



What the soil reveals: Potential total ecosystem C stores of the Pacific Northwest region, USA

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Abstract

How much organic C can a region naturally store in its ecosystems? How can this be determined, when land management has altered the vegetation of the landscape substantially? The answers may lie in the soil: this study synthesized the spatial distribution of soil properties derived from the state soils geographic database with empirical measurements of old-growth forest ecosystem C to yield a regional distribution of potential maximum total-ecosystem organic C stores. The region under consideration is 179,000 square kilometers extending from the southern Oregon border to the northern Washington border, and from the Pacific Ocean to the east side of the Cascade Mountains. Total ecosystem organic C (TEC) was measured in 16 diverse old-growth forests encompassing 35 stands and 79 pedons to a depth of 100 cm. The TEC ranged between 185 and 1200 Mg C ha⁻¹. On an average, 63% of TEC was in the vegetation, 13% in woody detritus, 3% in the forest floor, 7% in the 0–20 cm mineral soil, and 13% in 20–100 cm mineral soil. The TEC was strongly related to soil organic C (SOC) in the 0–20 cm mineral soil, yielding a monotonically increasing, curvilinear relation. To apply this relation to estimate the TEC distribution throughout the region, 211 map units of the state soils geographic database (STATSGO) were used. The SOC in the 0–20 cm mineral soil of the map units was consistent with values from previously measured pedons distributed throughout the region. Resampling of 13 second-growth forests 25 years after initial sampling indicated no regional change in mineral SOC, and supported the use of a static state soils map. The SOC spatial distribution combined with the quantitative old-growth TEC–SOC relation yielded an estimate of potential TEC storage throughout the region under the hypothetical condition of old-growth forest coverage. The area-weighted TEC was 760 Mg C ha⁻¹. This is ~100 Mg C ha⁻¹ more than a previous estimate based on a coarser resolution of six physiographic provinces, and ~400 Mg C ha⁻¹ more than current regional stores. The map of potential TEC may be useful in forecasting regional C dynamics and in land-management decisions related to C sequestration.

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1. Introduction

Sequestration of C in forests may help moderate the continuing increase in atmospheric CO₂ concentrations (Vitousek, 1991; Brown, 1996). The difference between current C stores and maximum potential C stores in forest ecosystems can constrain predictions on the amount of C that can be sequestered in the future (Smithwick et al., 2002). Such information would be valuable for making forest management decisions related to C sequestration.

Current forest C stores over broad, diverse areas can be estimated through forest inventory, remote sensing, and soil survey data bases (Birdsey, 1992; Cohen et al., 1996; Homann et al., 1998). Determination of maximum potential C stores, however, poses more substantial difficulty. Forest management and natural disturbance have reduced forest C stores in many areas (Harmon et al., 1990; Smithwick et al., 2002), thereby precluding empirical assessment in those areas. Modeling of potential C stores across a region may be feasible, but it requires empirical values for model calibration and validation.

Old-growth forests contain higher C per-unit-area than occurs in early succession (Odum, 1969) or in managed forests (Cooper, 1983). Thus, old-growth forests can serve as estimates of potential C stores (Smithwick et al., 2002). However, limited temperate-region old-growth forests severely restrict our ability to map potential C storage. In the Pacific Northwest, studies of remaining old-growth forests indicate they average more than twice the C of forests in other regions, but that values vary considerably within the region (Smithwick et al., 2002). Spatial comparisons have been made only among broad physiographic provinces (Smithwick et al., 2002). A finer spatial scale would be more useful for forest management decisions related to C sequestration. With limited old-growth forests remaining and the great expense and difficulty of empirical evaluations of their C pools, a substantial challenge remains in developing a spatial distribution of potential C stores at a finer scale.

The objective of this study was to determine the spatial distribution of potential total ecosystem organic C (TEC) over the Pacific Northwest region. Potential TEC is based on all ecosystem components of old-growth forests, including mineral soil to a depth of 100 cm. The predicted spatial distribution is based

on a strong relation of TEC to soil organic C (SOC) developed in this study, in combination with the SOC map of the region, which is an extension of the work of Homann et al. (1998). This study expands the work of Smithwick et al. (2002) by dividing the region into more than 200 units based on soil properties, compared with their six physiographic provinces, thereby substantially increasing the spatial resolution of potential TEC and the applicability of potential TEC to forest management decisions.

2. Methods

2.1. Study area

The 179,000-km² study area encompasses the western portions of the states of Washington and Oregon. The study area is bounded on the north by the northern border of Washington at 49°N lat, on the south by the southern border of Oregon at 42°N lat, by the Pacific Ocean on the west and by the eastern slope of the Cascade Mountains on the east. The area is mostly forest, but it also contains natural grasslands, cultivated areas, alpine meadows, rock outcrops, glaciers, and urban areas.

2.2. Old-growth forest C pools

Carbon pools were measured in 16 old-growth forests distributed over five physiographic provinces in western Washington and Oregon (Table 1, Fig. 1). Mature to old-growth coniferous trees (150–1000 years old) dominate each forest. Mean annual temperature ranges from 5.5 to 10.4 °C (Table 1). Mean annual precipitation ranges from 400 to 3700 mm, although only the two Oregon eastside forests have values less than 1800 mm (Table 1).

