Chapter 9
Distribution of Soil Organic Carbon in the Conterminous United States

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Abstract The U.S. Soil Survey Geographic (SSURGO) database provides detailed soil mapping for most of the conterminous United States (CONUS). These data have been used to formulate estimates of soil carbon stocks, and have been useful for environmental models, including plant productivity models, hydrologic models, and ecological models for studies of greenhouse gas exchange. The data were compiled by the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) from 1:24,000-scale or 1:12,000-scale maps. It was found that the total soil organic carbon stock in CONUS to 1 m depth is 57 Pg C and for the total profile is 73 Pg C, as estimated from SSURGO with data gaps filled from the 1:250,000-scale Digital General Soil Map. We explore the non-linear distribution of soil carbon on the landscape and with depth in the soil, and the implications for sampling strategies that result from the observed soil carbon variability.

Keywords Soil organic carbon • Conterminous United States • Soil survey

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Introduction

Soil organic carbon (SOC) is of considerable scientific interest because it is part of the carbon cycle. The carbon cycle includes the atmosphere, the oceans, sediments, rocks, and soil. The buildup of carbon dioxide (CO_2) and methane (CH_4) in the atmosphere are major causes of climatic warming and global changes. Soils interact with the atmosphere by absorbing or releasing CO_2 and CH_4 in processes that include plant growth (photosynthesis) and decomposition by microorganisms. Processes that increase or decrease soil carbon can happen simultaneously, so separating the effects and making recommendations for strategies that will increase carbon storage and contribute to mitigating climate change requires understanding processes at many time scales and spatial scales (Sundquist et al. 2009).

Soil organic carbon is also important in agriculture and forestry because organic matter contributes to soil fertility by helping to retain soil moisture and supply plant nutrients (UNEP 2012). SOC is among the soil properties used by hydrologic modelers to predict how precipitation is processed by the land surface and contributes to stream flow, and surface water and groundwater quantity and quality (Saxton and Rawls 2006). Our objectives are to quantify stocks of SOC, to understand relationships with land use and land cover to guide land management decisions, to advise sampling protocols for improving estimates of SOC stocks, and to make data easily available to scientists and the public through the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) and the U.S. Environmental Protection Agency (USEPA).

Materials and Methods

A single database model is used to organize information in both the Soil Survey Geographic database (SSURGO) and the Digital General Soil Map of the United States (also called STATSGO2). Analyses in this chapter are based on a 30 m resolution version of the SSURGO data, with gaps (unmapped areas) filled with the more generalized STATSGO2 data. The NRCS is responsible for the leadership of soil survey activities and coordination of the National Cooperative Soil Survey (NCSS). There are two primary types of data in a soil geographic database: spatial data and attribute data. Spatial data represent the location of soil map units, and may be in either vector (as digitized from traditional soil maps) or raster (grid cell) format. The attribute data contain information on the soil properties for each map unit, and are represented by a hierarchy of tables in a relational database structure. At the top of the hierarchy is information about map units, and each of the lower levels represent increasing spatial and attribute detail. The SSURGO data were most often compiled at map scales from 1:12,000 to 1:24,000, and the STATSGO2 data were compiled at the 1:250,000 map scale. We used data obtained on December 30, 2009 from the NRCS Geospatial Research Unit (USDA-NRCS 2009).

