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Quantity and Spatial Variability of Soil Carbon in the Conterminous United States

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ABSTRACT

We estimated the soil organic carbon (SOC) and soil inorganic carbon (SIC) inventory for the conterminous USA using the State Soil Geographic Database (STATSGO). The relative contribution of each soil order and Land Resource Region (LRR) to the national SOC and SIC inventory was determined. There are 302 to 1499 $\times 10^8$ Mg of SOC and 226 to 937 $\times$ 10^8 Mg of SIC in the upper 2 m of soil in the conterminous USA. About 30 and 80% of the upper 2-m SOC is in the 0- to 0.20- and 0- to 1.0-m soil layers, respectively. For SIC, only about 8% of the upper 2-m SIC is in the upper 0.2 m, and about 50% is in the top 1.0-m layer. The relative spatial variability of SOC increases dramatically as soil depth increases while the largest relative variability of SIC is in the surface layer. Because of its large area (27% of the soil area in the conterminous USA), Mollisols are the largest contributors both to the SOC stock (about 31 to 39%) and to the SIC stock (about 43 to 44%) in the conterminous USA. The results of this study provide a view of soil C partitioning by taxonomic group and land resource area, information that may be useful for assessing the impact of land use and climatic change on SOC and SIC pools.

An accurate assessment of U.S. soil C storage is needed as a baseline for evaluating the overall U.S. C budget and the impact of land cover/use change on the inventory. Numerous studies have estimated the U.S. SOC pools at local and regional scales (Franzmeier et al., 1985; Sims and Neilsen, 1986; Huntington et al., 1988; Davidson and Lefebvre, 1993; Davidson, 1995; Homann et al., 1998; Brejda et al., 2001; Galbraith et al., 2003). Kern (1994), using data from 3700 pedons, estimated that U.S. soils have between 62.1 and 84.5 Pg (Pg = 10^{15} g) of SOC in the upper 1.0 m. Bliss et al. (1995), using averages (midpoint values) from the STATSGO, estimated SOC storage (total soil profile) in 40 states. Lacelle et al. (2001) later generated a map of SOC in the upper 1.0 m of the soils of North America, with the U.S. portion calculated using the midpoint values from the STASTGO database.

Soil inorganic C is also a large C pool. However, studies on SIC storage and content have only focused on local or regional assessments (Schlesinger, 1982; Grossman et al., 1995; Monger and Matrinez-Rios, 2000). Estimates of the SIC pools at a national or global scale have been more tentative than estimates of SOC pools (Lal et al., 1998b). Nonetheless, most of the SIC, which exists as carbonates, is believed to occur in soils of arid and semiarid regions (Grossman et al., 1995; Schlesinger, 1997; Lal et al., 1998b). Monger and Matrinez-Rios (2000) estimated the amount of soil carbonate in grazing lands of the USA by focusing on the woodlands, shrublands, and grasslands that occur within aridic, ustic, and xeric moisture regimes using random sampling for at least 25 sites per ecoregion. An estimation of SIC storage for the entire USA has not been made.

The STATSGO database is not only amenable for exploring the national distribution of soil properties, but also for examining soil properties within LRR and among the taxa within Soil Taxonomy categories. At this time, no systematic studies of SOC and SIC partitioning by LRRs or soil orders at a national scale have been performed.

The STATSGO database used in this study is a geographic information system (GIS) based relational database compiled by the National Resources Conservation Service (NRCS), which was made by generalizing detailed soil survey data. The level of detail in STATSGO is based on its intended use for planning and management covering state, multi-state, and regional areas. Most importantly, it is the only soil database currently available for evaluating national soil resources (SCS, 1992; Reybold and Gale, 1989). The mapping scale for the STATSGO data is 1:250 000 (with the exception of Alaska) with a minimum mapping unit area of 6.25 km^2, equivalent to a square cell of 2.5 by 2.5 km. The basic structure of STATSGO is the map unit and its components. Components are the finest horizontal entities (units) for data recording. A map unit may contain 1 to 21 components. In the conterminous USA (excluding water, urban land, bare rock, and other non-soil bodies), there are 10 441 STATSGO map units (74 590 polygons) and 111 247 components (regions within the map units). For each component, its area percentage (%) within the map unit, its soil classification (Soil Survey Staff, 1999), and its properties for each soil layer ("O" horizon excluded) are reported in a relational database format by experienced local soil scientists based on soil survey results.

The purpose of this study is to calculate total SOC and SIC inventories, as well as the contents (e.g., concentrations, kg m^{-2}), within three depth intervals (0–0.2, 0–1.0, and 0–2.0 m) for the conterminous USA using the STATSGO database, and to examine the partitioning of SOC and SIC pools by natural land resource region and by soil orders in Soil Taxonomy. Our analysis of SOC expands previous STATSGO SOC analyses, and our analyses of SIC for the nation is, to our knowledge, an

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Abbreviations: GIS, geographical information system; LRR, land resource region; MRLA, major land resource areas; NRCS, Natural Resources Conservation Service; OM, organic matter; SIC, soil inorganic carbon; SOC, soil organic carbon; STATSGO, state soil geographical database.

entirely new contribution to the soil carbon inventory literature.

MATERIALS AND METHODS

Data Sources and Structure

Soil organic C is estimated from the organic matter (OM) data recorded in STATSGO as percentage in <2.0-mm size fraction. Low (OML) and high (OMH) percentage limits of the OM for each soil layer of a component are reported. SIC is given as the calcium carbonate equivalent ($CaCO_3$) percentage in the <2.0-mm size fraction ($CaCO_3$ in limestone gravel is not included). Low ($CaCO_3L$) and high ($CaCO_3H$) percentage limits of SIC for each soil layer of a component are recorded in STATSGO. The data in the 48 conterminous USA were used in the study.

Determination of Soil Carbon Storage and Variation

To calculate the soil C (SOC or SIC) storage, the OM and $CaCO_3$ data (reported on a <2.0-mm fraction) was normalized for gravel content. Soil and rock fragment fractions for each soil layer of a component are reported as inch10 (>250 mm), inch3 (75–250 mm), and 'no10' (<2.0-mm fraction from that which has passed through a 75-mm sieve). The high (H) and low (L) gravel estimates (%) for each fraction (USDA-NRCS, 2003) are recorded in STATSGO.

The low and high fractions of the soil in the <2-mm diameter fraction for a given layer of the soil components within STATSGO were calculated as follows:

$$Q_{ijkp}(L) = \left(1 - \frac{\text{Inch10}H_{ijkp}}{100} - \frac{\text{inch3}H_{ijkp}}{100}\right) \times \left(\frac{\text{no10}L_{ijkp}}{100}\right)$$

$$Q_{ijkp}(H) = \left(1 - \frac{\text{Inch10}L_{ijkp}}{100} - \frac{\text{inch3}L_{ijkp}}{100}\right) \times \left(\frac{\text{no10}L_{ijkp}}{100}\right) \quad [1]$$

Where i is the i^{th} state
j is the j^{th} map unit in the i^{th} state
k is the k^{th} component in the ij^{th} map unit
p is the p^{th} layer in the ijk^{th} component

The midpoint fraction of soil <2 mm in diameter for each layer of the component $Q_{ijkp}(M)$ as well as the rock fragment conversion factor (f_{ijkp}) used to adjust for the volume of rocks in a given layer were calculated in the way used by Bliss et al. (1995).

Soil organic C and SIC storage for each layer of a component was calculated:

$$\text{SOCT}_{ijkp}(Z) = (\text{Volume})_{ijkp} \times f_{ijkp}(Z) \times \left(\frac{\text{OM}_{ijkp}(Z)}{100}\right) \times \text{BD}_{ijkp}(Z) \times 0.58$$

$$\text{SICT}_{ijkp}(Z) = (\text{Volume})_{ijkp} \times f_{ijkp}(Z) \times \left[\frac{(\text{CaCO}_3)_{ijkp}(Z)}{100}\right] \times \text{BD}_{ijkp}(Z) \times \frac{12}{100}$$

$$(\text{Z} = \text{low limit, midpoint, high limit}) \quad [2]$$

where i,j,k and p are defined in Eq. [1]; SOCT_{ijkp} (Z) is the SOC (in Mg) of the $ijkp^{th}$ layer; $(\text{Volume})_{ijkp}$ is the layer volume (m^3) calculated by multiplying area (m^2) with depth (m); $f_{ijkp}(Z)$ is the rock fragment conversion factor; $\text{OM}_{ijkp}(Z)$ is the percent of organic matter; $\text{BD}_{ijkp}(Z)$ is the bulk density; 0.58 is the factor used to convert organic matter to organic C (Bliss et al., 1995); $\text{SICT}_{ijkp}(Z)$ is the soil inorganic C (in Mg) within the $ijkp$th layer; $\text{CaCO}_{3ijkp}(Z)$ is the percentage of $CaCO_3$; 12/100 is the conversion coefficient used to convert $CaCO_3$ to inorganic C on a molar basis.

