of 1 kg C m^{-2}.

Effect of Uncertainties

Our ability to explain only 50% of SOC variability in mineral soil and 12% in O horizon with site characteristics may be attributed to (i) soil variability at individual sites, (ii) uncertainty in C content values, (iii) uncertainty in site characteristics, and (iv) exclusion of important site characteristics.

Variability of SOC at a specific site can be high. For three sites in our study area where three or four pits were sampled at each site (Means et al., 1992; Binkley et al., 1992), CV of SOC ranged from 17 to 85% for O horizon, 12 to 28% for the 0- to 20-cm mineral soil, and 0 to 16% for the 0- to 100-cm mineral soil. For a 23-ha watershed in New Hampshire in which 59 pits were sampled, CV of organic C was 74% for O horizon and 45% for mineral soil to the bottom of the B horizon (Huntington et al., 1988). Therefore, a single pedon at a site may differ considerably from the average for the site.

Uncertainty in SOC of mineral soil arises from uncertainties in C concentration, bulk density, and rock volume. Analytical precision of replicate measurements for C concentration differs between methods (Soil Survey Laboratory Staff, 1992). Different methods can yield different average values for C concentration (Nelson and Sommers, 1982) and bulk density (Blake and Hartge, 1986). Rock volume uncertainties arise from visual field estimates, which are acknowledged to be subjective for large rock fragments (Soil Survey Laboratory Staff, 1992), and from calculation of volume from rock mass using assumed rock densities (Grigal and Ohmann, 1992; Soil Survey Laboratory Staff, 1992).

Our comparison between climatic measurements at western Oregon weather stations and the GIS-based estimates for those weather station locations (r = 0.92 for T, 0.88 for PCP, 0.93 for PET, and 0.97 for AET) indicates uncertainty of the GIS-derived values. Additional uncertainty is likely for the pedons, whose point locations may be influenced by micro- and mesoscale geomorphic and microclimatic influences not accounted for by the GIS climate layers. Furthermore, when attempting to relate SOC to climatic data, the appropriate duration of climatic data to use depends on how rapidly SOC responds to climatic shifts, which is largely unknown. The total SOC has been described conceptually to consist of several pools with different stabilities or turnover rates (Balesdent et al., 1988; Parton et al., 1987); temporal response of total SOC to climate would depend on the sum of changes of these individual pools. In practice, there are limited long-term climatic data available, particularly in mountainous terrain, so the climatic data used for soil assessments may be less than ideal.

Uncertainty is also associated with nonclimatic site characteristics. For example, because of dispersion difficulties and the presence of noncrystalline minerals (Maeda et al., 1977), particle-size (clay and silt) data may relate differently to SOC in volcanic-ash soils than in others.

To determine if uncertainties can account for our inability to explain more than 50% of the variation in SOC, we conducted a sensitivity analysis. Based on our data set, we formulated a synthetic data set of 134 observations in which SOC (0–20 cm depth) was totally explained by AET^2. Then singly or in combination, we introduced errors into (i) each term used to calculate SOC—C concentration, bulk density, rock volume—to simulate measurement error; (ii) SOC to simulate within-site variability; and (iii) AET to simulate uncertainty in site characteristics. These errors were randomly selected from normal distributions defined by the SD of replicate measurements (Table 6). We then recalculated the regression relation between SOC and AET^2.

The sensitivity analysis indicated that the combined errors reduced the explained variation in SOC from 100% under a hypothetically perfect situation to 62% under more realistic conditions (Table 6), yielding 38% unexplained variation. The actual contribution of these errors to unexplained variation will differ among studies, depending on specific analytical techniques, selection of pedon locations at sites, and methods of determining site characteristics. For our data set, 36% of SOC variation was explained by AET^2, leaving 64% unexplained. Comparison with the sensitivity analysis indicates that a large proportion of this unexplained variation in regression analyses of SOC vs. site characteristics may be due solely to errors in measurement, natural within-site variability, and uncertainty in site characteristics.