Within each forest, vegetation and detrital C pools were estimated in one to eight stands, each having an area of 0.3–4.5 ha. Details of measurements and calculations are presented in Smithwick et al. (2002). Briefly, estimation of above and belowground tree C included the following pools: stem wood, stem bark, live and dead branches, foliage, live and dead coarse roots, and fine roots. In each stand, the diameters-at-breast-height of all trees >5 cm diameter were measured. The biomass of stem wood, stem bark,

Table 1
Characteristics of Pacific Northwest old-growth forests

Province and forest	Location	Stands ^a	No. of pedons	Latitude (°N)	Longitude (°W)	Elevation (m)	Tree age (year)	Annual temperature ^b (°C)	Annual precipitation ^c (mm)	Dominant tree species ^d
Washington Coast	A. Quinalt RNA	HS02 HS03	4	47.43	123.87	122	230	8.9	2900	ss, wh
	B. South Fork Hoh River	HR01, HR02, HR03, HR04	8	47.78	123.91	247	280	8.2	3700	ss, wh
	C. Twin Creeks RNA	HS04	2	47.83	123.99	152	230	8.9	3000	ss, wh
Oregon Coast	D. Cascade Head	CH01, CH03, CH12	7	45.05	123.90	288	150	8.5	2700	ss, wh
	E. Cascade Head	CH04, CH05, CH07, CH08	8	45.06	123.94	258	150	8.9	2600	ss, wh
	F. Cascade Head	CH10	2	45.06	123.99	396	150	7.9	2400	ss, wh
Washington Cascades	G. Carbon River	AV14, TO11	4	46.98	121.86	845	875	6.0	2300	df, psf, wh
	H. Nisqually River	AE10, AG05, AV06, TO04	7	46.76	121.80	1020	625	6.3	2500	ac, df, psf, wh, wr
	I. Ohanapecosh River	AO03, AV02	2	46.83	121.55	847	1000	6.0	2300	psf, wh
	J. White River	AB08	2	46.92	121.54	1050	500	7.3	2100	wh, wr
	K. Munger RNA	MUNA	8	45.83	121.97	411	470	7.8	2500	df, wh
Oregon Cascades	L. HJ Andrews	RS20	1	44.22	122.25	700	450	10.4	1900	df, sp
	M. HJ Andrews	RS23, RS29	4	44.23	122.13	910	450	7.6	1800	df, wh, wr
	N. HJ Andrews	RS22, RS27, RS31	6	44.26	122.17	993	450	6.8	2200	df, nf, wh, wr
Oregon Eastside	Q. Metolius RNA	MRNA	4	44.49	121.63	933	300	8.1	400	pp
	R. Pringle Falls RNA	PF27, PF28, PF29	6	43.71	121.61	1359	430	5.5	500	lp, pp

^a Official stand designation of Forest Sciences Data Bank, Oregon State University, Corvallis, OR.

^b Temperature data were from the potential temperature (POTT) model (Dodson and Marks, 1997) for 1960–1990.

^c Precipitation data were from PRISM (precipitation-elevation Regressions on Independent Slopes Model; Daly et al., 1994) for 1960–1990.

^d Species abbreviations: ac, Alaska cedar, *Chamaecyparis nootkatensis* (D. Don) Spach; df, Douglas fir, *Pseudotsuga menziesii* Franco (Mirb.); lp, lodgepole pine, *Pinus contorta* Dougl.; nf, noble fir, *Abies procera* Rehd.; pp, Ponderosa pine, *Pinus ponderosa* Laws.; psf, Pacific silver fir, *Abies amabilis* (Dougl.) Forb.; sp, sugar pine, *Pinus lambertiana* Dougl.; ss, Sitka spruce, *Picea sitchensis* (Bong.) Carr.; wh, western hemlock, *Tsuga heterophylla* (Rafn.) Sarg.; wr, western redcedar, *Thuja plicata* Donn.

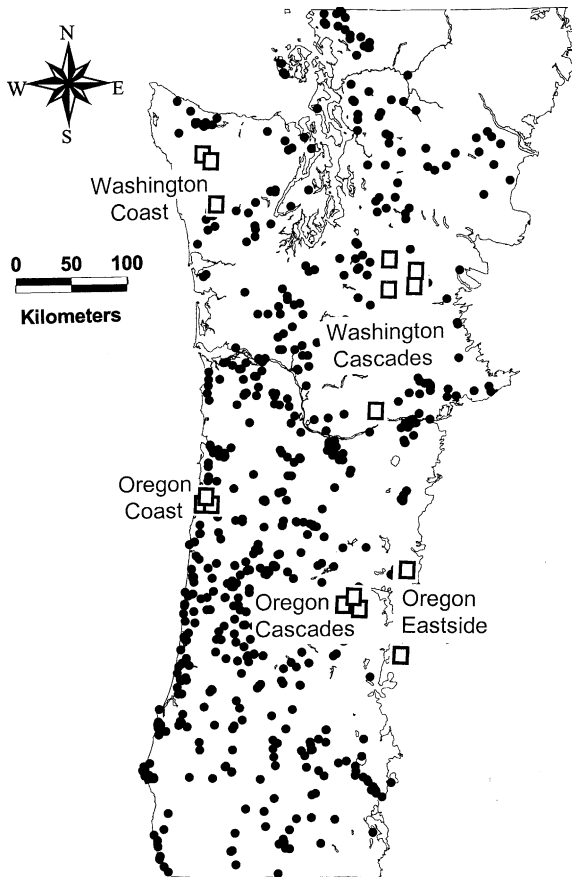


Fig. 1. Locations of Pacific Northwest old-growth forests for which total ecosystem C was determined (squares), and locations of pedons (dots) that were compared with STATSGO SOC (dots).

and live and dead attached branches, were calculated by applying species-specific allometric equations from BIOPAK (Means et al., 1994). We estimated live, coarse-root biomass (>10 mm diameter) for each tree from equations for *P. menziesii* in Santantonio et al. (1977) and corrected the values for different tree species using species-specific green densities (US Forest Products Laboratory, 1974). Understory C was estimated from shrub and herb cover and allometric biomass equations (Means et al., 1994; Smithwick et al., 2002). Fallen log and snag C were estimated from diameter, length, and stage of decay; surface rotten wood was fallen material in extreme stage of decay. Fine woody debris C was measured by collecting 1–10 cm diameter material from 1 m² plots.