The SOC and SIC storage in the 0- to 0.2-, 0- to 1-, and 0- to 2-m depths of each soil component was calculated by summing the SOC and SIC of the corresponding soil layers, weighted by depth.

The SOC (or SIC) content to 0.2, 1, and 2 m of each soil component (kg m^{-2}) was calculated as follows:

$$\text{SCD}_{ijk}(ZD) = \frac{\text{SCT}_{ijk}(ZD)}{(\text{Area})_{ijk}} \times 1000$$
$$(\text{Z} = \text{low limit, midpoint, high limit})$$
$$(\text{D} = 0\text{–}0.02 \text{ m}, 0\text{–}1.0 \text{ m}, 0\text{–}2.0 \text{ m}) \quad [3]$$

where i,j, and k are defined in Eq.[1]; $\text{SCD}_{ijk}(ZD)$ is SOC (or SIC) content (kg m^{-2}) of the ijk^{th} component for depth (D) and method (Z); $\text{SCT}_{ijk}(ZD)$ is total SOC (or SIC) storage (in Mg) of the ijk^{th} component for depth (D) and method (Z). $(\text{Area})_{ijk}$ is the ijk^{th} soil component area (m^2).

Total SOC (or SIC) storage $\text{SCT}_{ij}(ZD)$ and content $\text{SCD}_{ij}(ZD)$ in each map unit were estimated as follows:

$$\text{SCT}_{ij}(ZD) = \sum_{k}^{p} \text{SCT}_{ijk}(ZD)$$
$$\text{SCD}_{ij}(ZD) = \sum_{k}^{p} \frac{(\text{Area})_{ijk}}{\sum_{k}^{p} (\text{Area})_{ijk}} \times \text{SCD}_{ijk}(ZD)$$
$$(Z = \text{low limit, midpoint, high limit})$$
$$(D = 0\text{–}0.02 \text{ m}, 0\text{–}1 \text{ m}, 0\text{–}2 \text{ m}) \quad [4]$$

where p is the number of the soil components (non-soils excluded) in the ijth the map unit; SCT_{ijk}(ZD), $(\text{Area})_{ijk,}$ and $\text{SCD}_{ijk}(ZD)$ are defined in Eq. [3].

Soil organic C (or SIC) storage $\text{SCT}_i(ZD)$ and content $\text{SCD}_i(ZD)$ in the ith state were estimated as follows:

$$\text{SCT}_i(ZD) = \sum_{j}^{t} \text{SCT}_{ij}(ZD)$$
$$\text{SCD}_i(ZD) = \sum_{j}^{t} \frac{(\text{Area})_{ij}}{\sum_{l}^{t} (\text{Area})_{ij}} \times \text{SCD}_{ij}(ZD)$$
$$(\text{Z} = \text{low limit, midpoint, high limit})$$
$$(\text{D} = 0\text{–}0.02 \text{ m}, 0\text{–}1 \text{ m}, 0\text{–}2 \text{ m}) \quad [5]$$

where t is the number of the map units (non-soil bodies excluded) within the i^{th} state. SCT_{ij} (ZD) and SCD_{ij} (ZD) are defined in Eq. [4]. $(\text{Area})_{ij}$ is soil area of the ij^{th} map units.

Soil organic C (or SIC) storage SCT(ZD) and content SCD(ZD) for the conterminous USA were calculated in a way similar to Eq. [5].

The variance SCS^2 $(D)_i$, and the coefficient of variation $\text{CV}(D)_i$, of SOC (or SIC) among soil components in the i^{th} state using the midpoint approach was calculated as follows (Gnedenko and Khinchin, 1962):

$$\text{SCS}^2(D)_i = \sum_{j}^{t}\sum_{k}^{p} \frac{(\text{Area})_{ijk}}{\sum_{j}^{t}\sum_{k}^{p}(\text{Area})_{ijk}} \times [\text{SCD}(D)_{ijk}]^2 - \left[\sum_{j}^{t}\sum_{k}^{p} \frac{(\text{Area})_{ijk}}{\sum_{j}^{t}\sum_{k}^{p}(\text{Area})_{ijk}} \times \text{SCD}(D)_{ijk}\right]^2$$

$$\text{CV}(D)_i = \frac{\sqrt{\text{SCS}^2(D)_i}}{\text{SCD}(D)_i} \times 100$$
$$(D = 0\text{–}0.02 \text{ m}, 0\text{–}1 \text{ m}, 0\text{–}2 \text{ m}) \quad [6]$$

where $SCD(D)_i$ is SOC (or SIC) content in the i^{th} state; $Area_{ijk}$, and $SCD_{ijk}(D)$ are the same as those defined in Eq. [3].

The area weighted variance $SCS^2(D)$, and the coefficient of variation $CV(D)$, of SOC (or SIC) among soil components in the conterminous USA determined by the midpoint approach were calculated in a way similar to Eq. [6].

Determination of Total Soil Carbon within a Land Resource Region

Land resource regions are geographically associated land resource units defined by USDA–NRCS (USDA-SCS, 1981). Land resource regions are designated by capital letters and identified by a descriptive name. Land resource regions, A through U, with the exception of Q, are found in the conterminous 48 states. Each LRR is further divided into Major Land Resources Areas (MLRAs). We calculated the SOC (or SIC) for each MLRA. Then, the SOC (or SIC) in each LRR was calculated from the MLRAs within the LRR. The area weighted variance and coefficient of variation for SOC (or SIC) of the soil components within each LRR, and within LRRs, using the midpoint approach were determined in the way similar to the Eq. [6].

Determination of Soil Carbon Storage within Each Soil Order

The six taxonomic categories (in order of increasing detail: order, suborder, great group, subgroup, family, and series) of each soil component are given in STATSGO. We calculated the SOC and SIC storage and content for each soil order. The variance and coefficient of variation of SOC (or SIC) among soil components in each taxon of the Soil Taxonomy were estimated in the way similar to Eq. [6].

Treatment of Missing Data

Each empty record (blank or zero value) of 12 fields (OML, OMH, BDL, BDH, no10L, no10H, inch3L, inch3H, inch10L, inch10H, $CaCO_3L$, and $CaCO_3H$) was checked to determine the completeness of the dataset.

The following assumptions were used to determine if an empty record in OML and OMH fields is a missing datum: (1) OML and OMH should be zero for the following textures: WB (weathered bedrock), UWB (unweathered bedrock), CEM (cemented), and IND (indurated); (2) a zero value is acceptable for OMH if the texture is ICE (ice or frozen soil), FRAG (fragmental material), G (gravel), and CIND (cinders); (3) a zero value for OML is acceptable in mineral or inorganic, but not for organic or organic-modified textures. All other empty records were considered to be missing data if found in OML and OMH fields. If a missing datum occurs in the middle layer of a soil profile, the average OM (OML or OMH) values of its next (upper and lower) layers were used to fill in the missing data. For the remaining missing records determined in the OMH and OML fields, the method of Amichev and Galbraith (2004) was used to estimate values for the missing data.

An empty bulk density record in the BDL and BDH fields is considered to be missing data if the other soil properties such as OM (OML, OMH), no10 (no10L, no10H), etc. in the same layer have non-zero values. The missing bulk density values were first estimated according to Brejda et al. (2001). The method of Amichev and Galbraith (2004) was then used to estimate values for missing data that were unable to be determined by the method of Brejda et al.

An empty soil fraction record (<2 mm in size) in no10L and no10H fields is considered as a missing data point if the records of the other soil properties such as OM (OML, OMH) and bulk density (BDL, BDH) in the same layer have a nonzero value. If a missing data point occurs in the middle layer of a soil profile, the average no10 value (no10L or no10H) of the adjacent (upper and lower) layers was used to fill in the missing data. For the remainder of the missing data in the no10L and no10H fields, the method of Amichev and Galbraith (2004) was used to calculate the missing data.

