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Regional Soil Organic Carbon Storage Estimates for Western Oregon by Multiple Approaches

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ABSTRACT

Soil is an important factor in regional and global C budgets because it serves as a reservoir of large amounts of organic C. In our study, we compared six approaches of estimating soil organic C (kg C m^{-2}, not including the surface organic horizon, hereafter called *soil C*) and its spatial pattern in the mountainous, largely forested western Oregon region. The approaches were (i) USDA NRCS pedons, (ii) other pedons, (iii) the State Soil Geographic Data Base (STATSGO), (iv) the United Nations Soil Map of the World, (v) the National Soil Geographic Data Base (NATSGO), and (vi) an ecosystem-complex map. Agreement between approaches varied with scale. For the entire region (10^5 km^2), estimates of average soil C varied from 4.3 to 6.8 kg C m^{-2} for the 0- to 20-cm depth and from 12.1 to 16.9 kg C m^{-2} for the 0- to 100-cm depth. At the subregional scale ($\approx$10^4 km^2), all approaches indicated higher soil C in the coastal area than in the inland southern area, but relative amounts in other subregions varied among the approaches. At the subsubregional scale ($\approx$10^3 km^2), soil C was consistent between individual STATSGO map units and NRCS pedons within those map units, but there was less agreement with other pedons. Rigorous testing of soil-C maps requires data from pedons that are located by objective criteria, in contrast to the subjectively located pedons now available. The uncertainty associated with regional soil-C amounts and spatial patterns should be considered when soil-C maps are integrated into regional or global assessments of physical and biotic processes because simulation-model outputs may be sensitive to soil C.

Understanding the role of soil C in the global C cycle requires knowledge of its amount and spatial pattern. Soil contains on the order of twice as much organic C as terrestrial vegetation (Dixon et al., 1994), making it an important global pool. Estimates vary considerably (Bohn, 1982; Post et al., 1982; Eswaran et al., 1993), however, and uncertainties of those estimates are difficult to determine. One approach to improve estimates of soil C and track associated uncertainties at coarse scales is to synthesize information at finer scales (Liski and Westman, 1997b). Thus, fine-scale regional evaluations may contribute to improved assessments of continental and global soil-C stores.

The amount of soil C provides a basis to evaluate its potential decrease or increase. Changes in soil-C stores may result from pedogenesis, land use, and climate change (Sollins et al., 1983; Mann, 1986; Schlesinger, 1986; Burke et al., 1989; Jenkinson et al., 1991; Liski and Westman 1997a). The amount of change that may occur is often expressed as a fraction of the extant soil C (Bouwman and Leemans, 1995), thus requiring extant soil C in order to make projections in its potential decrease or increase and the corresponding transfers to or from other pools of the C cycle.

In dynamic spatial models of the C cycle, changes in soil C are often proportional to either total soil C or its various fractions (Bouwman and Leemans, 1995). These models have been implemented across broad areas, including the entire globe (Schimel et al., 1996; Thompson et al., 1996; Den Elzen et al., 1997; Post et al., 1997). Other coarse-scale models of C dynamics include soil C as an input variable (Hunt et al., 1996). Regional assessments of soil-C amounts and spatial patterns may contribute improved databases for calibration and evaluation of these modeling efforts.

Regional evaluations of amounts and spatial patterns of soil C have been conducted by a variety of approaches. For our study, we defined soil C as organic C in kg C m^{-2} to a specified depth, not including the surface organic horizon. For a specified area, average soil C is the organic C in soil (kg) in that specified area to a specified depth divided by the size of the area (m^2). Soil-C concentration, bulk density, rock volume, and depth to bedrock are required to calculate soil C. These attributes for pedons allowed calculation of point estimates of soil C and its relation to climate, soil texture, and land use in Great Plains grasslands, Lake States

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Abbreviations: MLRA, major land resource area; NATSGO, National Soil Geographic Data Base; NRI, National Resources Inventory; SIR, Soil Interpretation Records; STATSGO, State Soil Geographic Data Base.