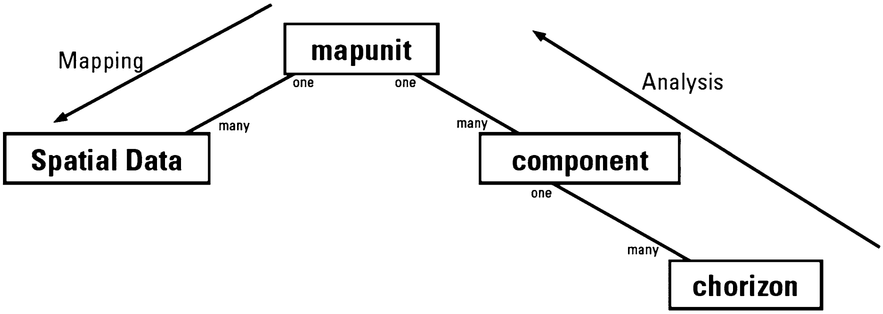

Fig. 9.1 A simplified diagram of the relational data structure for SSURGO and STATSGO2 data. The **mapunit** table is critical for linking attribute data to the spatial data. The relational key variable **mukey** occurs in all of the top level tables (the Spatial Data, the **mapunit** table, and the **component** table). Together, the **mapunit** and **component** tables represent the two-dimensional land surface. The component horizon table (**chorizon**) represents soil properties that change with depth into the ground. The "analysis" process proceeds from the lowest level tables on the right side of the diagram and summarizes results to the map unit level. The "mapping" process copies these results to the spatial data, either adding an attribute or making a new version

Figure 9.1 shows a diagram of a small portion of the relational data structure. On the left side, spatial data represent each map unit. On the right side, attribute tables have information on soil properties and relationships. An analysis proceeds from the right side, summarizing information to define a result at the map unit level. The result is transferred to the spatial data, creating a new spatial data set with the results of the analysis.

Map units are conceptually subdivided into components to retain information on how soils and miscellaneous land types change on the landscape for areas too small to be map units. Map units and components represent the two-dimensions of the surface of the landscape. Horizons represent how soil changes with depth from the surface to complete a three-dimensional view. For each component, the percentage of the map unit area represented by the component (**comppct_r**) is in the database. The horizons have detailed information on how soil properties change with depth. Taken together, all the soil horizons for a soil component represent the soil profile.

Components of map units can represent non-soil areas, such as water, bedrock at the surface, paved areas, gravel pits, fill, and dumps. If some components represent non-soils, the soil properties of interest (such as SOC) are given zero values for the soil property, and these zeros would be included in the averages computed at the map unit level. By including zero for the areas without component information then the quantities of interest are appropriately scaled for multiplying by the total area of the map unit and accumulating sums for the study area.

The SSURGO and STATSGO2 databases do not have a separate attribute for soil organic carbon. Although SOC is measured in the laboratory, it is reported in the soil geographic databases as soil organic matter (e.g., **om_r**) on the component horizon (chorizon) table. The organic matter was calculated as SOC divided by 0.58, reflecting an assumption that soil organic matter is 58 % carbon (USDA-NRCS 2004, p. 347). We reverse this calculation to convert organic matter back to soil organic carbon by multiplying by 0.58. The **om_r** attribute is defined as "The amount by weight of decomposed plant and animal residue expressed as a weight percentage of the less than 2 mm soil material," and thus excludes large roots, surface duff, and decaying trees.

At the horizon level, the SOC (g C) is calculated using the mass fraction soil fines (M_f) on a unit surface area basis (cm^{-2} is implicit), where the M_f is computed from the soil bulk density and three other variables that define the rock content:

$$^{h}SOC = {}^{h}Mf * 0.58 * \mathbf{om\_r} * 0.01 \tag{9.1}$$

where the 0.01 converts **om_r** from a percentage to a ratio.

The horizon (*h*) level SOC values are summarized to the component (*c*) level as a sum:

$$^{c}SOC = \sum_{h} {}^{h}SOC \tag{9.2}$$

The component level SOC values are summarized to the map unit (*m*) level as a weighted sum, with a corrected component percentage (*comppct_r_fix*) as the weighting factor:

$$^{m}SOC = \frac{\sum_{c} {}^{c}SOC * comppct\_r\_fix}{\sum_{c} comppct\_r\_fix} \tag{9.3}$$

Total carbon stocks for the conterminous United States are summed from the product of the unit area estimates of SOC for a map unit (Eq. 9.3) and the area of the map unit.

Results

A map of SOC is shown in Fig. 9.2, representing the total depth of profile and with gaps in SSURGO filled from STATSGO2. Areas of high SOC include areas with substantial wetlands along the border with Canada, in the Northeast, and along the Atlantic and Gulf coasts. There are prominent glacial influences that created areas of poorly drained soils from North Dakota to central Iowa. In the Pacific Northwest, the high rainfall and volcanic soils contribute to the retention of SOC, whereas in Texas, bands of high SOC soils are apparent where organic matter is tightly bound in soils with a high clay content.