An empty rock fragment fraction record (>250 mm is size) in the inch10L and inch10H fields is considered to be missing data if the TEXTUREs-left (rock fragment modifier) code is ST (stony), STV (very stony), STX (extremely stony), BY (bouldery), BYV (very bouldery), and BYX (extremely bouldery), indicating that the layer should contain ≥ 15% volume of stones. Missing data was assumed if there is an empty record in the smaller sized rock fragment fraction (75–250 mm in size) of the inch3L and inch3H fields when the TEXTUREs-left code is CB (cobbly), CBA (angular cobbly), CBV (very cobbly), CBX (extremely cobbly), CN (channery), CNV (very channery), CNX (extremely channery), FL (flaggy), FLV (very flaggy), and FLX (extremely flaggy). It was also assumed that a soil layer with stones should also contain smaller size rock fragments. The missing data of the rock fragment fraction (inch10L, inch10H, inch3L, and inch3H) were estimated according to Amichev and Galbraith (2004).

If all data layers of a component are empty in $CaCO_3L$ and $CaCO_3H$ fields when the soil has the formative element "Calc" at great group or subgroup taxonomy levels, or has the "carbonatic" element at family level of Soil Taxonomy, the component is considered to have at least one missing datum in the $CaCO_3L$ and CaCO3H fields. This missing component was then estimated using the average $CaCO_3L$ (or $CaCO_3H$) values of the same layer in other soil components that have the same taxon (filling in priority: the series, family, subgroup, and great group in Soil Taxonomy) within the same map unit, or within in nearby map units of the same MLRA, and or the map units of the same land resource region.

The 368 942 layers of data for 111 247 components (excluding water, urban land, bare rock, and other non-soil bodies) in STATSGO were checked, and the missing values were filled in based on the assumptions and the filling methods described above.

The original projection of STATSGO was retained except the datum was changed from NAD27 to NAD83 using ARC/INFO software (Environmental Systems Research Institute, 1998). All calculations were processed using programs written by the senior author using the visual basic language in Microsoft Access (Microsoft Corporation, 2000) and Avenue language in ArcView (Environmental Systems Research Institute, 1999).

RESULTS AND DISCUSSION

Soil Carbon by State, Resource Region, and the USA

The results of the SOC and SIC calculations for the three depth intervals are presented in Table 1. For the total reported (in STATSGO) soil area in the conterminous USA (737×10^4 km^2), the SOC and SIC sequestered in the upper 2-m ranges between 302 and 1499 $\times 10^8$ Mg and 226 to 937 $\times 10^8$ Mg, respectively. About 30% of the SOC in the upper 2 m is stored in the 0- to 0.2-m surface layer and about 80% is in the upper 1.0 m. For SIC, only about 8% was found in the surface layer, and about 50% was in the top 1.0 m. Soil inorganic C is less than SOC based on the data in STATSGO.

Table 1. Soil C storage and content in the conterminous USA by soil depth.

	Organic C							Inorganic C							
	Total storage, 10^8 Mg			Content, kg m^{-2}				Total storage, 10^8 Mg			Content, kg m^{-2}				
Depth	Min†	Mid‡	Max§	Min	Mid	Max	CV¶	Min	Mid	Max	Min	Mid	Max	CV	*r*#
cm															
0–20	116	238	392	1.57	3.23	5.31	115	18	41	71	0.25	0.56	0.96	333	0.0033
20–100	138	401	740	1.87	5.44	10.03	209	102	240	414	1.38	3.26	5.61	261	0.0004
100–200	48	187	368	0.65	2.54	4.99	321	106	260	453	1.43	3.53	6.15	279	0.0006
0–200	302	826	1499	4.09	11.20	20.33	190	226	541	937	3.07	7.34	12.71	248	0.0004

† Minimum.
‡ Midpoint.
§ Maximum.
¶ Coefficient of variation (%) among soil components with midpoint approach.
# Coefficient of correlation in soil components with midpoint approach.

However, it should be mentioned that SIC in this study refers only to SIC in <2-mm size fraction, and the $CaCO_3$ within limestone gravel is not included.

The coefficient of variation of SOC (or SIC) illustrates the relative spatial variability of SOC (or SIC) among the soil components. The relative spatial variability of SOC increases dramatically as soil depth increases, while the largest relative spatial variability of SIC is in the surface layer. No obvious linear correlation relationship between SOC and SIC, at any soil depth, was found.

Use of multiple data sources or methods to estimate the U.S. SOC pool should improve the confidence in these estimates, though STATSGO is the only national soil database presently available. In previous work, Bliss et al. (1995) used midpoint values from STATSGO to determine the SOC storage (total in the soil profile) in 40 states. Lacelle et al. (2001) generated a map of SOC in the upper 1 m of North America (the U.S. portion was again based on STATSGO midpoint values). While the midpoint value may yield reasonable stock estimates, low and high limits provide conservative bounds to the U.S. soil C stocks.

Most estimates of SOC in the USA are limited to the upper 1 m. Here, we calculated that the SOC in the upper 1.0 m of the conterminous USA ranges from 254 to 1131 $\times 10^8$ Mg, with a midpoint value of 639 $\times$ 10^8 Mg. Using laboratory data from 3700 pedons, Kern (1994) estimated that the SOC in the upper 1 m in the USA is between 621 and 845 $\times 10^8$ Mg, a range obtained by scaling up the pedon data using three approaches: ecosystem, great-group taxonomic unit, and soil map of world-based methods. In general, Kern's result is similar to our estimated midpoint value suggesting that the STATSGO data and approach are reliable for C inventory analyses.

The spatial distribution of SOC and SIC in the upper 2.0 m is presented in Fig. 1 and Fig. 2. The spatial SOC distribution is similar in most details to the map generated by Kern (1994) to 1.0 m and to the SOC map of North America by Lacelle et al. (2001). The eastern Great Plains and Midwest have the highest SOC content, though some high SOC regions in the East Coast, Gulf Coast, and Pacific Northwest also occur. For SIC, the highest SIC storage is in Texas, though the Midwest also has a high SIC storage in the Upper 2.0 m. There are some obvious SIC changes across state boundaries—for example between Iowa and South Dakota. This indicates that some SIC data might be still missing in these states or the soil survey results should be correlated between states since current results were based on surveys conducted separately in each state.

Considering the soil C by USDA-NRCS regions, about 23 to 32% of the U.S. SOC is in the Midwest, 17 to 20% in the Southeast, 18 to 19% in the Northern Plains, 15 to 16% in the West, and 13 to 15% in the South Central regions (Table 2). When C in each state is compared, Texas has the largest SOC (to 2.0 m) with 2544 to 12 509 $\times 10^6$ Mg, accounting for 8% of the total SOC in the conterminous USA. This value is followed by Minnesota (2315 to 9523 $\times 10^6$ Mg, 6 to 8%), Florida (1686 to 8734 $\times 10^6$ Mg, 6%), Michigan and Iowa (about 4% using midpoint values, respectively). In terms of the SOC content (top 2.0 m by the midpoint value), Florida has the highest average content (35.3 kg m^{-2}), followed by Minnesota (25.9 kg m^{-2}), Michigan (24.1 kg m^{-2}), Wisconsin (20.6 kg m^{-2}), and Iowa (20.5 kg m^{-2}).

The spatial pattern of SIC in the upper 2.0 m is different from that of SOC. About 37 to 40% of total SIC is in the South Central region, 23 to 26% in the West, 19% in the Northern Plains, and 14 to 20% in the Midwest regions. The East and Southeast regions have little SIC. State wise, Texas has the largest SIC with 867 832 to 3240 934 $\times 10^4$ Mg (about 35 to 38%), followed by New Mexico (about 7%, midpoint method), Montana (6%), Utah (6%), and Minnesota (5%). Analysis of the SIC content (to 2.0 m) using the midpoint approach showed that Texas has the highest SIC at 29.0 kg m^{-2}, followed by Utah (18.0 kg m^{-2}), Minnesota (14.1 kg m^{-2}), New Mexico (13.1 kg m^{-2}), and Michigan (12.2 kg m^{-2}).