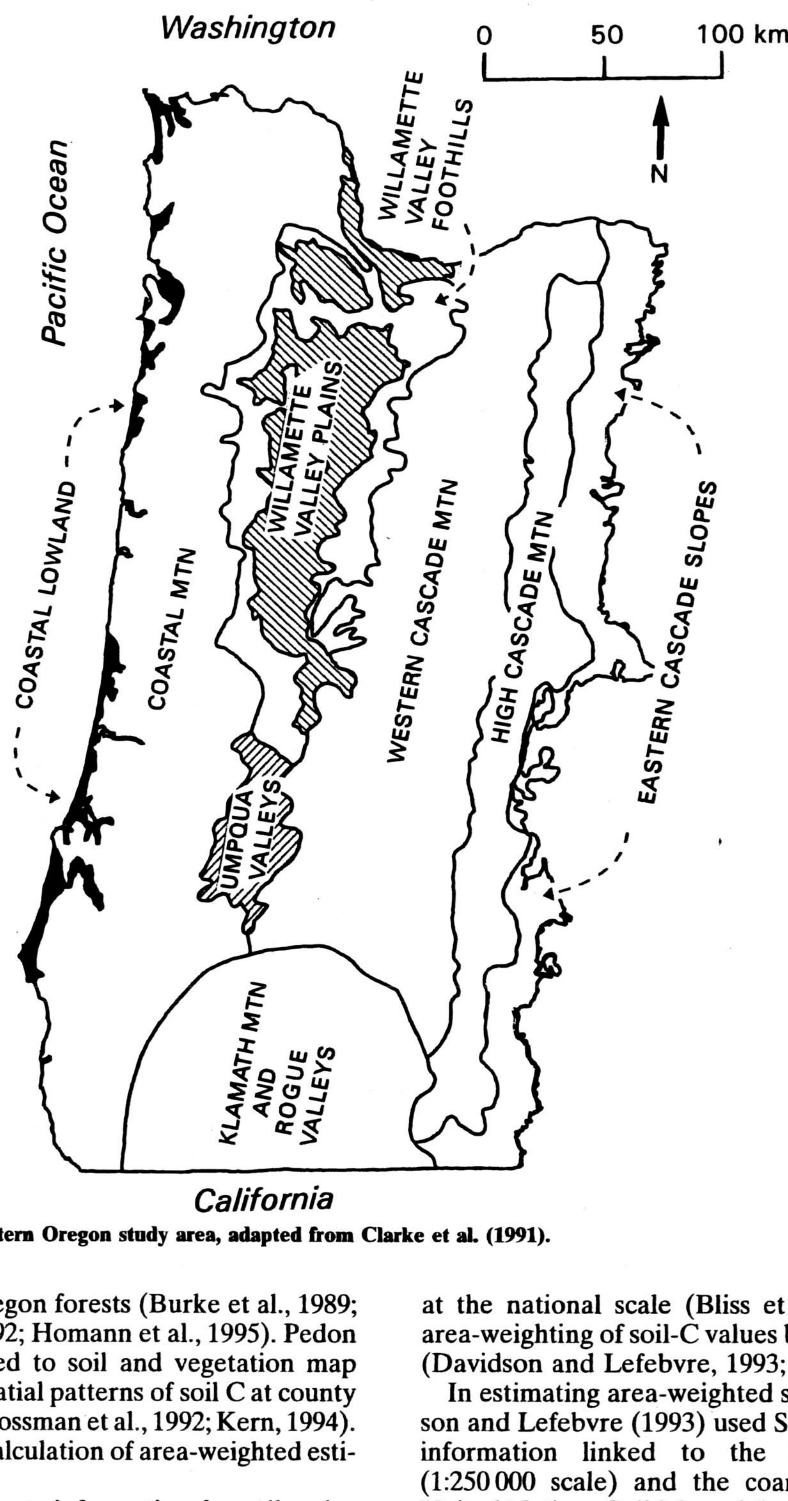

Fig. 1. Ecoregions of the western Oregon study area, adapted from Clarke et al. (1991).

forests, and western Oregon forests (Burke et al., 1989; Grigal and Ohmann, 1992; Homann et al., 1995). Pedon values of soil C assigned to soil and vegetation map units yielded maps of spatial patterns of soil C at county to continental scales (Grossman et al., 1992; Kern, 1994). These maps permitted calculation of area-weighted estimates of soil C.

Generalized soil-attribute information for soil series or soil types provides an alternative to pedons for estimating soil C. In the USA, this information is based on the expert judgments of soil-survey personnel and is stored in the Soil Interpretation Records (SIR) (Statistical Lab., Iowa State Univ., Ames, IA). It consists of ranges of values for a variety of soil attributes, including those required to calculate soil C. The information is linked to soil map units in STATSGO at the state scale (National Soil Survey Center, 1994) and in NATSGO at the national scale (Bliss et al., 1995). This allows area-weighting of soil-C values based on map-unit areas (Davidson and Lefebvre, 1993; Bliss et al., 1995).

In estimating area-weighted soil C for Maine, Davidson and Lefebvre (1993) used STATSGO soil-attribute information linked to the STATSGO soil map (1:250 000 scale) and the coarser scale (1:5 000 000) United Nations Soil Map of the World. They found the latter approach to yield estimates 8 to 30% higher than the former, depending on the assumed correlation between United Nations and U.S. soil taxonomy. An alternative approach in using the Soil Map of the World is to link it with the pedon data that accompanies it (Kern, 1994).

In our study, we examined soil C and its spatial pattern in the mountainous, largely forested region of western Oregon. Our objective was to compare estimates of

Table 1. Primary-information sources for soil attributes and area-weighting for approaches to estimate soil organic C in western Oregon study area. Date in parentheses indicates the last year primary information was obtained from that source.

Approach†	Sources for soil attributes	Sources for area weighting
NRCS pedons	NRCS pedons within study area (1991) for C concentration (measured), bulk density (measured, or estimated from soil C concentration, Homann et al., 1995), rock content (measured or visually estimated in field).	Clark et al. (1991) ecological region map; or not weighted for arithmetic means
Non-NRCS pedons	Non-NRCS pedons within study area (1991) for C or soil organic matter concentration (measured), bulk density (measured, or estimated from soil C concentration, Homann et al., 1995), rock content (measured or visually estimated in field).	Clarke et al. (1991) ecological region map; or not weighted for arithmetic means
STATSGO	generalized soil-attribute information, possibly based on NRCS soil surveys (1991), USDA soil inventories (1991), NRCS pedons within and outside study area (1991)	NRCS soil surveys (1991); USDA soil inventories (1991)
Soil Map of the World	NRCS and nonNRCS pedons outside study area (1975) for C concentration (measured), bulk density (measured, or estimated from texture, Kern, 1994). Map-unit descriptions (1969) for rock content (40% for stony, 0% otherwise).	NRCS soil surveys (1969); USDA soil inventories (1969)
NATSGO	NRCS pedons within and outside study area (1991) for C concentration (measured), bulk density (measured). NRI‡ (1982) for rock content (from taxonomic texture modifier).	NRCS soil surveys (1981); USDA soil inventories (1981); NRI (1982)
Ecosystem complexes	NRCS and nonNRCS pedons within and outside study area (1984) for C concentration (measured), bulk density (measured, or estimated from C concentration, Zinke et al., 1994), rock content (measured or visually estimated in field).	Ecosystem complex map (1985)

† STATSGO is State Soil Geographical Data Base; NATSGO is National Soil Geographic Data Base.
‡ NRI is National Resources Inventory.

average soil C from six approaches at regional, subregional, and subsubregional scales. The approaches were (i) NRCS pedons from within the region, (ii) other pedons from within the region, (iii) Oregon STATSGO, (iv) the United Nations Soil Map of the World, (v) NATSGO, and (vi) an ecosystem-complex map. The latter three approaches are coarse-scale soil-C maps based on pedons from within and outside the region.