Forest floor and mineral SOC pools were measured in one to eight pedons per forest (Table 1). Details of sampling and analysis are presented in Remillard (1999). Forest floor samples were taken at five points above the sampling face of a pedon with a 5-cm diameter corer, composited, oven dried (70 °C), weighed, and analyzed for C on a LECO CNS 2000 analyzer (Leco Corp., St. Joseph, MI). The forest floor SOC pool (Mg C ha⁻¹) was determined as

$$\text{forest floor C pool} = C \times \frac{M}{A} \times 100 \quad (1)$$

where *C* is the total C concentration (g C kg⁻¹ oven-dried mass), *M* the oven-dried sample mass (g), *A* the total cross-sectional area of the five cores (cm²), and 100 is a units-conversion factor.

Three mineral soil layers (0–20, 20–50, and 50–100 cm) were sampled from pedon faces. The samples were air-dried and then processed with 2 and 4 mm sieves. Sieves were repeatedly shaken by hand and material was broken up with a rubber stopper repeatedly run over the surfaces of the sieves. Based on observed morphology and color, the resulting 2–4 mm and >4 mm fractions were sorted by hand into 2–4 mm C-bearing soil fraction, >4 mm C-bearing soil fraction, >2 mm rock (non-C bearing), and >2 mm buried wood, roots, charcoal. Each component was weighed. The >2-mm buried wood, roots, and charcoal accounted for less than 3% of the sample masses, and were not considered as part of the soil C pools. Subsamples of <2 mm, 2–4 mm, and >4 mm C-bearing fractions were analyzed for total C concentration using a LECO CNS 2000. Total C concentrations were obtained as g kg⁻¹ at 60 °C and converted to a 105 °C basis based on moisture determination of subsamples. We assume the SOC concentrations are equivalent to the total C concentrations in these conifer-dominated, acidic forest soils.

The mineral SOC pool (Mg C ha⁻¹) for each of three soil layers (0–20, 20–50, and 50–100 cm) and each of three size classes (air-dried <2 mm, 2–4 mm, and >4 mm) was determined as

$$\text{Pool}_i = C_i \times D_c \times V_c \times \frac{M_i}{M_c} \times L \times 100 \quad (2)$$

where *C_i* is the total C concentration (g C kg⁻¹ dry mass) of size class *i*; *i* refers to the air-dried <2 mm, 2–4 mm, and >4 mm C-bearing size classes. *D_c* is the

bulk density (g cm^{-3}) of all C-bearing material, which was determined by the core method. V_c is the volume of the C-bearing material as a fraction of total sample volume. M_i is the oven-dried mass (g sample^{-1}) of material in size class i , and M_c is the oven-dried mass (g sample^{-1}) of all C-bearing material. L is layer thickness (cm), and 100 is a unit-conversion factor. Total mineral SOC for each layer was calculated as the sum of the air-dried <2 mm, 2–4 mm, and >4 mm SOC pools.

The USDA-NRCS (1996) methods call for chemical disruption of aggregates to determine the <2 mm fraction for chemical analysis. To be consistent with those procedures, we assessed the amount of SOC in our >2 mm air-dried fractions that would have been in a <2 mm fraction following chemical disruption of aggregates. For each province having >2 mm C-bearing fractions, five air-dried C-bearing 2–4 mm samples were swirled in sodium hexametaphosphate solution (35.7 g $(\text{NaPO}_3)_6$ and 7.94 g Na_2CO_3 per L; USDA-NRCS, 1996) for 1 min every 15 min for 1 h, allowed to soak for 10 h, and swirled for 1 min every 15 min for one additional hour. The proportion of >2 mm C that passed through the 2-mm sieve as a result of this treatment was added to air-dried <2 mm SOC to yield the value for overall <2 mm SOC that was used in subsequent data analyses. The overall >2 mm SOC was calculated as the difference between total SOC and overall <2 mm SOC.

Pearson correlation was used to explore the correlation between the <2-mm 0–20 cm mineral SOC and 11 C pools: aboveground live tree, belowground live tree, understory, snags, logs, rotten wood, fine woody debris, forest floor, >2 mm 0–20 cm mineral soil, <2 mm 20–100 cm mineral soil, and >2 mm 20–100 cm mineral soil. Linear regression was used to quantify the relation between the <2 mm 0–20 cm mineral SOC and the sum of all other C pools. The <2 mm 0–20 cm mineral SOC pool was used as the independent variable, because the spatial distribution of this variable has been mapped across the Pacific Northwest study area (see below).

2.3. STATSGO map of soil C

The assessment of western Oregon by Homann et al. (1998) was extended to the entire Pacific

Northwest study area. STATSGO is an electronically based state soils map with associated attribute tables (National Soil Survey Center, 1994). STATSGO map units are spatially explicit. Each consists of 1–21 components whose attributes and percentage contribution to the map-unit area are specified, but whose locations within map units are not indicated. STATSGO attribute tables contain descriptive, physical and chemical information for each component. Each component represents a phase of a soil series, a water body or a miscellaneous land area. For the components based on phases of soil series, physical and chemical soil characteristics are derived from the soil interpretation records database (NRCS-SOI-5, Statistical Laboratory, Iowa State University, Ames, IA). As noted by Davidson and Lefebvre (1993), data are not provided in STATSGO attribute tables for forest floors (O horizons), except for Histosols or histic epipedons.

Oregon STATSGO (1994 version) and Washington STATSGO (1994 version) were obtained from the Natural Resources Conservation Service (www.ftw.nrcs.usda.gov/stat_data.html). Oregon STATSGO had 87 map units and Washington STATSGO had 171 map units in the study area. For each map unit having organic matter concentration, bulk density, and rock content for $\geq 70\%$ of the map-unit area, SOC (Mg C ha^{-1}) of the 0–20 cm surface soil layer of each component was calculated from means of the minima and maxima of relevant variables (Davidson and Lefebvre, 1993; Bliss et al., 1995; Homann et al., 1998). Then, area-weighted SOC for the map unit was calculated by

$$\begin{aligned} & \text{area-weighted STATSGO SOC} (\text{Mg C ha}^{-1}) \\ &= \frac{\sum (A_c \times \text{SOC}_c)}{\sum A_c} \end{aligned} \quad (3)$$

where A_c is the area (ha) of component, c , SOC_c the SOC (Mg C ha^{-1}) in the 0–20 cm mineral soil of component, c and the summations are over all components with sufficient information to calculate SOC_c . Of the 258 map units in the study area, 211 met the criterion of having relevant information for $\geq 70\%$ of the map-unit area. Urban areas were not specifically excluded from the analysis, but they may have been ruled out due to lack of soil information.