It is widely recognized that SIC occurs in soils of arid and semiarid regions (Grossman et al., 1995; Schlesinger, 1997; Lal et al., 1998b; Monger and Matrinez-Rios, 2000), a pattern also observed here for the upper 1.0 m. However, when SIC to 2.0 m in soil depth is considered, our results show that there is a large SIC pool in the Midwest, where mean annual precipitation (MAP) is about 700 to 1000 mm. While the SIC in the upper 1.0 m is generally leached out in these climates (Jenny and Leonard, 1934), the deeper depth increments still retain a mixture of both primary and secondary carbonates. In the Midwest, the SIC to 2.0 m strongly correlates spatially with the extent of the last

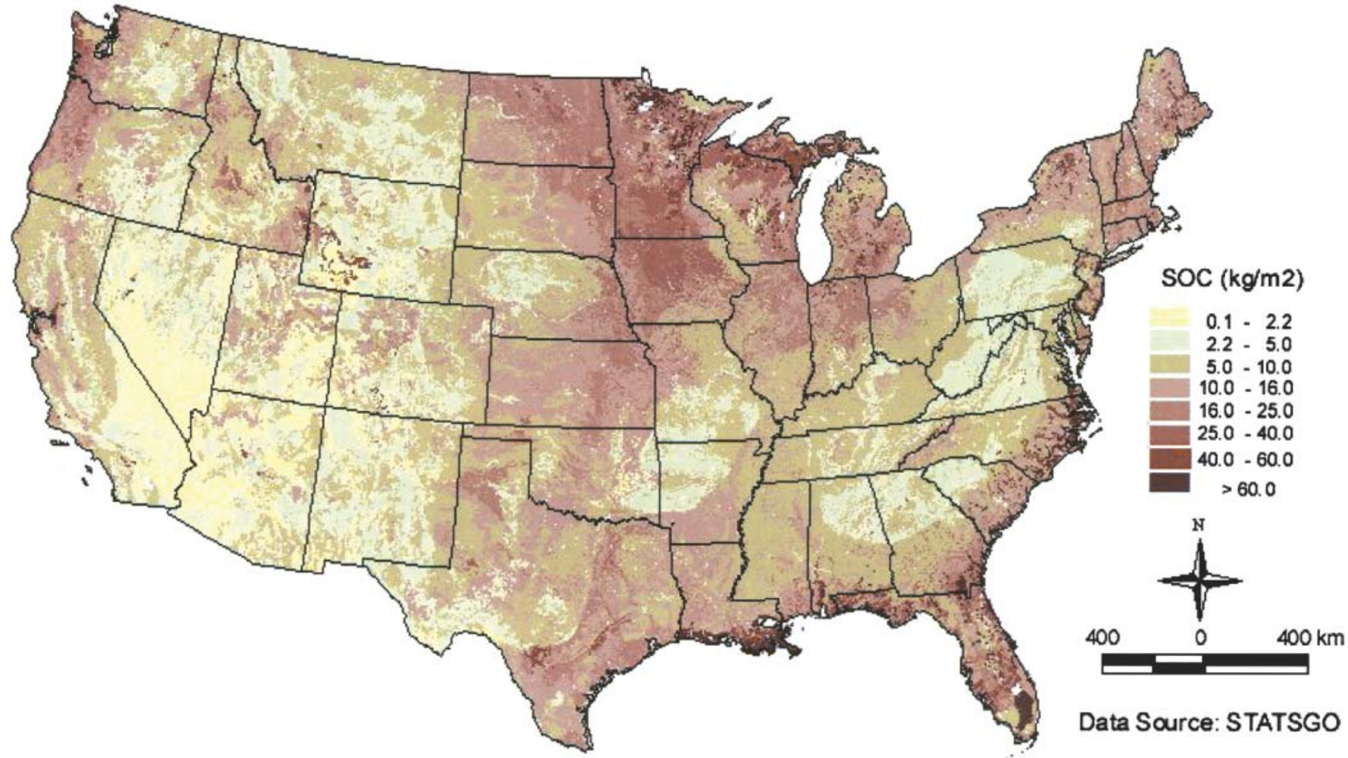

Fig. 1. Spatial distribution of soil organic C (SOC) content to 2-m soil depths in the conterminous USA (midpoint method).

glaciation (Schruben et al., 1998), suggesting these recently rejuvenated areas retain carbonate derived from calcareous sediments of various types. The SIC pattern in the south central plains (particularly Texas) matches the pattern of bedrock (Schruben et al., 1998). There is little SIC in the East and Southeast to 2.0-m depths because of the high mean annual precipitation (MAP). In contrast, there is high SIC in the West due to the arid

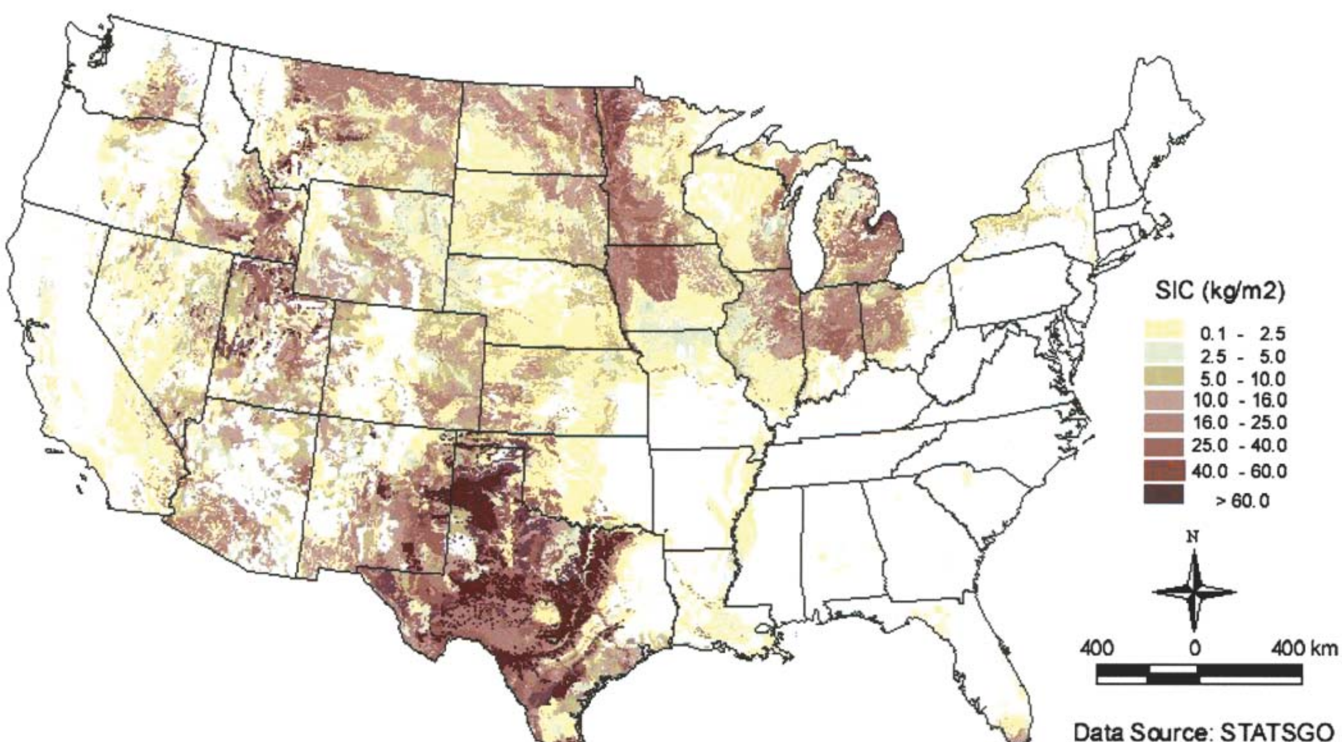

Fig. 2. Spatial distribution of soil inorganic C (SIC) content, to 2-m soil depths, in the conterminous USA (midpoint method).

and semiarid climate and to the bedrock and aerosol sources of carbonate (Monger and Matrinez-Rios, 2000).

Quantity and Spatial Variability of Soil Carbon in the Land Resource Regions

The C storage and content in each LRR are presented in Table 3. About 12 to 20% of total U.S. SOC is in LRR M (Central Feed Grains and Livestock Region) and 9 to 10% is in both the LRR T (Atlantic and Gulf Coast Lowland Forest and Crop Region) and the LRR K (Northern Lake States Forest and Forage Region) regions. The highest SOC content (2.0 m, midpoint method) is LRR U (Florida Subtropical Fruit, Truck Crop, and Range Region) with 39.6 kg m^{-2}. Other regions with remarkable SOC contents are: LRR T (Atlantic and Gulf Coast Lowland Forest and Crop Region) with 35.3 kg m^{-2}, LRR K (Northern Lake States Forest and Forage Region) with 25.2 kg m^{-2}, and LRR L (Lake States Fruit, Truck, and Dairy Region) with 20.9 kg

Table 2. Soil C storage and content in the upper 2-m depth soil of each state (region).