METHODS

General

Our study area comprised the western portion of the state of Oregon (Fig. 1). It is bordered by the Columbia River on the north, by 42° N lat. on the south, the Pacific Ocean on the west, and the eastern slope of the Cascade Mountains on the east. The exact eastern border was determined by boundaries of STATSGO map units. To provide a common basis for comparison among approaches, we considered four subregions: the coast, which includes the coastal lowland and mountains; Willamette, which includes the Willamette Valley plains and foothills; Cascade, which includes western Cascade Mountains, high Cascade Mountains, and eastern Cascade slopes; and the southern subregion, which includes Klamath Mountains, Rogue valleys, and Umpqua valleys (Fig. 1).

The primary data for the six approaches overlapped to different extents with respect to where, when, and how they were collected (Table 1). Typically, the data had been collected for a period of one to several decades, although the collection period was not always stated in original documentation. The treatment of the primary data with respect to assumptions, missing data, and data synthesis also differed among approaches and is documented in Kern (1994), Homann et al. (1995), and below. We evaluated soil C in the 0- to 20- and 0- to 100-cm depths.

Pedons

There were 499 pedons with known locations within the study area that had sufficient information for us to calculate soil C to specified depths (Homann et al., 1995). Those pedons met the following minimum requirements: (i) 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, (ii) organic C concentration and rock content (either volumetric or gravimetric) measured for the surface mineral-soil horizon, and (iii) measurements of organic C concentration and rock content missing for no more than 20% of the pedon depth. Calculation of soil C, including accounting for missing data, was described by Homann et al. (1995). Surface organic (O) horizons were not included, because relevant data were often missing (Homann et al., 1995).

The pedons comprised two groups. (i) NRCS pedons were those in published soil surveys; in the National Soil Characterization Database, National Soil Survey Center, Lincoln, NE; or on file in the NRCS Oregon state office, Portland, OR. (ii) NonNRCS pedons were from theses, dissertations, and published and unpublished research projects (Homann et al., 1995). Regional estimates of average soil C based on each set of pedons were made by two approaches: (i) arithmetic mean was calculated for the entire region, and (ii) arithmetic means were calculated for each of the four subregions and a regional area-weighted average was calculated based on those means and the areas of the subregions.

State Soil Geographic Data Base

State Soil Geographic Data Base is an electronically based state soils map with associated attribute tables (National Soil Survey Center, 1994). It was developed by NRCS from published and unpublished soil surveys, county- and state-level soil maps, major land resource area (MLRA) maps, LANDSAT images, and other soil, geologic, topographic, and climatic information. It was designed primarily for planning, management, and monitoring at the regional, multistate, state, and river-basin scale (National Soil Survey Center, 1994).

State Soil Geographic Data Base map units are spatially explicit. Each consists of 1 to 21 components whose attributes and percentage contribution to the map-unit area are specified, but whose locations within map units are not indicated. The STATSGO attribute tables contain descriptive, physical, and chemical information for each component. Each component represents a phase of a soil series, water, or a miscellaneous land area. For the components based on phases of soil series, physical and chemical soil characteristics are derived from the SIR (NRCS-SOI-5) database (Statistical Laboratory, Iowa State Univ., Ames, IA). Characteristics are presented as minimum and maximum values and adhere to specific rules. For example, for organic matter as weight percentage of <2 mm material, whole numbers are used for >1%, tenths from 0.5 to 1%, and <0.5% for below 0.5%. For weight percentage of material >75 mm in size, values are presented to the nearest 5% (Soil Conservation Service, 1983). Examples of relevant

Table 2. Example of map-component variables in State Soil Geographic Data Base (STATSGO) attribute table used to calculate soil organic C (kg m^{-2}) for the map component. Values are for Component 10 of Map Unit 10 in Oregon STATSGO.

Variable	Units†	Layer 1	2	3	4
Horizon top	cm	0	10	23	46
Horizon bottom	cm	10	23	46	61
Minimum organic matter	mg (g <2 mm)$^{-1}$	20	10	10	10
Maximum organic matter	mg (g <2 mm)$^{-1}$	40	30	20	20
Minimum bulk density	g cm^{-3}	1.25	1.25	1.3	1.3
Maximum bulk density	g cm^{-3}	1.35	1.35	1.4	1.4
Minimum % <2 mm mass	% of <75 mm mass	70	70	45	45
Maximum % <2 mm mass	% of <75 mm mass	100	100	100	100
Minimum % 75–250 mm mass	% of total soil mass	15	10	20	25
Maximum % 75–250 mm mass	% of total soil mass	30	25	30	35
Minimum % >250 mm mass	% of total soil mass	15	15	30	40
Maximum % >250 mm mass	% of total soil mass	40	25	50	55

† Some units and values were converted from the English units presented in STATSGO.

data from the STATSGO attribute table are presented in Table 2. As noted by Davidson and Lefebvre (1993), data are not provided in STATSGO attribute tables for O horizons, except for Histosols or histic epipedons.