2.4. STATSGO C versus pedon C

For each of 37 STATSGO mapping units, the STATSGO SOC was compared with average SOC of pedons located within the mapping unit. Each of these mapping units had five or more pedons and average, rather than individual pedon, values were used, because a STATSGO value represents an average over a large map unit and is not expected to provide an accurate value for any specific location within that area (Homann et al., 1998). Locations of pedons are shown in Fig. 1.

The pedon data are expanded from the western Oregon data set described by Homann et al. (1995). These pedons do not include organic soils. Sources of pedon data were National Soil Survey Center, Lincoln, NB; Natural Resources Conservation Service, Portland, OR; Stand Management Cooperative, University of Washington, Seattle, WA; theses; soil surveys; and unpublished data (Homann et al., 1995). The pedons met the following minimum requirements: (1) depth of at least 50 cm or to a rock horizon (designated as bedrock or rock, or by horizon abbreviation R or Cr) if that horizon was within the upper 50 cm, (2) organic C concentration and rock content (either volumetric or gravimetric) measured for the surface mineral-soil horizon, and (3) values were missing for organic C concentration and rock content for no more than 20% of the pedon depth. Homann et al. (1995) described the calculation of SOC, including methods to account for missing data. Pearson correlation between STATSGO SOC and average pedon SOC was performed.

2.5. Change in soil C pools

The STATSGO SOC values are based on soil survey information that was collected and synthesized over decades. Because a change in forest SOC pools in the Pacific Northwest study area over that period would lessen the utility of the current use of the STATSGO map of SOC, we investigated the possibility of SOC change. The forest floor and surface (0–15 cm) mineral SOC pools in 13 second-growth Douglas-fir stands were measured in 1995 (Homann et al., 2001) and compared with measurements from 1969 to 1970 (Edmonds and Hsiang, 1987; Edmonds and Chappell, 1994). Within each stand, the 1969–1970

values are from a pre-fertilization sampling, and the 1995 values are from a nearby non-fertilized control plot. Paired *t*-test was used to evaluate differences between 1969–1970 and 1995, with a stand serving as a pair.

3. Results and discussion

3.1. Old-growth C pools

Old-growth forest C pools differ among locations (Fig. 2). Compared with the coastal Sitka spruce and Cascade Douglas-fir forests, the Oregon eastside Ponderosa pine forests tend to have lower C in all pools (Fig. 2). Compared with coastal forests, Cascade forests tend to have lower C in mineral soil, but other C pools are similar. Many variables may contribute to these differences: the old-growth coniferous forests in this study span broad ranges of tree age, annual temperature, and annual precipitation (Table 1). Above-ground live tree C is somewhat related to annual precipitation (Fig. 3a), with the eastside Ponderosa pine forests having both low precipitation and low C pools. Relations of C pools to temperature and tree age, however, do not show consistent patterns (Fig. 3b and c). This is not unexpected, because the forests of this study do not represent climosequences and chronosequences, which would require all variables except climate or age to be relatively constant. Indeed, the lack of strong relations of C pools with individual variables suggests a complex interplay among climate, tree species and age, and soil properties, such as texture (Homann et al., 1995).

The C storage in the old-growth forests was dominated by the live trees, which constituted more than 60% of the TEC (Table 2). Woody detrital material, including snags, logs, rotten wood, and fine woody debris, averaged 12.5% of TEC (Table 2). Forest floor C was only 3.4% of TEC (Table 2). Forest floor C varies considerably among the old-growth forests (Table 2; Fig. 2c), a pattern that has also been observed in previous studies. Assuming C is 45% of loss-on-ignition, forest floor C ranged from 6 to 27 Mg C ha⁻¹ in hundred-year-old Douglas-fir forests in the Oregon Coast Range (Youngberg, 1966), and averaged 35 Mg C ha⁻¹ in duff mull and 62 Mg C ha⁻¹ in mor forest floors of old-growth

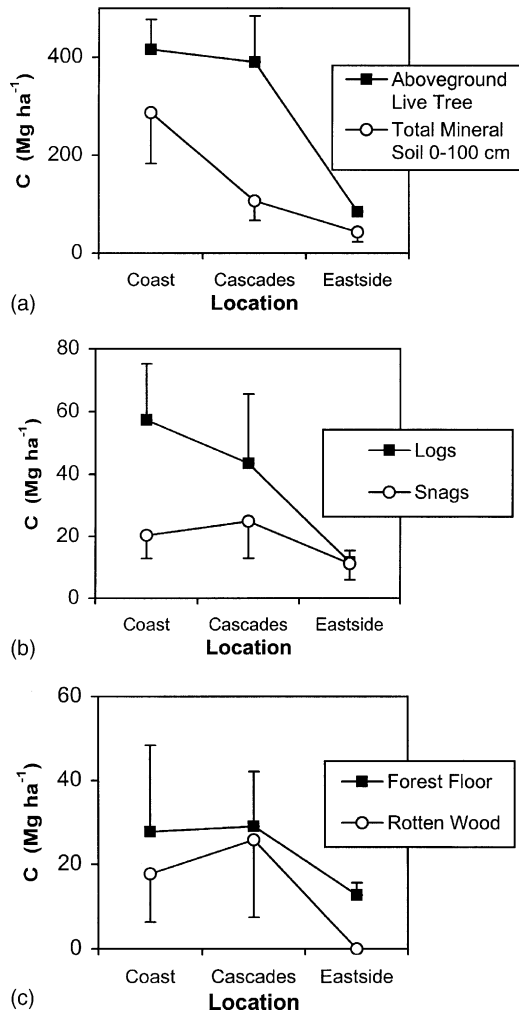


Fig. 2. Carbon pools (mean plus or minus S.D.) of Pacific Northwest old-growth forests in Washington plus Oregon coast ($n = 6$), Washington plus Oregon Cascades ($n = 8$), and Oregon eastside ($n = 2$) provinces: (a) aboveground live tree and total mineral soil to depth of 100 cm, (b) logs and snags and (c) forest floor and rotten wood.

forests in western Washington (Gessel and Balci, 1965).