		Organic C							Inorganic C						
		Total storage, 10^6 Mg			Content, kg m^{-2}				Total storage, 10^4 Mg			Content, kg m^{-2}			
States (Regions)	Area†	Min‡	Mid§	Max¶	Min	Mid	Max	CV#	Min	Mid	Max	Min	Mid	Max	CV
	km^2														
Connecticut	12 406	50	195	423	4.1	15.7	34.1	196	14	84	200	0.0	0.1	0.2	2204
Delaware	5 043	28	134	290	5.6	26.6	57.5	190	0	0	0	0.0	0.0	0.0	
Massachusetts	18 918	75	324	696	4.0	17.1	36.8	173	1	53	130	0.0	0.0	0.1	1822
Maryland	25 266	83	338	724	3.3	13.4	28.7	271	0	0	0	0.0	0.0	0.0	
Maine	80 584	422	1 331	2 676	5.2	16.5	33.2	160	20	77	156	0.0	0.0	0.0	4970
New Hampshire	22 801	68	357	807	3.0	15.6	35.4	122	0	8	19	0.0	0.0	0.0	4012
New Jersey	17 788	105	295	588	5.9	16.6	33.0	171	1	47	112	0.0	0.0	0.1	1587
New York	118 432	480	1 595	3 236	4.1	13.5	27.3	135	2 321	15 149	34 835	0.2	1.3	2.9	320
Pennsylvania	115 291	168	683	1 481	1.5	5.9	12.8	95	0	321	892	0.0	0.0	0.1	2027
Rhode Island	2 583	13	45	96	5.1	17.5	37.1	174	0	2	5	0.0	0.0	0.0	834
Vermont	23 764	65	344	775	2.7	14.5	32.6	90	263	1 312	2 951	0.1	0.6	1.2	796
West Virginia	61 448	65	296	640	1.1	4.8	10.4	43	53	253	472	0.0	0.0	0.1	2835
(East)	504 325	1 622	5 937	12 431	3.2	11.8	24.6	175	2 674	17 306	39 773	0.1	0.3	0.8	682
Iowa	143 801	1 915	2 944	4 087	13.3	20.5	28.4	74	40 155	167 537	314 423	2.8	11.7	21.9	118
Illinois	143 948	914	1 828	2 889	6.3	12.7	20.1	84	14 878	107 565	222 676	1.0	7.5	15.5	138
Indiana	93 584	534	1 309	2 273	5.7	14.0	24.3	189	35 224	110 397	205 506	3.8	11.8	22.0	123
Michigan	147 532	1 655	3 561	5 978	11.2	24.1	40.5	182	74 503	179 879	318 875	5.0	12.2	21.6	130
Minnesota	209 223	2 315	5 416	9 523	11.1	25.9	45.5	119	110 233	295 235	523 666	5.3	14.1	25.0	125
Missouri	177 484	665	1 557	2 698	3.7	8.8	15.2	82	2 647	21 428	43 194	0.1	1.2	2.4	404
Ohio	105 442	339	1 071	2 025	3.2	10.2	19.2	121	21 220	66 209	124 664	2.0	6.3	11.8	192
Wisconsin	140 542	1 251	2 889	5 077	8.9	20.6	36.1	184	11 383	55 132	116 698	0.8	3.9	8.3	229
(Midwest)	1 161 556	9 587	20 574	34 550	8.3	17.7	29.7	155	310 243	1 003 383	1 869 702	2.7	8.6	16.1	159
Arkansas	135 832	337	1 075	2 031	2.5	7.9	15.0	60	566	4 653	9 739	0.0	0.3	0.7	646
Louisiana	109 273	446	2 180	4 765	4.1	20.0	43.6	155	4 084	17 525	34 661	0.4	1.6	3.2	502
Oklahoma	176 647	579	1 675	3 006	3.3	9.5	17.0	70	41 115	93 171	156 070	2.3	5.3	8.8	331
Texas	660 649	2 544	7 002	12 509	3.9	10.6	18.9	82	867 832	1 918 841	3 240 934	13.1	29.0	49.1	133
(South Central)	1 082 402	3 905	11 932	22 312	3.6	11.0	20.6	115	913 597	2 034 190	3 441 404	8.4	18.8	31.8	179
Alabama	130 948	336	1 207	2 312	2.6	9.2	17.7	265	199	350	525	0.0	0.0	0.0	2481
Florida	136 490	1 686	4 816	8 734	12.4	35.3	64.0	180	4 815	8 572	13 161	0.4	0.6	1.0	758
Georgia	149 285	658	2 015	3 684	4.4	13.5	24.7	249	379	1 119	2 002	0.0	0.1	0.1	1081
Kentucky	101 847	194	742	1 482	1.9	7.3	14.6	56	341	1 466	2 726	0.0	0.1	0.3	1273
Mississippi	122 583	279	1 279	2 475	2.3	10.4	20.2	256	0	3 411	7 708	0.0	0.3	0.6	427
North Carolina	125 522	1 044	2 789	5 046	8.3	22.2	40.2	245	0	67	148	0.0	0.0	0.0	2840
South Carolina	78 489	413	1 410	2 638	5.3	18.0	33.6	237	513	1 483	2 642	0.1	0.2	0.3	680
Tennessee	104 277	168	738	1 484	1.6	7.1	14.2	61	3	319	715	0.0	0.0	0.1	1306
Virginia	102 714	216	824	1 625	2.1	8.0	15.8	301	0	212	468	0.0	0.0	0.0	1441
(Southeast)	1 052 154	4 993	15 819	29 479	4.7	15.0	28.0	255	6 249	16 998	30 095	0.1	0.2	0.3	1202
Colorado	253 888	631	1 739	3 136	2.5	6.8	12.4	161	50 653	144 537	256 260	2.0	5.7	10.1	191
Kansas	212 325	1 120	2 776	4 653	5.3	13.1	21.9	51	54 371	100 554	153 816	2.6	4.7	7.2	230
Montana	350 837	874	2 287	4 168	2.5	6.5	11.9	99	162 908	340 038	574 851	4.6	9.7	16.4	156
North Dakota	178 589	924	2 869	5 316	5.2	16.1	29.8	53	67 613	181 420	325 895	3.8	10.2	18.2	156
Nebraska	198 419	796	1 985	3 319	4.0	10.0	16.7	68	9 010	49 848	96 853	0.5	2.5	4.9	235
South Dakota	191 914	823	2 295	4 043	4.3	12.0	21.1	64	40 247	106 339	185 273	2.1	5.5	9.7	201
Wyoming	229 275	389	1 340	2 511	1.7	5.8	11.0	259	55 411	132 376	226 474	2.4	5.8	9.9	175
(Northern Plains)	1 615 247	5 556	15 292	27 147	3.4	9.5	16.8	105	440 213	1 055 112	1 819 422	2.7	6.5	11.3	188
Arizona	266 867	218	1 001	1 979	0.8	3.8	7.4	90	67 154	195 767	357 557	2.5	7.3	13.4	165
California	353 973	892	2 680	4 843	2.5	7.6	13.7	252	15 451	40 133	75 087	0.4	1.1	2.1	542
Idaho	197 155	660	1 836	3 430	3.3	9.3	17.4	128	70 248	159 972	281 553	3.6	8.1	14.3	193
New Mexico	284 358	338	1 491	2 898	1.2	5.2	10.2	93	177 792	371 331	612 609	6.3	13.1	21.5	189
Nevada	269 415	243	891	1 764	0.9	3.3	6.5	168	48 777	108 776	188 662	1.8	4.0	7.0	277
Oregon	239 876	1 016	2 388	4 194	4.2	10.0	17.5	91	14 818	31 231	51 805	0.6	1.3	2.2	419
Utah	185 030	398	1 047	1 873	2.2	5.7	10.1	120	170 462	332 320	529 510	9.2	18.0	28.6	152
Washington	161 881	728	1 709	3 016	4.5	10.6	18.6	129	23 579	47 480	76 557	1.5	2.9	4.7	282
(West)	1 958 556	4 492	13 043	23 998	2.3	6.7	12.3	168	588 282	1 287 010	2 173 340	3.0	6.6	11.1	248

† Soil area reported in STATSGO that excludes water, urban, bare rock, and other non-soil bodies.
‡ Minimum.
§ Midpoint.
¶ Maximum.
# Coefficient of variation (%) among soil components in each state (region) with midpoint approach.