Oregon STATSGO (October 1994 CD-ROM, National Soil Survey Center, NRCS, Lincoln, NE) consists of 217 map units, of which 87 were in the study area. For the study area and for each map unit, estimates of average soil C were calculated as area-weighted soil C (kg C m^{-2}) in 0- to 20- and 0- to 100-cm depths as described by Davidson and Lefebvre (1993) and Bliss et al. (1995), with the following exceptions: (i) A value of 2.0 was assigned to particle density of rocks, based on measurements made in Oregon (Flint and Childs, 1984). (ii) If data were missing between 18 and 20 cm for the 0- to 20-cm calculation, or between 81 and 100 cm for the 0- to 100-cm calculation, bulk density and rock volume were assumed to be equivalent to the layer above, and the organic matter concentration was assigned one-half of the value of the layer above, based on trends of decreased organic matter concentration with increased depth (Kern, 1994). (iii) The layer below the deepest reported layer was assumed to be bedrock.

The methods of Davidson and Lefebvre (1993) and Bliss et al. (1995) used the means of the minimums and maximums to determine representative values for the variables in Table 2. These procedures inherently assume symmetrical distributions of those variables. Many soil characteristics are skewed rather than symmetrically distributed (Grigal et al., 1991). Therefore, calculations were also performed assuming skewed distributions by calculating the value of a map-component variable as:

$$\text{value} = \text{minimum} + \text{coefficient}(\text{maximum} - \text{minimum}) \quad [1]$$

where the coefficient was 0.39 for organic matter concentration, 0.49 for bulk density, and 0.38 for the >2-mm masses. These coefficients are based on 271 soil cores, each 10 by 15 by 30 cm deep, taken in a 15-km^2 area in southwestern Oregon (Homann, Bormann, and Boyle, 1997, unpublished data).

Oregon STATSGO indicated 97.5% of the 89 795 km^2 study area was covered by soil, 1.5% by rock outcrops and lava flows, 0.3% by mountain glaciers, and 0.7% by water. Of the soil area, 95% had sufficient data to calculate area-weighted soil C for the 0- to 20-cm depth, but only 63% for the 0- to 100-cm depth. To better represent the entire study area, we adjusted the initially calculated 0- to 100-cm value for this 63% area by multiplying it by the ratio (0- to 20-cm soil C in the 95% area)/(0- to 20-cm soil C in the 63% area).

Coarse-Scale Maps

Area-weighted soil C of the western Oregon study area and its subregions was calculated from coarse-scale soil-C maps of the contiguous United States. Those maps had been developed by Kern (1994) using three approaches: (i) The Soil Map of the World approach used both spatial and pedon data from the Food and Agriculture Organization (1971–1981). The spatial data was based on pre-1969 soil survey and resource inventory data. (ii) The NATSGO approach was based on the spatial pattern of MLRAs, which are areas with similar patterns of soils, climate, water resources, and land use (Soil Conservation Service, 1981). The areal extents of soil great groups within each MLRA were determined from the 1982 National Resources Inventory (NRI) (Reybold and TeSelle, 1989). The arithmetic mean soil C of pedons within each great group was calculated from the National Soil Characterization Database (National Soil Survey Center, Lincoln, NE), except

Table 3. Estimates of average soil organic C for the western Oregon region and ranges of individual pedon and map-unit values contributing to those estimates. Surface organic horizons are not included.

Approach†	Soil organic C estimate (range) 0- to 20-cm depth	0- to 100-cm depth
	kg C m^{-2}	kg C m^{-2}
NRCS pedons, arithmetic mean of 291 pedons	6.3 (0.9–24.3)	15.1 (2.3–80.3)
NRCS pedons, area-weighted average of 4 map units	5.9 (4.4–7.9)	13.6 (8.5–21.0)
NonNRCS pedons, arithmetic mean of 208 pedons	6.8 (1.1–23.6)	16.9 (3.6–88.2)
NonNRCS pedons, area-weighted average of 4 map units	5.7 (4.3–9.5)	14.2 (6.5–24.6)
STATSGO, area-weighted average of 87 map units, symmetric distribution of soil properties assumed	5.1 (1.5–10.8)	13.8 (3.8–33.7)
STATSGO, area-weighted average of 87 map units, skewed distribution of soil properties assumed	4.8 (1.4–10.3)	12.9 (3.4–31.4)
Soil Map of the World, area-weighted average of 7 map units	5.8 (2.5–14.7)	12.1 (6.3–27.6)
NATSGO, area-weighted average of 6 map units	4.3 (2.4–5.3)	12.1 (7.0–15.6)
Ecosystem complexes, area-weighted average of 6 map units	not available	12.3 (5.9–23.4)

† STATSGO is State Soil Geographic Data Base; NATSGO is National Soil Geographic Data Base.

Table 4. Relative average soil organic C per square meter, excluding surface organic horizons, for subregions of western Oregon.

Approach†	Relative order of subregions
NRCS pedons	Coast > Willamette > Southern > Cascade
NonNRCS pedons	Coast > Willamette > Cascade > Southern
STATSGO	Coast > Willamette > Cascade > Southern
Soil Map of the World	Willamette > Coast > Cascade > Southern
NATSGO	Coast > Cascade > Willamette > Southern
Ecosystem complexes	Coast = Cascade > Willamette > Southern

† STATSGO is State Soil Geographic Data Base; NATSGO is National Soil Geographic Data Base.

rock content was taken from the NRI and depth to bedrock from a 1982 version of the SIR. (iii) The ecosystem-complex approach was based on the spatial pattern of ecosystem types (Olson et al., 1985) and arithmetic mean soil C of pedons falling within each ecosystem type, using pedon data from Zinke et al. (1984).