The mineral soil contained $\sim 20\%$ of the TEC (Table 2), more than half of which was below 20 cm depth. Ninety percent of the mineral SOC was in the < 2 mm fraction. Six of the 16 forests contained C in the > 2 mm fraction: Washington Coast forests A and B; Oregon Coast forests D, E, and F; and Washington Cascade forest J. For those six forests, the > 2 mm fraction contained an average of 20% of 0–100 cm

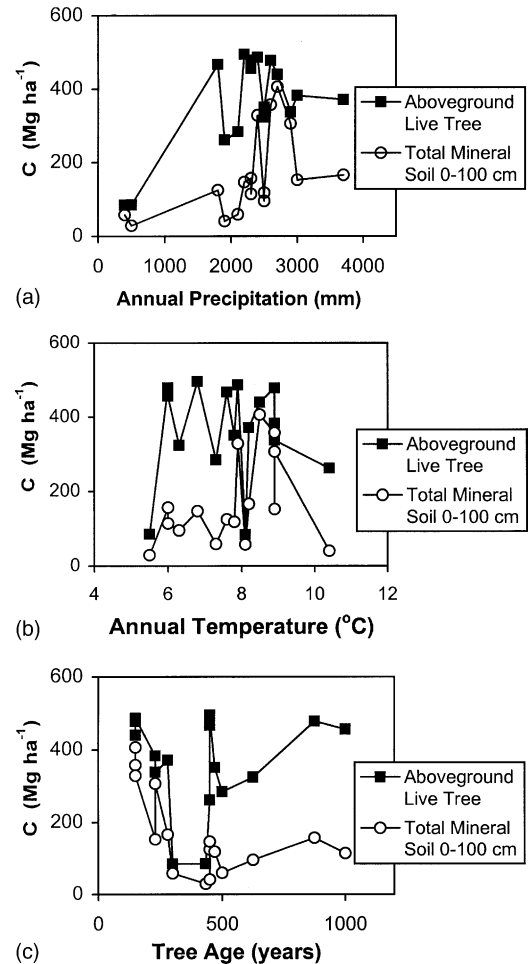


Fig. 3. Carbon pools of aboveground live tree and total mineral soil to depth of 100 cm in 16 Pacific Northwest old-growth forests vs. (a) annual precipitation, (b) annual temperature and (c) tree age.

whole-soil C, with a maximum of 30% in Oregon Coast forest F. This is consistent with the results of Cromack et al. (1999), who examined an Oregon coast forest soil and found 37% of whole-soil C in the > 2 -mm fraction, when air-dried (40°C) soil was sieved for 2 min on a motor-driven shaker sieve. The sieving of air-dried material through 2, 3, or 4 mm sieves and analysis of the resulting fine fraction is a common procedure to assess forest soil C concentration (Grigal and Ohmann, 1992; Canary et al., 2000; Parker et al., 2001; Brejda et al., 2001; Homann et al., 2001). As indicated by our results, assessment of the fine fraction alone underestimates whole-soil C pools in some forest soils.

Table 2

C pools in western Washington and Oregon old-growth forests and their correlations with the <2 mm 0–20 cm mineral soil C pool

C Pool	C (Mg ha ⁻¹) ^a				Total ecosystem C (%)	Correlation with SOC < 2 mm 0–20 cm	
	Mean	S.D.	Min.	Max.		r	P
SOC < 2 mm 0–20 cm	57	32	16	111	7.3	n/a ^b	n/a
Other ecosystem C							
Aboveground live tree	362	131	85	494	46.2	0.63	0.009
Belowground live tree	129	53	34	187	16.4	0.61	0.01
Understory	1.1	0.6	0.0	2.2	0.1	0.23	0.4
Snags	22	11	6.3	39	2.8	0.24	0.4
Logs	45	23	9	87	5.7	0.45	0.08
Rotten wood	20	16	0	61	2.5	-0.07	0.8
Fine woody debris	12	4	6	18	1.5	0.44	0.09
Forest floor	27	16	11	60	3.4	0.11	0.7
SOC > 2 mm 0–20 cm	10	17	0	47	1.3	0.80	0.0002
SOC < 2 mm 20–100 cm	92	65	12	242	11.8	0.86	0.0001
SOC > 2 mm 20–100 cm	7	13	0	37	0.9	0.66	0.005
Sum of other ecosystem C	725	277	168	1100	92.7	0.75	0.0008
Total ecosystem C	782	302	185	1200	100	n/a	n/a

n = 16 forests.

^a Summarized from Remillard (1999), Smithwick et al. (2002) and Homann, unpublished data (2001).^b n/a, Not applicable.

We compared several ecosystem C pools with the <2-mm SOC pool in the 0–20-cm mineral soil (Table 2), because of the potential to interface ecosystem C pools with soil C maps generated from state soil geographic data bases (Homann et al., 1998). The above and belowground tree C, which together average 62% of TEC, are well related to the <2-mm SOC pool in the 0–20-cm mineral soil ($r = 0.63$ and 0.61 , respectively, Table 2). The cause of this strong relation likely involves multiple interacting mechanisms. Limited water availability is an important constraint to tree growth in the old-growth coniferous forests (Waring and Franklin, 1979). Precipitation across the old-growth forests of the Pacific Northwest study area varies by an order of magnitude (Table 1). Higher precipitation can enhance tree productivity and hasten soil development. Finer textured soils resulting from soil development generally enhance water-holding capacity (Rawls et al., 1982), and hence productivity, as well as the stability of soil organic matter (Sollins et al., 1996). Higher production may yield both higher standing biomass as well as detrital production of foliar and root litter, which becomes the precursor of soil organic matter.