Other unexplained variation in SOC is caused by excluding potentially important site characteristics from the regression analysis. Grigal and Ohmann (1992) found forest species to be important in explaining the variability of SOC in both O horizon and mineral soil. However, we excluded forest type as a factor because it was often not reported in pedon descriptions, although SOC differs considerably with tree species in our study area. For example, alder increases SOC compared with conifers (Binkley et al., 1992; Cole et al., 1995). Grigal and Ohmann (1992) found stand age to be important in ex-

Table 6. Influence of random error on the fraction of variation (r^2) of soil C content explained by actual evapotranspiration (AET) based on a synthetic data set.†

Source of error	Standard deviation of error	r^2
None		1.00
Measurement		
C concentration‡	0.05 × C concentration (g kg^{-1})	0.97
Bulk density§	0.06 × bulk density (g cm^{-3})	0.95
Rock volume¶	0.05 m^3 m^{-3}	0.96
All of above		0.89
Within-site variability#	0.18 × C content (kg m^{-2})	0.72
AET††	2 cm yr^{-1}	0.95
All of above		0.62

† A synthetic data set was developed based on the 134 pedons used in the regression analysis in this study (Table 4). For this synthetic data set, without error, soil organic C content (kg C m^{-2} to 20-cm depth) = 1.2 + 0.0017 × AET^2, r^2 = 1.00. Error was assigned to each observation based on random selection from a normal distribution with the indicated standard deviation (SD). The SD are based on information from the sources listed below.

‡ Soil Survey Laboratory Staff (1992). For the Walkley–Black method, the SD of replicate C concentration measurements was 0.017 × C concentration. For the high-temperature combustion method, the SD of replicate C concentration measurements was 0.055 × C concentration.

§ Vincent and Chadwick (1994). For bulk density by the clod method, SD of replicate measurements was 0.04 × bulk density for an A horizon and 0.06 × bulk density for a B horizon.

¶ Estimates of rock volume on pedon field descriptions are often presented in increments of 0.05 or 0.10 m^3 m^{-3}, but uncertainty of these estimates is not documented.

Means et al. (1992) and Binkley et al. (1992). Based on replicate soil pits at each of three sites.

†† Based on comparison of AET calculated from 1951–1980 average monthly temperature and precipitation values (National Oceanic and Atmospheric Admin., 1990) for western Oregon weather stations that were not used to develop the GIS data layers used in this study and AET calculated from the GIS data layers for those weather station locations.

plaining O horizon SOC. This reflects site history, which was generally not reported in pedon descriptions but may be important with respect to fire effects on O horizon. The SOC may be related to and influenced by geomorphic site characteristics, including slope position, slope curvature, and aspect. Aspect might influence SOC through its effect on radiation balance and temperature and, hence, detrital production and decomposition rate. Aspect was reported on pedon descriptions for only 89 of the 134 forest pedons used in the regression analysis. An attempt to modify AET estimates by considering aspect did not improve the relation between AET and SOC. A micrometeorological modeling approach to account for aspect may be needed, but this would require additional site-specific information.

CONCLUSIONS

Average SOC in the upper 100 cm of forest mineral soils was higher in western Oregon than in several other areas of the contiguous USA. The SOC varied more than twentyfold among western Oregon pedons. Up to 50% of this variation was explained in regression analyses by site characteristics, such as climatic variables, soil texture, and slope. Half of the unexplained variation may be attributed to within-site variability and errors in soil measurements and site characteristics. Therefore, statistical relations between SOC and site characteristics can be improved by improving measurements, as well as documenting additional site characteristics that may contribute to SOC variation, such as geomorphology, disturbance history, and composition of vegetation.

Although texture and climate explain much of the SOC variation in both western Oregon and other regions, relations differ among the regions both qualitatively and quantitatively. For example, in our study of western Oregon forests, SOC in mineral soil was higher in areas of higher annual temperature, while an opposite trend was found in the Great Plains grasslands (Burke et al., 1989). Therefore, relations with site characteristics may be useful in interpolating SOC within regions to help determine estimates of regional soil C stores, but using the relations outside of their areas of development may not be appropriate.

Statistical models of SOC vs. site variables might reflect underlying mechanistic controls and provide support for process models (Parton et al., 1987; Burke et al., 1989). Contrasting SOC–temperature relations might reflect regional differences of temperature effects on detrital production and decomposition processes, the balance of which influences SOC. If so, SOC may respond oppositely in different regions to a given temperature change. Alternatively, statistical models may reflect only correlative rather than mechanistic relations, and climatic variables may co-vary with site characteristics that influence SOC but that have not been consistently or sufficiently quantified. Therefore, a better basis for hypothesizing mechanistic controls on SOC and developing process models for the western Oregon forest region requires a more comprehensive set of site characteristics at locations where SOC is known.

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