Effect of Spatial Pattern

To examine the influence of spatial patterns on estimates of potential change in soil-C stores, we applied a simple empirical steady-state model to the spatial patterns developed from the six approaches. The model is from Homann et al. (1995) and is based on soil pedons in western Oregon:

$$\text{soil C in 0- to 100-cm depth (kg m}^{-2}) = -0.2 + (0.0035)\text{AET}^2 - (0.00008)\text{PCP}^2 + 0.0026(\text{PCP})\text{AWC} \quad [2]$$

where AET (cm) is actual evapotranspiration calculated from monthly precipitation and monthly air temperature by the method of Thornthwaite and Mather (1955), PCP (cm) is annual precipitation, and AWC (cm) is available water holding capacity. For each of the four subregions, monthly precipitation and temperature were calculated as the averages of 50 to 183 pedon locations (Homann et al., 1995). For each approach, AWC was adjusted to yield the initial area-weighted soil C for each subregion. Then soil C was calculated under a scenario of a 4°C increase in air temperature concomitant with a 3-cm increase in monthly precipitation in all subregions.

RESULTS

The approaches yielded regional estimates of 4.3 to 6.8 kg C m^{-2} for the 0- to 20-cm depth and 12.1 to 16.9 kg C m^{-2} for the 0- to 100-cm depth (Table 3). Highest values were from arithmetic means of pedons and lowest values from the NATSGO approach. Area-weighting reduced the estimates based on pedons, indicating an under-representation of pedon locations in areas with low soil C. The assumption of skewed rather than symmetrical distributions of soil properties reduced the STATSGO estimates. Further results are reported only for the STATSGO estimates based on symmetrical distribution of soil properties because of their better agreement with the other approaches.

At the subregional scale, all approaches indicated higher soil C along the coast and in the Willamette Valley and foothills than in the southern subregion (Table 4). For all but the ecosystem-complex approach, the coast had higher soil C than the Cascades. For all but the Soil Map of the World, the coast had higher soil C than the Willamette Valley and foothills. The soil-C stores and patterns from the various approaches yielded different amounts of soil-C change under a scenario of temperature and precipitation alteration (Table 5).

Table 5. The influence of initial soil organic C spatial pattern on change in average soil organic C of the western Oregon region. The change is the result of 4°C increase in air temperature concomitant with a 3-cm increase in monthly precipitation.

	Soil organic C		
Basis of spatial pattern†	Initial	Final	Change
	kg C m^{-2}		
NRCS pedons	13.6	18.9	5.3
NonNRCS pedons	14.2	19.1	4.9
STATSGO	13.8	18.6	4.8
Soil Map of the World	12.1	17.0	4.9
NATSGO	12.1	17.0	4.9
Ecosystem complexes	12.3	17.3	5.0

† STATSGO is State Soil Geographic Data Base; NATSGO is National Soil Geographic Base.

Only STATSGO and pedon approaches allowed comparison at a finer scale. For the 87 Oregon STATSGO map units in the study area, one was water, one was lava flows, one was mountain glaciers, and 84 had soil. Of those with soil, 81 had sufficient information to calculate area-weighted soil C to a depth of 20 cm for ≥70% of their areas (Fig. 2). The highest soil-C levels were in the coastal lowlands and adjacent coastal mountains, in the Willamette Valley foothills, which are dominated by Xeric Haplohumults and Palehumults, and in valleys of the Coastal and Cascade Mountains (Fig. 1 and 2). Low values occurred in the high Cascade Mountains and on the eastern Cascade slopes, as well as the Umpqua valleys, Klamath Mountains, and Rogue valleys.

We compared STATSGO values for individual map units with values for NRCS and nonNRCS pedons located within those map units. The comparison was made only for map units that had five or more NRCS pedons or five or more nonNRCS pedons. Average, rather than individual, pedon values were used, because a STATSGO value represents an average for a large map unit and is not expected to provide an accurate value for any specific location within that area. There was good agreement between STATSGO and NRCS pedons for the 0- to 20-cm (r = 0.82) and 0- to 100-cm depths (r = 0.80, Fig. 3). The map units with the most deviation had unusual characteristics for one or both data sets, such as relatively constant C concentration throughout the profile, extreme decrease in C concentration with increased depth, and very high rock volume at depth. There were poorer relations between STATSGO and nonNRCS pedons (r = 0.63 to 0.72, Fig. 3).

DISCUSSION

Regional evaluation of soil C may be used to improve continental and global estimates of soil-C stores in two ways. First, estimates for a number of regions may be combined to yield an estimate for a broader area. Second, regional estimates may be used to check estimates made at coarser scales by other approaches. For western Oregon, the coarse-scale soil-C maps yielded values for the 0- to 100-cm depth that were 5 to 30% lower than those based on the regional pedon and STATSGO approaches. Whether this is representative of other regions can only be determined through further evaluation. Davidson and Lefebvre (1993) found an alternate coarse-scale approach to yield higher values than STATSGO for the state of Maine.