Table 3. Soil C storage and content in the upper 2-m depth soil of Land Resources Regions (LRRs).

		Organic C						Inorganic C					
		Total storage, 10^6 Mg			Content, kg m^{-2}			Total storage, 10^4 Mg			Content, kg m^{-2}		
LRRs	Area†	Min‡	Mid§	Max¶	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max
	km^2												
A	181 215	1 058	2 576	4 583	5.8	14.2	25.3	7	166	466	0.0	0.0	0.0
B	259 284	861	2 033	3 564	3.3	7.8	13.7	95 124	204 258	346 910	3.7	7.9	13.4
C	146 884	530	1 476	2 523	3.6	10.1	17.2	2 149	5 989	10 315	0.1	0.4	0.7
D	1 268 922	1 571	5 644	10 839	1.2	4.4	8.5	509 899	1 148 860	1 961 895	4.0	9.1	15.5
E	521 994	1 459	4 114	7 783	2.8	7.9	14.9	88 883	193 339	339 461	1.7	3.7	6.5
F	351 842	1 645	4 807	8 750	4.7	13.7	24.9	173 262	418 782	730 236	4.9	11.9	20.8
G	521 442	1 070	3 141	5 579	2.1	6.0	10.7	153 627	369 138	624 753	2.9	7.1	12.0
H	583 820	2 320	6 440	11 218	4.0	11.0	19.2	443 497	967 082	1 607 667	7.6	16.6	27.5
I	169 689	616	1 697	3 131	3.6	10.0	18.4	252 231	590 386	1 027 697	14.9	34.8	60.6
J	139 624	635	1 649	2 868	4.5	11.8	20.5	212 092	413 207	657 484	15.2	29.6	47.1
K	300 269	3 136	7 559	13 557	10.4	25.2	45.1	58 618	197 945	384 521	2.0	6.6	12.8
L	119 997	1 119	2 503	4 269	9.3	20.9	35.6	58 287	140 490	248 896	4.9	11.7	20.7
M	717 615	6 031	11 679	18 287	8.4	16.3	25.5	185 435	663 473	1 240 558	2.6	9.2	17.3
N	603 434	933	3 595	7 406	1.5	6.0	12.3	782	5 365	11 814	0.0	0.1	0.2
O	94 652	269	1 029	2 037	2.8	10.9	21.5	3 418	19 869	40 275	0.4	2.1	4.3
P	677 160	1 702	6 173	11 581	2.5	9.1	17.1	1 509	4 862	8 884	0.0	0.1	0.1
R	300 536	1 147	4 185	8 750	3.8	13.9	29.1	921	7 656	17 945	0.0	0.3	0.6
S	99 147	217	743	1 546	2.2	7.5	15.6	0	65	213	0.0	0.0	0.0
T	231 303	2 674	8 166	15 492	11.6	35.3	67.0	16 700	54 611	100 832	0.7	2.4	4.4
U	85 410	1 161	3 386	6 157	13.6	39.6	72.1	4 815	8 458	12 914	0.6	1.0	1.5

† Soil area having Land Resources Region (LRRs) information reported in STATSGO.
‡ Minimum.
§ Midpoint.
¶ Maximum.

m^{-2}. In terms of SIC, 21 to 23% of the total is in LRR D (Western Range and Irrigated Region), 17 to 20% is in LRR H (Central Great Plains Winter Wheat and Range Region), and 8 to 13% is in LRR M (Central Feed Grains and Livestock Region). The highest SIC contents (to 2.0 m by midpoint) are in the LRR I (Southwest Plateaus and Plains Range and Cotton Region) with 34.8 kg m^{-2}, LRR J (Southwestern Prairies Cotton and Forage Region) with 29.6 kg m^{-2}, and LRR H (Central Great Plains Winter Wheat and Range Region) with 16.6 kg m^{-2}.

The spatial variability of SOC and SIC for the soil components in each LRR (three depths) is presented in Table 4. In most LRRs, as soil depth increases, the coefficient of variation of SOC in each LRR increases but that of SIC decreases. The variability of SOC and SIC varies with LRRs. The LRR C has the largest variability of SOC among the LRRs. Land resource region U, LRR T, LRR K, and LRR L have the highest SOC contents (Table 3), as well as the highest SOC variability. In contrast, LRR I and LRR J have relatively lower SIC variability although the

Table 4. Spatial variability of soil C within each land Resource Region (LRR).

		Organic C								Inorganic C							
		0–20 cm			0–100 cm			0–200 cm		0–20 cm			0–100 cm			0–200 cm	
LRR	Number of soil comp.†	Mean‡	Std§	CV¶	Mean	Std	CV	Std	CV	Mean	Std	CV	Mean	Std	CV	Std	CV
A	3 040	5.51	5.1	93	12.64	11.3	90	13.9	98	0.00	0.0	3631	0.01	0.3	3409	0.3	3406
B	5 465	2.50	1.7	68	6.67	6.4	95	8.3	106	0.44	1.4	327	4.48	8.9	199	14.6	186
C	4 621	3.12	3.9	124	8.17	17.9	218	27.7	276	0.03	0.3	850	0.24	1.5	650	2.4	587
D	17 318	1.37	1.6	116	3.52	5.2	148	7.4	166	1.11	2.4	216	5.73	11.2	195	18.7	207
E	9 142	2.81	2.7	97	6.65	8.8	132	12.5	158	0.28	1.1	399	2.37	7.8	327	12.2	329
F	4 378	4.95	2.9	59	11.70	7.2	61	8.2	60	0.53	1.2	220	7.28	10.0	137	15.4	130
G	6 555	2.03	1.2	58	4.96	3.1	63	3.9	64	0.73	1.7	230	4.61	8.3	179	13.3	188
H	6 613	2.67	1.2	46	7.97	4.2	53	6.4	58	0.75	2.0	269	6.54	13.4	206	30.0	181
I	1 460	2.42	1.0	43	7.05	6.2	88	10.9	109	4.46	4.8	107	19.47	21.9	113	41.5	119
J	1 285	2.36	1.2	52	8.05	6.0	75	9.1	77	2.80	4.6	166	15.53	24.2	156	42.9	145
K	4 608	6.50	7.5	116	19.43	28.8	148	39.6	157	0.09	0.5	549	2.72	6.2	227	11.9	181
L	1 939	6.19	6.0	97	15.98	26.0	163	38.2	183	0.07	0.5	777	3.75	6.8	182	15.5	132
M	9 413	4.96	3.1	63	13.48	12.6	93	16.9	104	0.28	1.0	375	3.39	7.2	212	13.5	146
N	10 048	2.48	1.3	52	5.00	3.1	61	3.9	65	0.01	0.1	2125	0.04	0.7	1821	1.4	1587
O	2 038	3.23	2.1	64	8.01	8.1	101	13.9	127	0.05	0.4	793	1.10	2.9	261	5.8	278
P	9 791	2.20	1.9	85	6.09	9.0	147	16.2	178	0.01	0.1	2480	0.03	0.7	2110	1.2	1639
R	7 708	4.81	4.7	98	11.25	14.5	129	20.9	150	0.01	0.1	1554	0.08	0.8	925	2.2	858
S	2 183	3.04	2.5	81	6.19	12.4	201	15.2	202	0.00	0.0	5299	0.00	0.2	4165	0.3	4069
T	3 100	6.10	7.4	122	22.70	37.6	166	63.7	180	0.09	0.5	559	0.99	3.9	398	8.5	360
U	542	7.79	10.7	137	28.97	52.6	181	66.6	168	0.32	2.1	635	0.87	5.5	635	6.0	605
Weighted average within LRR's		3.23	3.3	103	8.66	13.5	156	19.9	178	0.56	1.7	302	3.82	9.1	239	16.7	228

† The number of soil components having the Land Resource Region information reported in STATSGO.
‡ Mean (kg m^{-2}) among soil components within each LRR with midpoint approach. The means of 0–200 cm were presented as midpoint values in Table 3.
§ Std: Standard deviation (kg m^{-2}) among soil components within each LRR with midpoint approach.
¶ CV: Coefficient of variation (%) among soil components within each LRR with midpoint approach.

highest SIC contents are found here. The area-weighted coefficient of variation of SOC within each LRR at the 0- to 0.2-, 0- to 1.0-, and 0- to 2.0-m depth increments is 103, 156, and 178%, respectively, while the area-weighted coefficient of variation of SIC is 302, 239, and 228%, respectively. The greater variability of SIC contents compared with SOC might be explained by the fact that SOC is determined by the balance of C inputs and losses—which is generally climatically controlled. In contrast, the SIC content is also climatically driven, but depends additionally on parent material composition, location relative to dust sources, and age, all of which add considerably to the spatial variability of SIC in soils.