The non-linear distribution of SOC with land area is illustrated in Fig. 9.3. On the left half of the figure, the low-carbon half of land area (3,866,000 km^2) has about 20 % of the SOC, whereas on the right side of the figure, the high-carbon half of the land area has about 80 % of the SOC. By splitting the vertical axis into top and bottom

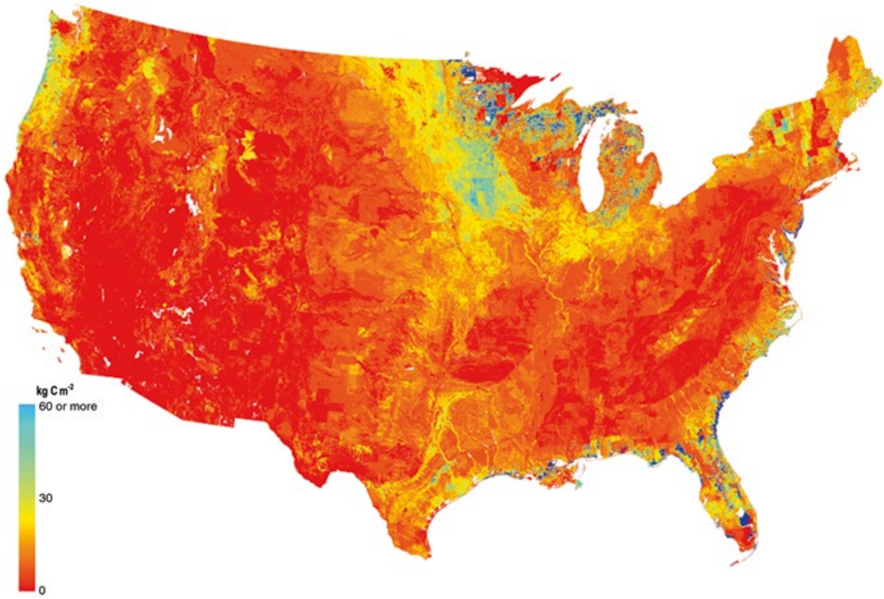

Fig. 9.2 Map of soil organic carbon in the conterminous United States for the total depth of the profile (which is variable). Gaps in the SSURGO data were filled using STATSGO2 data. Note that colors are scaled to show extreme patterns, so interpolation along the color scale is approximate. Abrupt changes in SOC along county or state boundaries often reflect the age of the survey (old versus recent) or the scale (SSURGO versus STATSGO2), and are being addressed by the NRCS with a major re-correlation effort

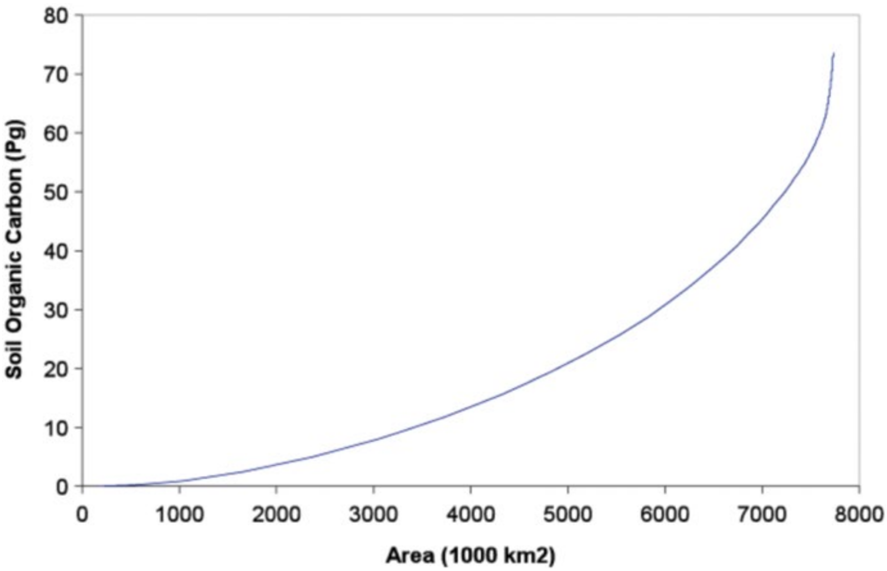

Fig. 9.3 Cumulative SOC by cumulative land area. The non-linear distribution indicates that small areas of high carbon soils are important contributors to the total SOC. The curve is based on SOC in the total profile for all land areas, so it is not directly comparable to Table 9.1

