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Analysis of Factors Controlling Soil Carbon in the Conterminous United States

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ABSTRACT

Maps of soil organic carbon (SOC) and inorganic carbon (SIC) were generated from the State Soil Geographical database (STATSGO) and were overlain with land-cover, topography (elevation and slope), mean annual precipitation (MAP), and mean annual temperature (MAT) databases to study the effects of environmental driving factors (or "state factors") in the conterminous USA. In the USA, human disturbance has significantly reduced SOC and SIC in the surface layer. The SOC decreases as elevation increases. Level topography has twice the SOC content of other slope classes. Soil organic C increases as MAP increases up to values of 700–850 mm yr^{-1}. There is no obvious pattern in SIC as MAP increases until MAP exceeds 1000 mm, at which point on SIC drops dramatically. For natural vegetation with MAP < 1000 mm, SOC decreases as MAT increases (within restricted ranges of elevation and topography). The relationship between SOC versus MAT varies with MAP, and SOC is most sensitive to temperature in low and moderate MAP regions and in the upper soil layers. This GIS-based analysis is a relatively coarse evaluation given the nature of the database, but does provide a first quantitative assessment of soil C to "state factors" for the USA as a whole using commonly available digital databases.

Soils and soil properties are known to be determined by the configuration of environmental, or state factors at a given location (Jenny, 1980). Soil C is one of many soil properties, but is a property of considerable interest in the rapidly growing human modification of the planet because a small change in this pool may have a major impact on the atmosphere (Birdsey et al., 1993; Turner et al., 1998).

Globally, land cover and land use change induced by deforestation and agriculture, is believed to be a major cause of rising CO_2 in the atmosphere (Adge and Brown, 1994; Lal et al., 1998a). In the USA, most soil C loss through land use occurred in the 19th and early 20th centuries. Now, efforts are focused on how existing stocks will respond to climate change, increased N deposition, and management.

Soil inorganic C is an additional large C pool in U.S. soils (Guo et al., 2006), one that has residence times that make it a less immediate environmental concern, but a C pool that is nonetheless susceptible to decadal scale management effects (Magaritz and Amiel, 1981; Amundson and Lund, 1987). Little is known about SIC pools within ecosystems at the national scale (Lal et al., 1998b), and the relationship to environmental factors has not yet been fully explored.

There is a wealth of previous soils research on C and N storage as a function of climate (Post et al., 1982; Nichols, 1984; Burke et al., 1989) and topography (Burke et al., 1991; Homann et al., 1995; Garten et al., 1999; Hontoria et al., 1999; Bolstad and Vose, 2001; Chaplot et al., 2001) at local to regional levels. The work clearly demonstrates fundamental relationships using (in some of the studies) carefully collected samples and site selection as a means of evaluating the effects of individual factors. Our goal here is to approach soil C/factor analyses from an entirely different spatial scale, that is, from the perspective of the forest rather than an individual tree, using data sets that lack local detail but that allow us to examine soil C storage, and the factors that control it, at a national to subcontinental scale. To do so, we used the soil survey data of STATSGO to calculate the SOC and SIC for the conterminous USA. Through overlays of SOC (and SIC) on georeferenced (spatially compatible) national land cover data (NLCD), topography, MAP, and MAT, we explored the effects of state factors on SOC and SIC at a national scale. We were able, to a certain degree, to examine the effect of individual factors on soil C distribution by controlling the range in variations of the other factors. The results allow us to discuss some of the major controls behind the geographical patterns of soil C, both organic and inorganic, for the USA.

MATERIALS AND METHODS

Data Sources and Structure

Soil Database

The State Soil Geographic Database (STATSGO, 1997 version) was used to calculate SOC and SIC for the conterminous USA (SCS, 1992; Reybold and Gale, 1989).

Soil organic C is estimated from the organic matter (OM) recorded in STATSGO as a percentage for the <2-mm size fraction. Low (OML) and high (OMH) limits of the OM for each soil layer of a component are reported. Soil inorganic C is given as calcium carbonate equivalent ($CaCO_3$) percentage in the <2-mm size fraction, with both low ($CaCO_3L$, %) and high ($CaCO_3H$, %) limits reported.