We expect up-to-date, detailed information from within an area to yield the most reliable estimate of average soil C. Thus, we expect the NRCS pedons, nonNRCS pedons, and STATSGO to be more reliable at regional and subregional scales than the coarse-scale approaches. State Soil Geographic Data Base represents the most detailed basis for spatially weighting soil-attribute information for regions of the USA, but the soil-C values derived from it are from generalized soil-attribute information based on expert judgment. Comparison with pedon values would test the adequacy of STATSGO soil-C values if the pedons within a specified area were randomly located and were not used to derive STATSGO values. The arithmetic mean of randomly located pedons would be the best estimate of average soil C within an area, irrespective of whether the statistical distribution of pedon soil-C values were symmetrical or skewed. Unfortunately, neither the NRCS nor nonNRCS pedons were randomly located, because sampling locations were chosen for specific purposes. Therefore, even if STATSGO values represented reality, perfect agreement between pedons and STATSGO would not be expected. In spite of this limitation, the agreement between the different approaches is encouraging.

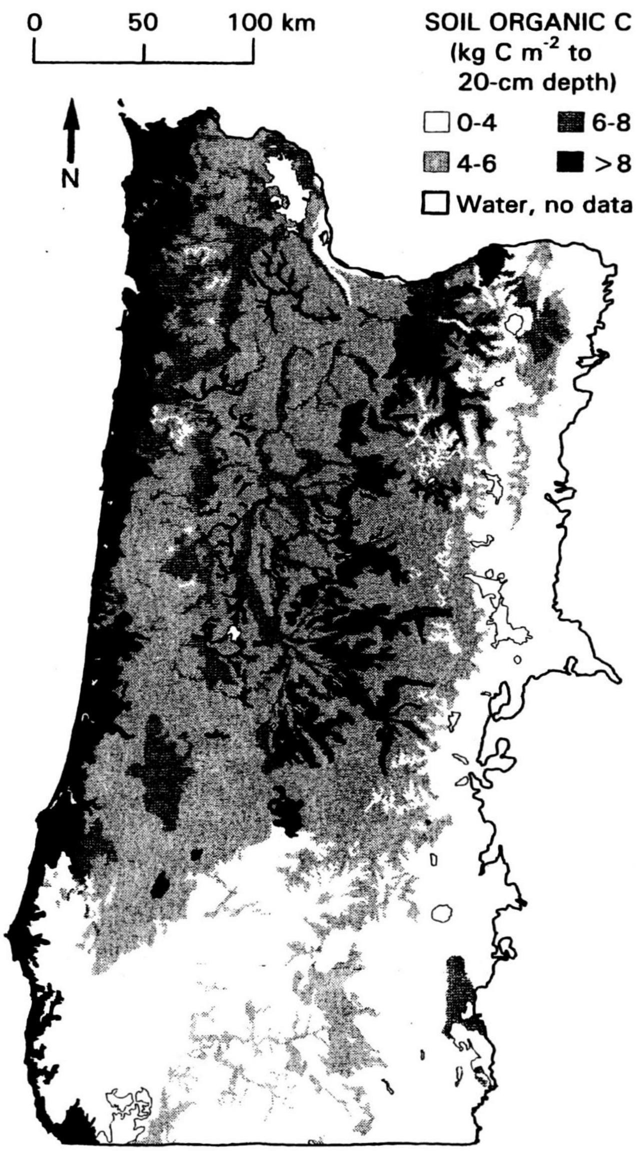

Fig. 2. Pattern of soil C (kg C m^{-2} in 0- to 20-cm depth), not including surface organic horizons, in western Oregon, based on State Soil Geographic Data Base (STATSGO). No data are presented for a map unit if <70% of its area had data for calculating soil C.

State Soil Geographic Data Base and nonNRCS pedons are independent data sets; i.e., the two approaches do not overlap in their primary data (Table 1). They were most consistent at the subregional scale and somewhat less consistent at coarser and finer scales. State Soil Geographic Data Base and NRCS pedons do overlap in their primary data. They were quite consistent at the regional scale for 0- to 100-cm depth and subsubregional scale for 0- to 20- and 0- to 100-cm depths. This agreement indicates NRCS pedon data were adequately considered and synthesized during the development of the SIR, from which the STATSGO attribute table was derived.

All approaches have one major drawback: the accuracy of, or conversely the uncertainty associated with, the estimate cannot be objectively assessed. Uncertainty of soil C of an individual pedon can be propagated statistically from uncertainties associated with C 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. There are no statistical procedures to account for possible bias in pedon locations that have been selected for specific purposes, however. 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 of previous studies.

Uncertainties associated with expert judgments are often not tractable or not evaluated. Expert judgments occur in all approaches. For pedons, assignments are made for missing values of soil attributes, and rock contents may be from visual field estimates. In the aggregation and generalization of soil spatial pattern, soils judged to have similar attributes are grouped, but those attributes may not be the most relevant for soil-C assessments. Soil attributes for areas with limited field data are extrapolated from soils outside map units.

Improvements in approaches to estimate regional soil C and its spatial pattern may take several forms. For pedons, unbiased locations combined with complete profile measurements would allow objective evaluation of uncertainty. Locations could be determined by ran-