halves, 84 % of the land area is needed to reach the 36.7 Pg SOC point on the curve, and the high-carbon land portion of the curve (between the 36.7 Pg C and the total 73.4 Pg C) represents just 16 % of the total land area.

Table 9.1 shows soil carbon stocks by groups of land cover class from the National Land Cover Database of 2001 (Homer et al. 2007). This table represents another view of the non-linear distribution of SOC by land area. The largest quantities of SOC are in the forest, grassland, and cropland areas, reflecting both large land areas in those groups and moderately high carbon stocks per unit area. Although wetlands have smaller land area (327,271 km^2), they have much larger SOC per unit land area (27.28 kg C m^{-2}), and so they have the fourth highest contribution to total SOC (8,929 Tg C in the 0–100 cm zone) in this table. The vertical distribution of carbon in the profile is also non-linear. Although the 0–30 cm depth zone has only 30 % of the soil volume compared to the 0–100 cm depth zone, it has more than half the SOC. Values in this table were calculated with an algorithm that compared the land cover class of a pixel to the dominant land cover class for the soil map unit. For pixels where the land cover matched the dominant land cover, the representative value of carbon content was used, reflecting the practice to map soil properties for the dominant land cover type. Where a pixel had a different land cover type than the dominant one, expert rules were used to select lower or higher organic matter content values as appropriate for the minority land cover classes (West et al. 2010).

Discussion

The spatial patterns of SOC as seen in Fig. 9.2 can be used as a guide for sampling to improve estimates of SOC stocks. Much of the data collection used to develop SSURGO and related databases was intended to describe many soil properties, and soil carbon was not necessarily the focus of the sample selection. When future surveys are designed to sample soil carbon, careful attention should be given to the "population" which is being sampled. One way to think of this is that the "population" is the total set of organically bound soil carbon atoms present in the study area (here the conterminous United States). An ideal sampling scheme would give equal probability for each of the carbon atoms to be included in the sample. Viewing the non-linear distribution of organic carbon on the landscape (as shown in Fig. 9.3), this scheme would imply that the sampling should be based on equal intervals of the vertical axis (cumulative carbon) rather than equal intervals of the horizontal axis (cumulative land area). When differences in carbon content, as known from soil mapping, are used to stratify the sampling, then an inverse transformation would need to be used to scale the new carbon measurements back to land area and study-area totals. In practice, a sampling strategy will be based on a partitioning of the land surface. Some approaches, such as stratified random sampling are likely to be impractical to obtain accurate estimates. Cluster sampling approaches, and strategies that account for rare populations (Lohr 2010) would be desirable for characterizing the distribution of soil carbon. A second consideration for sampling strategy

Table 9.1 Area (km^2), stocks of soil organic carbon (SOC, Tg C), and SOC per unit land area (SOC, kg C m^{-2}) by soil depth zone and by land cover group (generalized from the 2001 National Land Cover Database) for SSURGO data only

	Depth range (cm)	Water[a]	Developed[b]	Barren[c]	Forest[d]	Shrub/scrub[e]	Grass/pasture/hay[f]	Crop[g]	Wetland[h]	Total[i]
Area (km^2)		22,920	383,375	54,563	1,710,633	1,295,304	1,645,238	1,248,295	327,271	6,687,612
SOC (Tg C)	**0–30**	170	1,715	97	7,400	3,048	6,340	6,786	3,717	29,273
	0–100	377	3,273	197	13,144	5,612	12,330	13,361	8,929	57,224
SOC (kg C m^{-2})	**0–30**	7.43	4.47	1.77	4.33	2.35	3.85	5.44	11.36	4.38
	0–100	16.46	8.54	3.60	7.68	4.33	7.49	10.70	27.28	8.56