Land Cover/Use Database

The NLCD database was used to extract the spatial extent of major terrestrial ecosystems in the USA (Vogelmann et al., 1998). The NLCD was compiled as part of a cooperative project between the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (USEPA) to produce a consistent land-cover data layer for the conterminous USA

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Abbreviations: DEM, digital elevation model; GIS, geographical information system; NLCD, national land cover data; OM, organic matter; SIC, soil inorganic carbon; SOC, soil organic carbon; STATSGO, state soil geographical database.

based on 30 m resolution Landsat Thematic Mapper (TM) data acquired in the early 90's. The grid data set in each state meets state boundaries. There are 21 land cover/use categories in the NLCD. The NLCD were updated in 2000–2004, and were significantly improved over the previous version. For example, a number of zero data value pixels were corrected and some edge-matching was performed. However, this research was started before this release, and the initial release of the NLCD (Version 1999–12) was used in this study.

Terrain Database

GTOPO30 (in meters above sea level), a global digital elevation model (DEM) compiled by the USGS with a horizontal grid spacing of 30 arc seconds (approximately 1 km) was used to extract the spatial extent of each elevation gradient zone (Gesch and Larson, 1996). Slope (the maximum rate of change in value from each cell to its neighbors) was derived from the DEM data using Arcview Spatial Analysis software (Environmental Systems Research Institute, 1999).

Climate Database

Mean annual precipitation and MAT climate grid data sets, with a resolution of 2 km, were compiled by the Spatial Climate Analysis Service at Oregon State University and were used to extract the spatial extent of defined climate zones (Daly et al., 2001). Mean annual precipitation and MAT was produced by the Parameter-Elevation Regression on Independent Slopes Model (PRISM) with data from the climatological period of 1961–1990. The precipitation data were accepted by the USDA as the official precipitation maps for the USA, and are generated with data from 18 020 weather stations. Temperature data were reviewed and approved by the USDA-NRCS and U.S. National Climate Data Center and were generated with data from 12 840 weather stations.

The projections of all these data above were transformed to that of the NLCD using the ARC/INFO software (Environmental Systems Research Institute, 1998).

Creating Soil Organic Carbon and Soil Inorganic Carbon Content Attribute Tables

For each state, an attribute table of SOC and SIC content (kg m^{-2}) in three depth increments from the surface (0.2, 1, and 2 m) was created from STATSGO. To calculate the C content for a polygon in STATSGO, the C data (reported on a fraction <2 mm in diameter) must be normalized for gravel content. The methods used for calculating soil C are reported in detail in a companion paper (Guo et al., 2006). Content (kg m^{-2}) for each soil component was calculated in three depth increments (0.2, 1, and 2 m) based on low, high, and midpoint approaches. Contents for each map unit were calculated by averaging the soil components inside the map unit weighted by area. Finally, a SOC and SIC content attribute table with the polygon ID (unique identifiers of each polygon in STATSGO) as a key, was created by joining the GIS base map with the table of SOC and SIC content of map units.

Converting STATSGO Vector to Grid

The GIS coverage of STATSGO in each state was transformed from vector to grid with 30-m cells (the same scale as the NLCD database), with Polygon ID as the value of the cells, using Arcview Spatial Analysis software (Environmental Systems Research Institute, 1999). The converted STASTGO grid was then used as a base map to calculate SOC and SIC storage by terrestrial ecosystems, terrain classes, and climate zones based on the necessary assumption that SOC or SIC is homogeneous inside each polygon of STATSGO. In reality, soil C is not homogenous at polygon scales, which leads to unavoidable uncertainty in our analyses.

Soil Carbon Storage by Terrestrial Ecosystems and Land-Use

The spatial extent of ecosystems was based on the NLCD. There are three categories of upland forest in NLCD: deciduous (41), evergreen (42), and mixed (42) forests. Ecosystem dynamics are obviously different in these categories, which very likely influences SOC. However, their regional distributions are very different. For example, the majority of forest in California is evergreen, and only a very small portion is deciduous or mixed forest, much of which has an area of a single cell (resolution: 30 m) (NLCD version 1999–12, Initial release of preliminary dataset). For scale issues, these three forests (upland forest category in the NLCD) were aggregated to represent a general "forest ecosystems" in this study. Shrub land (51), grassland/herbaceous (71), and planted pasture/hay (81) were extracted as the "shrub ecosystem," "grass ecosystem," and "pasture ecosystem," respectively. Row crops (82), small grains (83), and fallow (84) were aggregated as the "agricultural (cropland) ecosystem." Woody wetlands (91) and emergent herbaceous wetland (92) of wetlands category in NLCD were combined as the "wetland ecosystem."