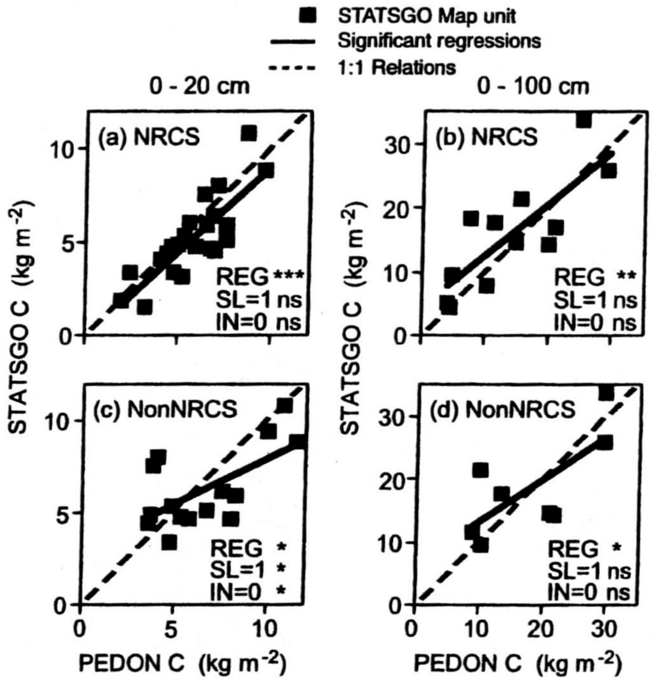

Fig. 3. State Soil Geographic Data Base (STATSGO) C (kg C m^{-2}) vs. pedon C (kg C m^{-2}) for NRCS pedons (a) 0- to 20-cm depth and (b) 0- to 100-cm depth, and nonNRCS pedons (c) 0- to 20-cm depth and (d) 0- to 100-cm depth. The STATSGO C is the area-weighted soil C for a map unit that has data for ≥70% of its area. Pedon C is the arithmetic mean soil C of at least five pedons within the map unit. Statistical results indicate significance of the regression (REG), deviation of slope from 1 (SL = 1), and deviation of intercept from 0 (IN = 0). *, **, * Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; ns is not significant.**

dom, grid-based (McGrath and Loveland, 1992), or geostatistical procedures. Comparison of current soil-C values of several map units with values obtained from these more complete and objective approaches would allow a rigorous test of the validity of current soil-C maps. Sampling and analysis of the surface O horizon as well as the mineral soil would allow whole-profile estimates of soil C. This has been done in some previous research studies (Huntington et al., 1988; Homann et al., 1995) and has been implemented in some recent NRCS investigations. In western Oregon, surface O horizons contain an average of 2 kg C m^{-2} (Homann et al., 1995), equivalent to ≈40% of the C in the 0- to 20-cm mineral soil (Table 3). Because the O horizon C storage can change quickly, e.g., during forest site preparation (Little and Ohmann, 1988), assessment of its spatial pattern is equally important as that of C in the mineral soil. Uncertainty associated with some expert judgments could be determined by duplicate assessments by independent professionals. In combination, these steps would result in improved estimates of regional soil C, its spatial pattern, and associated uncertainties.

This assessment of uncertainty is important because of the potential use of estimates of soil-C amounts and spatial patterns. Our simple model analysis (Table 5) suggests regional soil-C response to environmental perturbations may be influenced by initial amounts and spatial patterns. Spatial patterns of other soil properties also influence regional estimates of ecosystem properties and processes (Lathrop et al., 1995). For spatial models of C dynamics with C as an input variable (Hunt et al., 1996), model-specific sensitivity assessments would determine the extent to which model output is influenced by the uncertainty associated with soil-C amounts and spatial patterns. For other complex spatial models of the C cycle (Den Elzen et al., 1997; Post et al., 1997; Schimel et al. 1996; Thompson et al., 1996), calibration and evaluation would benefit from the best estimates of spatial patterns of soil C and their associated uncertainties.

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REFERENCES

Bliss, N.B., S.W. Waltman, and G.W. Petersen. 1995. Preparing a soil carbon inventory for the United States using geographic information systems. p. 275–295. *In* R. Lal et al. (ed.) Soils and global change. Lewis Publ., Boca Raton, FL.

Bohn, H.L. 1982. Estimate of organic carbon in world soils: II. Soil Sci. Soc. Am. J. 46:1118–1119.

Botkin, D.B., and L.G. Simpson. 1990. Biomass of the North American boreal forest. A step toward accurate global measures. Biogeochemistry 9:161–174.

Bouwman, A.F., and R. Leemans. 1995. The role of forest soils in the global carbon cycle. p. 503–525. *In* W.W. McFee and J.M. Kelly (ed.) Carbon forms and functions in forest soils. SSSA, Madison, WI.

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach, and D.S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. Soil Sci. Soc. Am. J. 53:800–805.

Clarke, S.E., D. White, and A.L. Schaedel. 1991. Oregon, USA, ecological regions and subregions for water quality management. Environ. Manage. 15:847–856.

Davidson, E.A., and P.A. Lefebvre. 1993. Estimating regional carbon stocks and spatially covarying edaphic factors using soil maps at three scales. Biogeochemistry 22:107–131.

Den Elzen, M.G.J., A.H.W. Beusen, and J. Rotmans. 1997. An integrated modeling approach to global carbon and nitrogen cycles: Balancing their budgets. Global Biogeochem. Cycles 11:191–215.

Dixon, R.K., S. Brown, R.A. Houghton, A.M. Solomon, M.C. Trexler, and J. Wisniewski. 1994. Carbon pools and flux of global forest ecosystems. Science 263:185–190.

Eswaran, H., E. van den Berg, and P. Reich. 1993. Organic carbon in soils of the world. Soil Sci. Soc. Am. J. 57:192–194.

Flint, A.L., and S.W. Childs. 1984. Physical properties of rock fragments and their effect on available water in skeletal soils. p. 91–103. *In* J.D. Nichols et al. (ed.) Erosion and productivity of soils containing rock fragments. SSSA Spec. Publ. 13. SSSA, Madison, WI.