One common method for calculating total SOC is to multiply the mean content of SOC by the area of a certain land use/cover or an ecosystem type. To estimate the mean SOC content, soil (pedon) data for each land use/cover or ecosystem are used (Post et al., 1982). Although the method is very useful for estimating SOC under different ecosystems and climates and for evaluating the impact of climate change on SOC pools, the accuracy of total SOC estimates obtained by this method is very variable. Based on the SOC of 111 247 soil components, we found that the area-weighed coefficients of variation for SOC at the 1.0- and 2.0-m depths within each LRR of the conterminous USA are 156 and 178%, respectively. This analysis is based on the assumption that the SOC in each soil component of STATSGO is homogeneous (the variance of SOC or SIC within a soil component cannot be estimated since only low and high limits of SOC or SIC are reported for each layer of component in STATSGO). The variability of SOC will be larger if variability of SOC in each soil component can be analyzed. However, no such data is presently available. As we discuss below (Table 7), these values of variance are larger than those arrived at through soil C tabulations made by soil taxa.

Quantity and Spatial Variability of Soil Carbon in Soil Orders

The SOC and SIC sequestered in each soil order of the USA is presented in Table 5. Due both to its large area (27% of the soil area in the conterminous USA) and modest SOC contents, SOC in Mollisols accounts for about 31 to 39% of the total U.S. SOC stock (11 843 to 46 102 × 10^6Mg), followed by Histosols (17–23%), Alfisols (10–12%), and Entisols (6–11%). Considering the SOC content to 2 m (midpoint approach), Histosols have the highest content (140.1 kg m^{-2}), followed by Vertisols (14.7 kg m^{-2}), Mollisols (13.5 kg m^{-2}), and Andisols (10.7 kg m^{-2}). Aridisols have the lowest SOC content with only 4.0 kg m^{-2}.

There is zero SIC in Ultisols and very little in Andisols, which contributed essentially no SIC to the national stock. Mollisols contain 9908 to 39 894 ×10^6 Mg of SIC, accounting for 43 to 44% of the national total. Aridsols are second with 5630 to 22 135 ×10^6 (24–25%), followed by Alfisols and Entisols (7–11% and 9%, respectively). In terms of SIC content, Vertisols have the highest mass at 23.2 kg m^{-2} (midpoint value), Aridisols are second with 15.9 kg m^{-2}, and Mollisols are third (11.5 kg m^{-2}).

The patterns of SOC and SIC storage vs. soil depth vary with the soil orders. Inceptisols and Alfisols have 35 and 39% (midpoint value) of their SOC in the upper 0.2 m, while only 16% of SOC is in the upper 0.2 m of Histosols. Unlike SOC, most of the SIC storage is in the deeper layers. However, there are some exceptions: Andisols and Entisols have 19 and 15% (midpoint value) of their total SIC in the upper 0.2 m.

There is a large spatial variability of SOC and SIC in each order and at all depths (Table 6). Standard deviation (Std) describes the absolute variability of SOC and SIC within each order, and the coefficient of variation indicates the relative variability of SOC and SIC, which can be used to compare the differences in the variation of SOC and SIC among the orders, since the means of SOC (or SIC) in each order are different. Entisols and Inceptisols have the largest CV (or relative variability) among the orders. In terms of SIC, Andisols and Spodosols have the smallest standard deviation due to their very low SIC content. Relative variability of SIC is much larger than that of SOC within any order.

The area-weighted variability of soil C within the taxa of any categorical level is reported in Table 7. The standard deviation of soil C (both SOC and SIC) in taxa decreases as the taxonomic category decreases (e.g.,

Table 5. Carbon storage and content in the upper 2 m of the soil orders.

		Organic C						Inorganic C					
		Total storage, 10^6 Mg			Content, kg m^{-2}			Total storage, 10^6 Mg			Content, kg m^{-2}		
Orders	Area†	Min‡	Mid§	Max¶	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max
	km^2												
Alfisols	1 274 102	2 964	9 603	17 974	2.3	7.5	14.1	1 649	5461	10 296	1.3	4.3	8.1
Andisols	68 666	327	731	1 286	4.8	10.7	18.7	1	2	3	0.0	0.0	0.0
Aridisols	809 423	942	3 260	6 179	1.2	4.0	7.6	5 630	12 890	22 135	7.0	15.9	27.3
Entisols	1 054 015	1 927	8 419	16 645	1.8	8.0	15.8	1 995	5 112	8 901	1.9	4.8	8.4
Histosols	107 249	6 852	15 022	26 157	63.9	140.1	243.9	63	260	534	0.6	2.4	5.0
Inceptisols	787 254	2 194	7 011	13 705	2.8	8.9	17.4	1 956	4 006	6 612	2.5	5.1	8.4
Mollisols	2 020 694	11 843	27 308	46 102	5.9	13.5	22.8	9 908	23 181	39 894	4.9	11.5	19.7
Spodosols	250 133	721	3071	6 379	2.9	12.3	25.5	50	149	282	0.2	0.6	1.1
Ultisols	860 170	1 636	6 125	11 927	1.9	7.1	13.9	0	0	0	0.0	0.0	0.0
Vertisols	132 433	712	1 941	3 371	5.4	14.7	25.5	1 360	3 075	5 072	10.3	23.2	38.3

† Soil area with taxonomic information reported in STATSGO.
‡ Minimum.
§ Midpoint.
¶ Maximum.

Table 6. Spatial variability of soil carbon in each soil order.

		Organic C								Inorganic C							
		0–20 cm			0–100 cm			0–200 cm		0–20 cm			0–100 cm			0–200 cm	
Order	Number of soil comp.¶	Mean§	Std†	CV‡	Mean	Std	CV	Std	CV	Mean	Std	CV	Mean	Std	CV	Std	CV
Alfisols	18 658	2.62	1.5	59	5.86	3.2	54	4.3	56	0.03	0.2	938	1.36	4.5	335	10.6	247
Andisols	798	3.48	2.6	74	9.20	6.8	74	8.2	77	0.01	0.1	1795	0.02	0.4	1949	0.5	1989
Aridisols	9 909	1.19	0.7	61	3.07	1.9	62	2.8	68	1.50	2.7	178	9.49	13.1	138	23.1	145
Entisols	16 724	1.91	2.7	142	5.42	11.4	211	20.6	258	0.76	2.0	257	3.30	8.7	263	13.2	273
Histosols	1 692	22.81	10.1	44	97.55	50.3	52	75.9	54	0.01	0.1	1539	0.91	2.9	317	7.4	305
Inceptisols	14 154	3.45	4.0	116	7.39	8.4	113	10.8	121	0.43	2.1	489	3.11	12.1	388	19.6	386
Mollisols	31 990	4.31	2.5	58	11.26	8.0	71	10.3	76	0.77	2.2	290	5.56	11.5	207	22.4	195
Spodosols	3 629	3.70	2.0	53	9.86	5.2	53	7.6	62	0.00	0.0	5361	0.17	1.1	652	3.5	594
Ultisols	11 788	2.31	1.6	71	5.35	3.8	71	4.7	66	0.00			0.00				
Vertisols	1 642	3.14	1.2	38	10.62	6.1	58	9.4	64	1.41	2.0	144	10.67	14.7	138	33.0	142

¶ The number of soil components having the Land Resource Region information reported in STATSGO.
§ Mean (kg m^{-2}) among soil components within each LRR with midpoint approach. The means of 0–200 cm were presented as midpoint values in Table 5.
† Std: Standard deviation (kg m^{-2}) among soil components within each LRR with midpoint approach.
‡ CV: Coefficient of variation (%) among soil components within each LRR with midpoint approach.

order to series). The relative variability (CV) of SIC is larger than that of SOC at each depth and taxonomic category. Relative variability increases in SOC but decreases in SIC as soil depth increases for all taxonomic categories (except for soil series in SOC).

The area-weighted variability of SOC in taxa at each taxonomic categorical level of each order is presented in Fig. 3. The variability of SOC in taxa decreases as taxonomic category decreases in all soil orders, which is especially obvious moving from the family to the series categories. In Entisols and Inceptisols, variability in taxa, at any taxonomic level, is larger than that in the other soil orders.