Soil C pools other than the <2-mm SOC pool in the 0–20-cm mineral soil comprise 14% of TEC. They are highly correlated with the <2-mm SOC pool in the 0–20-cm mineral soil (Table 2). The strong relation between surface SOC and subsurface SOC is consistent with trends observed in other forests, grasslands, and shrublands (Jobbágy and Jackson, 2000). Mechanisms behind these trends include root production and turnover associated with water and nutrient availability, and leaching, sorption, and decomposition of organic materials. In contrast with the tree and mineral soil C pools, the understory, woody detrital, and forest floor pools were poorly correlated with the <2-mm SOC pool in the 0–20-cm mineral soil, but they contained only 16% of TEC (Table 2). The poor correlation between forest floor C and surface mineral soil C might be due to different mixing processes under different tree-species and climatic regimes. For example, intra-annual variation in temperature and moisture is less in coastal forests than Cascade forests, even though annual temperature and precipitation may be similar. Such a climatic regime may promote faunal mixing of forest floor and surface mineral soil, which would

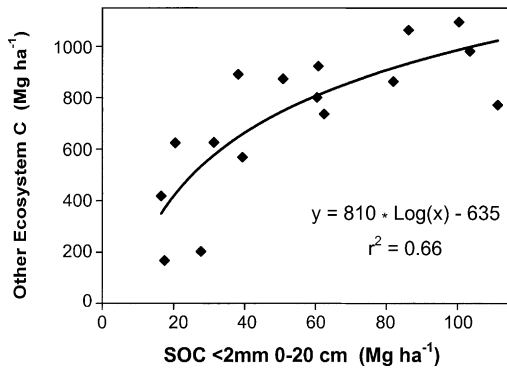


Fig. 4. Relation of other ecosystem C to soil organic C (SOC) in the <2 mm fraction of 0–20 cm mineral soil of 16-old-growth forests in the Pacific Northwest study area. Other ecosystem C is the total ecosystem C minus SOC in the <2 mm fraction of 0–20 cm mineral soil.

decrease forest floor C while increasing surface mineral soil C.

For further analysis, we considered TEC as two components:

total ecosystem C

$$= \text{SOC} < 2 \text{ mm} + \text{other ecosystem C} \quad (4)$$

where $\text{SOC} < 2 \text{ mm}$ is the <2-mm SOC pool in the 0–20-cm mineral soil (Mg C ha^{-1}) and all C pools have units of Mg C ha^{-1} . Other ecosystem C was strongly related to $\text{SOC} < 2 \text{ mm}$ in a monotonically increasing curve (Fig. 4)

other ecosystem C

$$= 810 \times \log(\text{SOC} < 2 \text{ mm}) - 635 \quad (5)$$

$$r^2 = 0.66$$

where all C pools have units of Mg C ha^{-1} . Because this is a curvilinear relation that fits the trend in the data, it explains more of the variation than a straight-line relation. By substituting Eq. (5) into Eq. (4), the following expression for TEC is obtained:

total ecosystem C

$$= \text{SOC} < 2 \text{ mm} + 810 \times \log(\text{SOC} < 2 \text{ mm}) - 635 \quad (6)$$

where all C pools have units of Mg C ha^{-1} . The expression allows prediction of TEC based upon only the SOC of the surface mineral soil.

3.2. STATSGO SOC

Of the 179,000- km^2 study area, 95.9% had mineral soil, 0.5% had organic soil (Histosols), and 3.6% had non-soil material, such as glaciers, rock outcrops, and possibly urban areas. Only mineral soil was included for further analysis because the old-growth analyses were restricted to systems with mineral soil. Of the area covered by mineral soil, 87.5% (211 map units) had sufficient information in the STATSGO database to calculate SOC for the 0–20 cm mineral soil. Values ranged from 1.3 to 152 Mg C ha^{-1} . There was generally good agreement between STATSGO SOC and pedon SOC (Fig. 5). STATSGO SOC averaged 92% of pedon SOC.

STATSGO represents the most detailed basis for spatially weighting soil attribute information for regions of the USA, but the SOC values derived from it are from generalized soil-attribute information based on expert judgment. Comparison with pedon values would test the adequacy of STATSGO SOC values, only if the pedons within a specified area were randomly located and were not used to derive

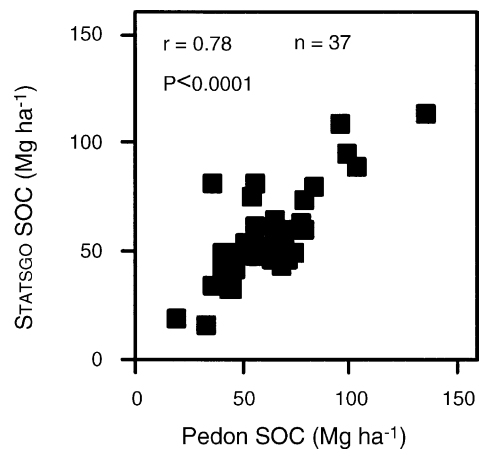


Fig. 5. Comparison of STATSGO SOC and pedon SOC for 0–20 cm mineral soil. Each point represents a STATSGO map unit in the Pacific Northwest study area. STATSGO SOC is the area-weighted SOC for the map unit; a map unit is included only if >70% of its area had data for calculating SOC. Pedon SOC is the average SOC of at least five pedons within the map unit.

STATSGO values. The arithmetic mean of randomly located pedons would be the best estimate of average SOC within an area. Unfortunately, pedons were not randomly located, because sampling locations were chosen for specific purposes (Homann et al., 1998). Therefore, even if STATSGO values represented reality, perfect agreement between pedons and STATSGO would not be expected. The general agreement between STATSGO and pedons suggests pedon data were adequately considered and synthesized during the development of the soil interpretation records, from which the STATSGO attribute table was derived.