The spatial extent of each terrestrial ecosystem extracted above was used as a mask in a state-by-state analysis to extract those particular ecosystem polygon IDs of STATSGO grids (standard GIS overlay techniques). The polygon IDs and their area under the terrestrial ecosystem being studied were joined with the SOC and SIC content tables. The total SOC (or SIC) and content under a given terrestrial ecosystem within a state was calculated and weighted by area using:

$$SCT_i(ZD) = \frac{\sum_j^t [SCC_{ij}(ZD) \times (Area)_{ij}]}{1000}$$

$$SCC_i(ZD) = \sum_j^t \frac{(Area)_{ij}}{\sum_j^t (Area)_{ij}} \times SCC_{ij}(ZD)$$

$$(Z = \text{low limit, midpoint, and high limit})$$
$$(\mathrm{D} = 0{-}0.2\ \mathrm{m},\ 0{-}1\ \mathrm{m},\ \text{and } 0{-}2\ \mathrm{m}) \quad [1]$$

where i is the i^{th} state; j is the j^{th} polygon within the ith state; SCT_i (ZD) are the total SOC or SIC (in Mg) to depth (D) using approach (Z). The variable t is the number of the polygons within the state. SCC_{ij} (ZD) and $(Area)_{ij}$ are SOC (or SIC) content (kg m^{-2}) and the polygon area (m^2) extracted. SCC_i (ZD) is SOC (or SIC) content (kg m^{-2}) within the i^{th} state to depth (D) using approach (Z).

Total SOC and SIC (in Mg) and content (kg m^{-2}) under a terrestrial ecosystem within the conterminous USA was summarized from the data of each state:

$$SCT(ZD) = \sum_i^t SCT_i(ZD)$$

$$SCC(ZD) = \sum_i^t \frac{(Area)_i}{\sum_i^t (Area)_i} \times SCC_i(ZD)$$

$$(Z = \text{low limit, midpoint, and high limit})$$
$$(\mathrm{D} = 0{-}0.2\ \mathrm{m},\ 0{-}1\ \mathrm{m},\ \text{and } 0{-}2\ \mathrm{m}) \quad [2]$$

where SCT(ZD) are the total SOC or SIC (in Mg) to depth (D) using approach (Z). t is the number of the states where a given terrestrial ecosystem exists. $SCC_i(ZD)$ and $(Area)_i$ are the same as that in Eq.[1]. The variable SCC (ZD) are SOC (or SIC) contents (kg m^{-2}) within the given terrestrial ecosystem for depth (D) and approach (Z).

The standard deviation (S) of SOC and SIC contents within each terrestrial ecosystem was calculated by the following method:

$$S = \sqrt{\sum_{i}^{48}\sum_{j}^{t}\frac{(Area)_{ij}}{\sum_{i}^{48}\sum_{j}^{t}(Area)_{ij}} \times [SCC_{ij}]^2 - \left[\sum_{i}^{48}\sum_{j}^{t}\frac{(Area)_{ij}}{\sum_{i}^{48}\sum_{j}^{t}(Area)_{ij}} \times (SCC_{ij})\right]^2} \quad [3]$$

where S is the standard deviation of SOC (or SIC) content in the upper 2 m using the midpoint approach. SCC_{ij} is SOC (or SIC) content (kg m^{-2}) within the ij^{th} polygon for the upper 2 m (midpoint approach) within a terrestrial ecosystem. $(Area)_{ij}$ and t are the same as that in Eq. [1].

Topographic Effects on Soil Carbon

The DEM data were divided into eight elevation zones of equal intervals (except for the last zone): <200-, 200- to 400-, 400- to 600-, 600- to 800-, 800- to 1000-, 1000- to 1200-, 1200- to 1400-, and 1400- to 4328-m (>1400-m) zones. Slope was also divided into eight classes: <1, 1 to 2, 2 to 3, 3 to 4, 4 to 5, 5 to 10, 10 to 20, and 20 to 30° zones. The spatial extent of each DEM zone and slope class was then used in the overlay analysis with the STATSGO grids. The total SOC and SIC (in Mg) as well as content (kg m^{-2}) within each zone (class) for the upper 0.2 , 1 , and 2 m was calculated in the manner made for the terrestrial ecosystems.

Climatic Effects on Soil Carbon

In the conterminous US, MAP ranges from 48 mm to 7108 mm and MAT from −4.2°C to 25.5°C. MAP was divided into 10 zones with a 150 mm interval except for the first and last zones: 48 to 100 (<100 mm), 100 to 250, 250 to 400, 400 to 550, 550 to 700, 700 to 850, 850 to 1000, 1000 to 1150, 1150 to 1300, and 1300 to 7108 mm (>1300 mm). MAT was divided into nine zones with a 3°C interval except for the first and last zones: −4.2 to 0 (<0°C), 0 to 3, 3 to 6, 6 to 9, 9 to 12, 12 to 15, 15 to 18, 18 to 21, and 21 to 25.5°C (>21°C) zones. The spatial extent of each climate zone was then overlaid on the STATSGO grids to calculate the total SOC (or SIC) and the content in each zone for the upper 0.2, 1, and 2 m.