Food and Agriculture Organization. 1971–1981. Soil map of the world, 1:5 000 000 scale. Vol. I–X. United Nations Educational, Scientific, and Cultural Organization, Paris.

Grigal, D.F., R.E. McRoberts, and L.F. Ohmann. 1991. Spatial variation in chemical properties of forest floor and surface mineral soil in the north central United States. Soil Sci. 151:282–290.

Grigal, D.F., and L.F. Ohmann. 1992. Carbon storage in upland forests of the Lake States. Soil Sci. Soc. Am. J. 56:935–943.

Grossman, R.B., E.C. Benham, J.R. Fortner, S.W. Waltman, J.M. Kimble, and C.E. Branham. 1992. A demonstration of the use of soil survey information to obtain areal estimates of organic carbon. *In* Technical papers, Remote sensing and data acquisition (Vol. 4:457–465). American Society of Photogrammetry and Remote Sensing and American Congress of Surveying and Mapping, Bethesda, MD.

Homann, P.S., P. Sollins, H.N. Chappell, and A.G. Stangenberger. 1995. Soil organic carbon content of a mountainous, forested region: Relation to site characteristics. Soil Sci. Soc. Am. J. 59: 1468–1475.

Hunt, E.R. Jr., S.C. Piper, R. Nemani, C.D. Keeling, R.D. Otto, and S.W. Running. 1996. Global net carbon exchange and intra-annual atmospheric CO_2 concentrations predicted by an ecosystem process model and three-dimensional atmospheric transport model. Global Biogeochem. Cycles 10:431–456.

Huntington, T.G., D.F. Ryan, and S.P. Hamburg. 1988. Estimating soil nitrogen and carbon pools in a northern hardwood forest ecosystem. Soil Sci. Soc. Am. J. 52:1162–1167.

Jenkinson, D.S., D.E. Adams, and A. Wild. 1991. Model estimates of CO_2 emissions from soil in response to global warming. Nature 351:304–306.

Kern, J.S. 1994. Spatial patterns of soil organic carbon in the contiguous United States. Soil Sci. Soc. Am. J. 58:439–455.

Lathrop, R.J. Jr., J.D. Aber, and J.A. Bognar. 1995. Spatial variability of digital soil maps and its impact on regional ecosystem modeling. Ecol. Model. 82:1–10.

Liski, J., and C.J. Westman. 1997a. Carbon storage in forest soil of Finland, 1. Effect of thermoclimate. Biogeochemistry 36:239–260.

Liski, J., and C.J. Westman. 1997b. Carbon storage in forest soil of Finland, 2. Size and regional patterns. Biogeochemistry 36:261–274.

Little, S.N., and J.L. Ohmann. 1988. Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/western hemlock clearcuts. For. Sci. 34:152–164.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142:279–288.

McGrath, S.P., and P.J. Loveland. 1992. The soil geochemical atlas of England and Wales. Blackie and Co., Glasgow, Scotland.

National Soil Survey Center. 1994. State Soil Geographic (STATSGO) data base, Data use information. Misc. Publ. no. 1492. USDA NRCS, Lincoln, NE.

Olson, J.S., J.A. Watts, and L.J. Allison. 1985. Major world ecosystem complexes ranked in live vegetation: A database. NDP-017. Carbon Dioxide Information Center, Oak Ridge Natl. Lab., Oak Ridge, TN.

Post, W.M., W.R. Emanuel, P.J. Zinke, and A.G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature 298:156–159.

Post, W.M., A.W. King, and S.D. Wullschleger. 1997. Historical variations in terrestrial biospheric carbon storage. Global Biogeochem. Cycles 11:99–109.

Reybold, W.U., and G.W. TeSelle. 1989. Soil geographic data bases. J. Soil Water Conserv. 41:28–29.

Schimel, D.S., B.H. Braswell, R. McKeown, D.S. Ojima, W.J. Parton, and W. Pulliam. 1996. Climate and nitrogen controls on the geography and timescales of terrestrial biogeochemical cycling. Global Biogeochem. Cycles 10:677–692.

Schlesinger, W.H. 1986. Changes in soil carbon storage and associated properties with disturbance and recovery. p. 194–220. *In* J.R. Trabalka and D.E. Reichle (ed.) The changing carbon cycle, a global analysis. Springer-Verlag, New York.

Soil Conservation Service. 1981. Land resources regions and major land resources areas of the US. USDA-SCS Agric. Handb. 296. U.S. Gov. Print. Office, Washington, DC.

Soil Conservation Service. 1983. National soils handbook. Soil Conservation Service, Washington, DC.

Sollins, P., G. Spycher, and C. Topik. 1983. Processes of soil organic-matter accretion at a mudflow chronosequence, Mt. Shasta, California. Ecology 64:1273–1282.

Thompson, M.V., J.T. Randerson, C.M. Malmstrom, and C.B. Field. 1996. Change in net primary production and heterotrophic respiration: How much is necessary to sustain the terrestrial carbon sink? Global Biogeochem. Cycles 10:711–726.

Thornthwaite, C.W., and J.R. Mather. 1955. The water balance. Publications in climatology. Vol. 8, no. 1. Drexel Inst. of Tech., Centerton, NJ.

Vincent, K.R., and O.A. Chadwick. 1994. Synthesizing bulk density for soils with abundant rock fragments. Soil Sci. Soc. Am. J. 58:455–464.

Zinke, P.J., A.G. Stangenberger, W.M. Post, W.R. Emanuel, and J.S. Olson. 1984. Worldwide organic soil carbon and nitrogen data. ORNL/TM-8857. Oak Ridge Natl. Lab., Oak Ridge, TN.