Both the STATSGO and pedon approaches have one major drawback: the accuracy of, or conversely the uncertainty associated with, the estimate cannot be objectively assessed. Uncertainty of SOC of an individual pedon can be propagated statistically from uncertainties associated with carbon concentration, bulk density, and rock content (Homann et al., 1995). Improvements in these measurements (e.g. Vincent and Chadwick, 1994) or use of volumetric sampling (Huntington et al., 1988) could reduce the uncertainty of soil C for an individual pedon. However, there are no statistical procedures to account for possible bias in pedon locations that have been selected for specific purposes. Subjectively selected sampling points can yield substantially different values of C storage

compared with random sampling. For example, in evaluating the boreal forest, Botkin and Simpson (1990) found random sampling to yield much lower estimates of vegetative C storage compared with subjectively chosen sampling points from previous studies. In spite of these uncertainties, the general agreement between STATSGO and pedons supports the use of the STATSGO SOC values.

3.3. Regional estimates of potential TEC storage

We used the old-growth TEC–SOC equation (Eq. (6)) and STATSGO SOC values to calculate potential TEC for the STATSGO map units in the study area. The application of the equation to the STATSGO SOC values is supported by four points. First, the equation and the STATSGO SOC values are for the same study area. Second, STATSGO was developed by NRCS and our procedures for defining the <2 mm SOC pool are based on NRCS guidelines. Third, of the STATSGO area with SOC values, 96% of the area had SOC values within the range of old-growth pedon values upon which the equation was based (Fig. 4), thereby minimizing extrapolation of the equation. For only two of the 211 mapping units, extremely low SOC values applied to Eq. (6) yielded TEC values less than SOC, and TEC was set equal to SOC. Fourth, the use of a soils map that was developed over a period of decades

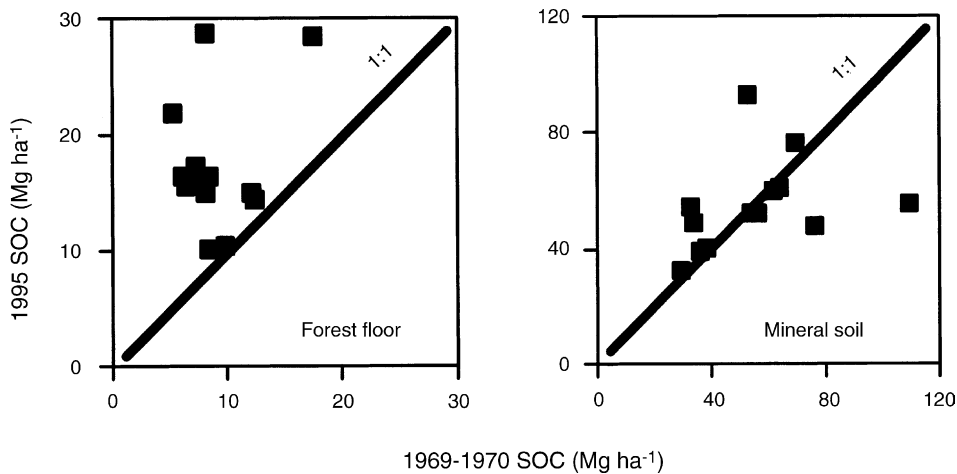


Fig. 6. Comparison of 1969–1970 and 1995 SOC in the forest floor and 0–15 cm mineral soil in second-growth Douglas-fir stands. Each point represents a stand sampled in 1969–1970 (Edmonds and Hsiang, 1987; Edmonds and Chappell, 1994) and resampled in 1995 (Homann et al., 2001). For forest floor, 1995 differs from 1969 to 1970 ($P = 0.001$, paired t -test, $n = 13$). For mineral soil, 1995 does not differ from 1969 to 1970 ($P = 0.8$, paired t -test, $n = 13$).

requires that SOC be relatively constant. This criterion is supported by the resampling of SOC in second-growth Douglas-fir stands at a 25-year interval (Fig. 6). No change was detected in surface (0–15 cm) mineral SOC of these stands, which are distributed throughout the study area.

Areas with high potential TEC are scattered throughout the study area (Fig. 7). They are prominent on the Pacific coast, along the western portion of the study area. In other parts of the study area, the high potential TEC occurs in lowlands and valleys. Low potential TEC areas exist in the eastern portion of the