Estimation of SOC based on Soil Taxonomy is another common approach for estimating the SOC pool of a nation or the world. Order or suborder taxa have been used to estimate the world SOC pool (Eswaran et al., 1993, 1995; Lal et al., 1998a). Likewise, taxa in the great-group category have been used to estimate the SOC pool in the conterminous USA (Kern, 1994). Results obtained in this study indicate that estimates of SOC based on taxa in the lower taxonomic levels will have higher accuracy if the sample size is fixed (Table 7). However, for large geographic areas, it is not feasible to use taxa in lower taxonomic levels since there may be too many taxa to practically evaluate. If taxa in higher taxonomic levels are used for estimating SOC, the larger the number of pedon data used, the greater the accuracy of the estimate. Due to high variability, there will be especially large inaccuracies in SIC estimations based on taxa at higher taxonomic categories. In contrast, SIC estimates made from series categories will be accurate, though subject to limitations posed by large amounts of data if applied to large spatial areas (Table 7).

The results obtained in this study (based on the analysis of 111 247 soil components) suggest that predicting the SOC pool using the LRR-based method will require a larger sample size than the taxonomy-based method to arrive at similar levels of accuracy. The coefficient of variation for SOC in LRRs is 103, 156, and 178% for the 0.2-, 1-, and 2-m depths, respectively (Table 4). In contrast, the coefficient of variation for SOC in the orders is 82, 107, and 125% for the same depths (Table 7), a modest improvement over the LRR approach. The

Table 7. Area-weighted variability of soil C in the taxa of each taxonomic category by depth.

	Taxonomy		Organic C			Inorganic C		
Depth	Category	Number of taxa	Std†	Mean‡	CV§	Std	Mean	CV
cm			%	kg m^{-2}		kg m^{-2}	%	
0–20	Order	10	2.64	3.22	82	1.80	0.56	322
	Suborder	48	2.32	3.22	72	1.71	0.56	305
	Great group	206	2.04	3.22	63	1.44	0.56	257
	Subgroup	1 057	1.71	3.21	53	1.28	0.56	227
	Family	5 959	1.20	3.21	37	0.59	0.56	105
	Series	12 788	0.61	3.21	19	0.38	0.56	67
0–100	Order	10	9.30	8.66	107	9.43	3.82	247
	Suborder	48	8.55	8.66	99	9.04	3.82	237
	Great group	206	7.41	8.64	86	7.89	3.82	207
	Subgroup	1 057	6.25	8.59	73	6.64	3.83	173
	Family	5 959	3.97	8.59	46	3.33	3.83	87
	Series	12 788	1.46	8.59	17	1.70	3.83	44
0–200	Order	10	14.02	11.20	125	17.40	7.35	237
	Suborder	48	13.12	11.20	117	16.70	7.35	227
	Great group	206	11.10	11.16	99	14.91	7.35	203
	Subgroup	1 057	9.17	11.08	83	12.65	7.38	171
	Family	5 959	5.60	11.08	51	6.62	7.38	90
	Series	12 788	2.26	11.08	20	2.91	7.38	39

† Std: Area-weighted standard deviation (kg m^{-2}) among soil components in each taxa with midpoint approach.
‡ Mean: Mean content of soil components with midpoint approach.
§ CV: Area-weighted coefficient of variation (%) among soil components in each taxa with midpoint approach.

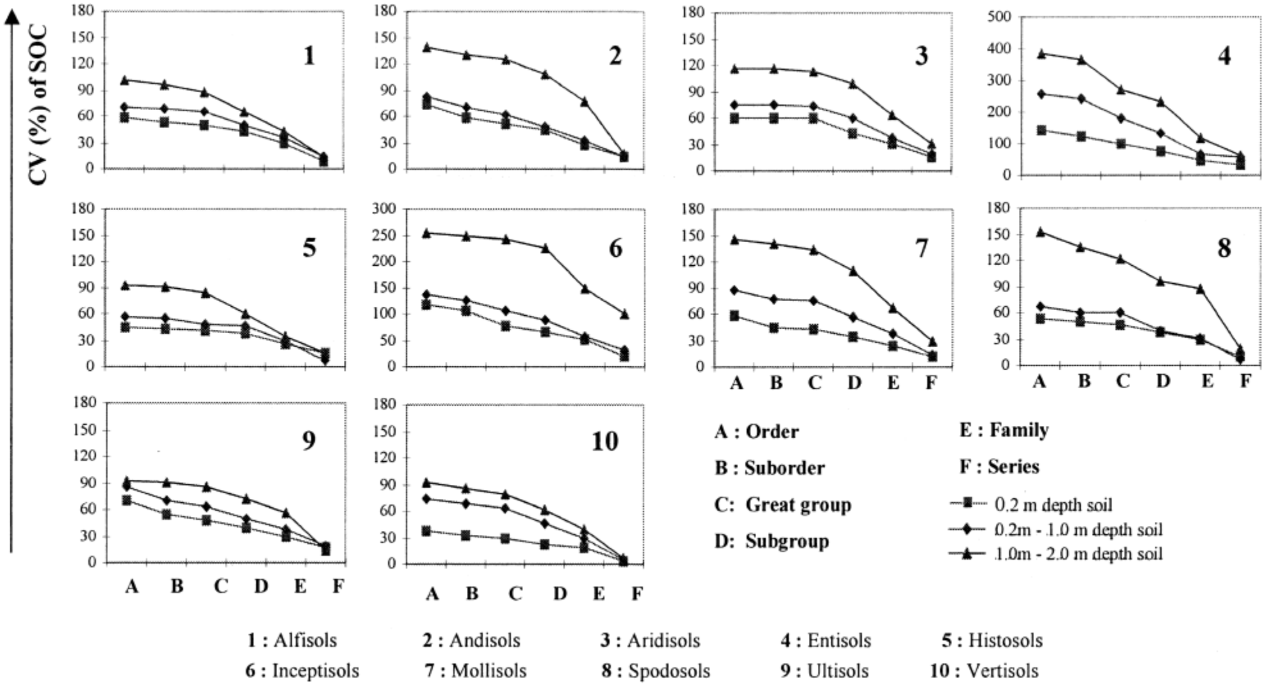

Fig. 3. Coefficient of variation (CV) of soil organic carbon (SOC) among soil components in taxa of each taxonomic category of each soil order, by soil depth (midpoint method).

coefficient of variation for SOC substantially decreases when estimates are based on soil order approach. This is undoubtedly due to the fact that taxonomic designations are successful at grouping soils of similar characteristics, whereas resource regions may indeed have one dominant state factor, while many others (which may have affects on soil C pools) vary considerably. Therefore, a higher accuracy estimate of SOC can be expected when taxa of lower taxonomic categories are used to estimate the SOC pool over a geographical area.

CONCLUSIONS

In this paper, the range of SOC and SIC in the USA was estimated using the STATSGO. Our analysis of SOC compliments previous studies using STATSGO by including the low and high limits in soil C estimates, the evaluation of C to greater soil depths, and by examining the variability in the data. Our analysis of SIC at a national scale was an exercise to contribute to the soil carbon inventory literature based on the STATSGO data.

To estimate soil C for a large area, we have observed that LRR (land cover or ecosystems)-based methods will need a larger sample size than the taxonomy-based method to achieve the same level of accuracy since the variation of SOC in a LRR population is larger than that in the Soil Taxonomy population. Variation within soil taxa becomes smaller as taxonomic category becomes more detailed, especially from the family to the series categories. Due to high variability, there will be especially large inaccuracies in SIC estimations based on taxa at higher taxonomic categories. An unanticipated finding was that a substantial SIC pool exists in the central USA between depths of 1 to 2 m. When SIC in the 2.0-m soil is considered, a large SIC pool was found in the Midwest where the mean annual precipitation (MAP) is about 700 to 1000 mm. While the SIC in the upper 1.0 m is generally leached out in these climates, the deeper depth increment still retains some combination of primary and secondary carbonates.

We conclude by noting that the patterns of SOC and SIC across the landscape are determined by the widely varying combinations of vegetation, climate (precipitation and temperature), topography, soil parent materials, and landform age (Jenny, 1994) that occur across the country. In this paper we have first focused only on soil C storage and its partitioning among LRRs and soil orders, with little discussion as to why the trends are present. In a companion paper, we examine the factors controlling soil C distribution and discuss the implications with respect to global change and land use activities.

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