[a]Combines NLCD 2001 classes 11 Open Water and 12 Permanent Ice/Snow (carbon contents are not applicable (NA)). SOC values are given in the Water class because the land cover classes were mapped at a more detailed scale than the soil classes, so sometimes generalized soil information was associated with water pixels

[b]Combines NLCD 2001 classes 21 Low Intensity Residential, 22 High Intensity Residential, 23 Commercial/Industrial/Transportation, and 24 Developed High Intensity (usually insufficient data for carbon calculations, so the values may not properly reflect national totals)

[c]Consists of NLCD 2001 class 31 Bare Rock/Sand/Clay

[d]Combines NLCD 2001 classes 41 Deciduous Forest, 42 Evergreen Forest, and 43 Mixed Forest

[e]Consists of NLCD 2001 class 52 Shrub/Scrub

[f]Combines NLCD 2001 classes 71 Grassland/Herbaceous and 81 Pasture/Hay

[g]Consists of NLCD 2001 class 82 Row Crops

[h]Combines NLCD 2001 classes 90 Woody Wetlands and 95 Emergent Herbaceous Wetlands

[i]The total area of the conterminous United States is approximately 7,700,000 km^2, whereas this table only includes the areas mapped with SSURGO (USDA-NRCS 2009)

would be the potential rate of change of the carbon stocks with anticipated changes in land management, climate change, or other forcing factors. Areas with a high potential for carbon sequestration or release may need special emphasis in the sampling design.

Models of the distribution and changes of carbon on the landscape may be empirical (as driven by remotely sensed data and flux tower data) (Wylie et al. 2007) or use process-based biogeochemical relationships to simulate how various carbon pools and driving forces will change carbon through time (Liu et al. 2003, 2011). The empirical models have the advantage that they can be more easily spatially validated. The process models have advantages for simulating future conditions. Each type of model may need inputs of soil data, including the water storage capacity of the soil, the soil carbon content, measures of infiltration, ease of water movement (permeability), and fertility (as rates of plant growth are often a control for the net sequestration or release of carbon at a location).

To make soil data easier for modelers to use, the gridded SSURGO (gSSURGO) has been recently developed. The original SSURGO vector map layer was reformatted into a grid cell (raster) format at 10-m resolution using an equal area projection for the United States. The gSSURGO data allow rapid visualization and use of soil properties for modeling for large land areas, and are available to the public for each state of the United States (USDA-NRCS 2013).

Many soil attributes, including SOC, will be available to scientists and the public through the USEPA's EnviroAtlas. The EnviroAtlas is a collection of tools and resources that provides geospatial data, maps, research, and analysis on the relationships between nature, people, health, and the economy. The atlas allows exploration of environmental services that humans receive from nature, such as clean air, clean and plentiful water, natural hazard mitigation, biodiversity conservation, food, fuel, and materials, recreational opportunities, and cultural and aesthetic value. Soil organic carbon data are one of the foundations for modeling and interpreting these ecosystem services (USEPA 2013).

Conclusions

The SOC total for the conterminous United States is approximately 73.4 Pg C in the total soil profile, as computed with SSURGO data with gaps filled with STATSGO2. This value compares to a prior estimate of 68 Pg C from STATSGO alone (Bliss 2003), however the differences are attributable to the data sources, and are not an estimate of SOC change. The quantity in the top 100 cm of soil is 57.2 Pg C, and in the top 30 cm of soil is 29.3 Pg C, as computed with SSURGO data. The SSURGO data represent most of the high value land, so the gaps in SSURGO generally represent mountainous and desert areas with much lower carbon contents.

The non-linear distribution of SOC stocks has implications for future sampling and modeling of carbon stocks and the interactions of soil carbon with the atmosphere and ground water. Land cover classes with high SOC stocks include forests, grasslands, and cropland, with wetlands representing a smaller total quantity but a much larger carbon stock per unit land area.

Soil organic carbon stocks form a starting point and calibration check for models that estimate changes in carbon stocks through time. Such models can guide management and policy decisions that will need to take into account changing land use and land cover patterns, climate change, changes in vegetation productivity, and conditions affecting microorganisms that decompose soil organic matter.

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