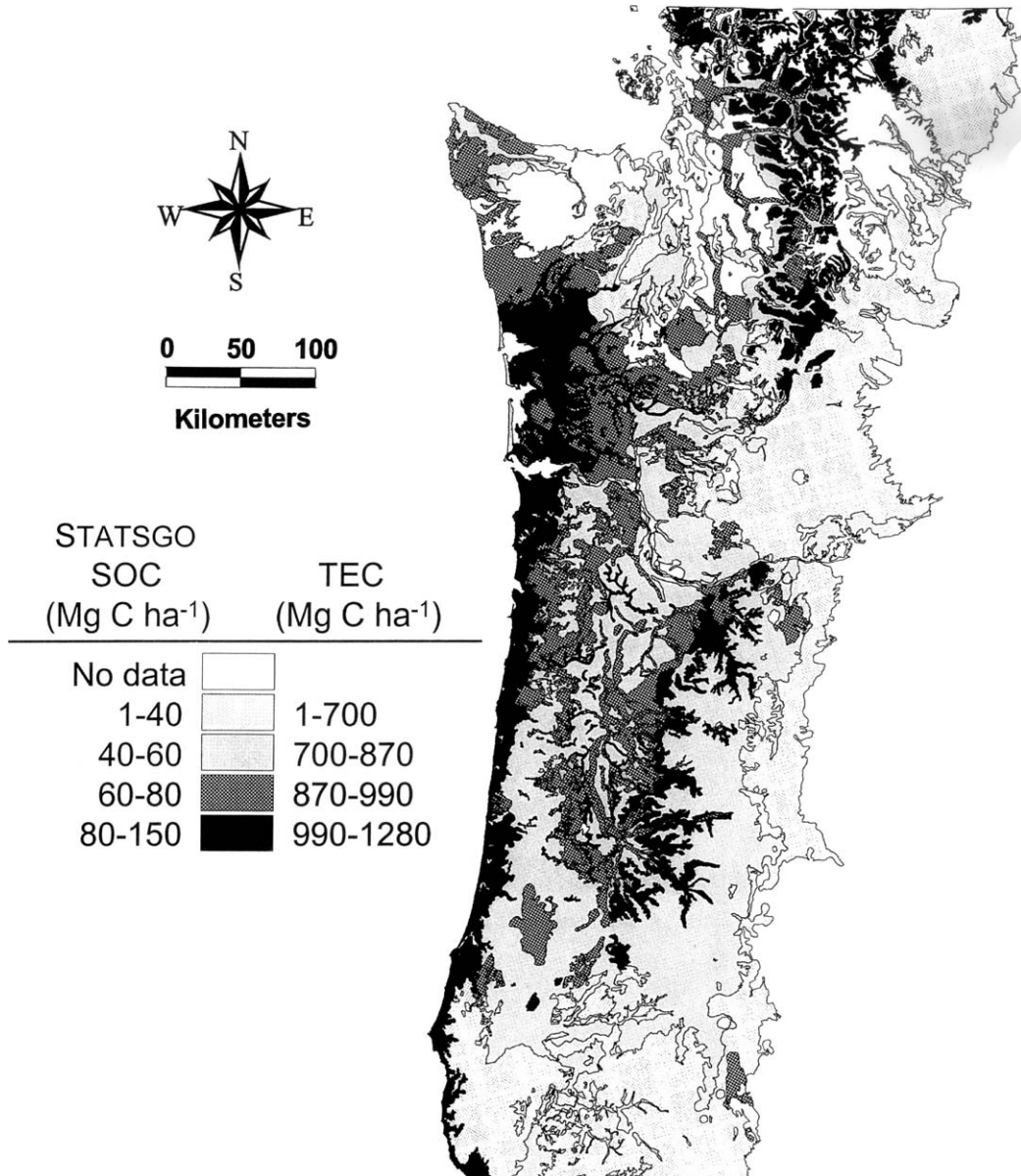


Fig. 7. Distributions of SOC (Mg C ha⁻¹ in 0–20 cm mineral-soil depth) and potential TEC (Mg C ha⁻¹) in the Pacific Northwest study area. The distributions are based on STATSGO SOC and the TEC–SOC relation observed in old-growth forests. No data are presented for a map unit if <70% of its area had data for calculating SOC.

study area, where low precipitation and pumice soils occur.

The area-weighted potential TEC for the Pacific Northwest study area was determined by:

area-weighted potential TEC

$$= \frac{\sum(\text{potential TEC of map unit} \times \text{map unit area})}{\sum(\text{map unit area})} \quad (7)$$

where the summation is over the 211 STATSGO map units with SOC values.

The area-weighted potential TEC for the study area is 760 Mg C ha^{-1} . This value is 13% greater than estimated by Smithwick et al. (2002) for a similar study area, even though the same old-growth forests were used as a basis of both analyses. There are two main causes for the difference. First, we included several areas not considered by Smithwick et al. (2002), such as a productive high SOC agricultural area but also a low SOC southern Oregon montane forest area. Second, our area-weighting schemes differed; Smithwick et al. (2002) used six provinces, while our weighting was based on 211 STATSGO map units.

The potential TEC is substantially larger than the current regional TEC of $\sim 200\text{--}300 \text{ Mg C ha}^{-1}$ (Birdsey, 1992; Turner et al., 1995). Much of the region has had substantial natural disturbance by catastrophic fire, wind, and landslide, and/or human disturbance by forest harvesting and land conversion. As a result, a large portion of the area is younger forest that currently contains substantially less C storage than potential TEC. The difference of $\sim 400 \text{ Mg C ha}^{-1}$ between potential TEC and current TEC indicates the amount of additional C accumulation that could occur if the region converted to a theoretical landscape without catastrophic natural or human disturbance. Although such a scenario is unrealistic, potential TEC provides a baseline against which alternative disturbance regimes and forest management strategies can be assessed.

By using the >200 map units of STATSGO, this study considerably improves the spatial resolution of potential TEC in the Pacific Northwest, compared with the six provinces used by Smithwick et al. (2002). The spatial resolution is sufficiently fine-scale to be useful in constraining models of C dynamics that are controlled by climatic and soil-texture driving variables (Homann et al., 2000). Such models may be

important for forecasting regional C dynamics. Further, the finer spatial resolution of potential TEC may allow improved land management decisions. With C sequestration acknowledged to have economic value (Romm et al., 1998), decisions on what land to manage for C sequestration will require information about both current and potential maximum C pools, and temporal shifts between the two.

The potential TEC of the future may differ from the values presented here. Factors that affect the vegetation growth, detrital production, and decomposition of organic matter include genetic stock, climate, soil genesis, atmospheric deposition of nutrients, and alteration of nutrient regimes through fertilization. These will likely differ between future centuries and the periods during which the old-growth forests of this study developed. The aggregate influence on potential TEC will be the result of a complex interaction among these factors, but it will not be quantified without considerable future efforts. In the meantime, our values of potential TEC serve as estimates, which will be improved as trends in global change become more evident.

4. Conclusions

Soil survey information and measurements of C in old-growth forests allowed us to predict the spatial distribution of potential TEC for the Pacific Northwest region. The C in the surface mineral soil provided a good indication of the amount of C that is stored in an entire old-growth forest ecosystem, which we assume to represent potential TEC. Digitized soil surveys provided spatial distribution of surface soil C across the region and, hence, provided a basis for the spatial distribution of potential TEC. Current C storage in the Pacific Northwest region is less than half potential TEC, indicating a substantial prospect to sequester C in the future, should land management and natural disturbance regimes move the region toward a landscape more dominated by old-growth forests.

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