Soil Organic Carbon Along Temperature Gradients

Further analysis of SOC versus MAT, on level topography, within each MAP zone was conducted for two natural ecosystems (grass and forest) because no obvious linear trend of SOC versus MAT was initially discovered for all data as a whole. The purpose of this analysis was to examine the specific role of a climatic factor certainly likely to change in this century and to examine soil sensitivity to climate change. The spatial extent of each precipitation zone (called 'specific precipitation zones') at <600-m elevation and <1° slope was extracted separately for grass and forest ecosystems, state by state. Under these 'specific precipitation zones' constraints, MAT and STATSGO were overlaid in ARC/INFO software (Environmental Systems Research Institute, 1998). Linear correlation coefficients between MAT and SOC in each MAP zone were derived for two depths (0.2 and 1 m) in grass ecosystems and for three depths (0.2, 1, and 2 m) in forest ecosystems:

$$\rho = \frac{\sum_{i=1}^{N} X_iY_i - \frac{(\sum_{i=1}^{N} X_i)(\sum_{i=1}^{N} Y_i)}{N}}{\sqrt{[\sum_{i=1}^{N} X_i^2 - \frac{(\sum_{i=1}^{N} X_i)^2}{N}][\sum_{i=1}^{N} Y_i^2 - \frac{(\sum_{i=1}^{N} Y_i)^2}{N}]}} \quad [4]$$

where X is MAT (°C),Y is SOC content (kg m^{-2}), and ρ is the correlation coefficient between SOC and MAT in a given MAP zone.

The linear and exponential regression of SOC on MAT was compared by residual variance. Exponential regression of SOC on MAT was analyzed for each MAP zone if the residual variance was smaller in the exponential model than the linear model. Exponential regressions of SOC on MAT were calculated as follows:

$$\begin{aligned} \ln(Y) &= \alpha + \beta X \\ Y &= e^{(\alpha + \beta X)} \\ &= e^{\alpha} \times e^{\beta X} \\ &= ce^{\beta X} \end{aligned} \quad [5]$$

where Y is SOC content (kg m^{-2}), X is MAT (°C), $c = e^{\alpha}$.

All map overlay analyses above were based on the necessary assumption that the features (land-cover/use, topography, and climate) inside each cell are homogeneous. All the calculations were processed with programs written by the senior author using the Visual Basic Language in Microsoft Access (Microsoft Corporation, 2000), Avenue in ArcView (Environmental Systems Research Institute, 1999), and ARC macro language (AML) in the Arc/Info software (Environmental Systems Research Institute, 1998).

RESULTS AND DISCUSSION

Soil Carbon Storage vs. Terrestrial Ecosystem and Land-Use

The total SOC and SIC sequestrated by each terrestrial ecosystem are reported in Table 1. For any depth examined, forests contain the greatest SOC stock. The total U.S. forest ecosystem, the largest ecosystem by area, contributes 30.8, 28.4, and 28.0%, respectively, to the upper 0.2-, 1-, and 2-m national SOC stocks. Agricultural land is the second largest contributor to national SOC stock for any depths considered. For the upper 2 m, the amount of SOC sequestrated in forests is 765 to 4406 × 10^7 Mg, and in agricultural land (cropland) it is 839 to 3306 × 10^7 Mg. These categories are followed by wetlands (13.6% of total), grass (12.3%), pasture (10.2%), and shrub (9.1%) ecosystems. Using the midpoint values, 31.7% of the SOC in the upper 2 m of forests is sequestered in the upper 0.2 m, while for grass, shrub, and pasture the value is 30.3%. Agricultural land has 29.6% of the upper 2 m SOC in the upper 0.2 m. When considering only the upper 1 m, forests have 40.4% of their SOC sequestrated in the upper 0.2 m, while for grass, shrub, and

Table 1. Soil C sequestrated in each terrestrial ecosystem.

Depth	Terrestrial ecosystem	Area†	Organic C, 10^7 Mg				Inorganic C, 10^7 Mg			
			Min‡	Mid§	Max¶	%#	Min	Mid	Max	%
m		$\times 10^4$ km^2								
0–0.2	Agriculture	132.6	327	579	877	24.3	20	54	94	13.1
	Forest	228.1	320	733	1 277	30.8	20	43	75	10.4
	Grass	124.7	154	308	492	12.9	51	113	190	27.2
	Pasture	72.9	130	254	407	10.7	9	23	40	5.5
	Shrub	142.6	102	228	390	9.6	84	188	326	45.5
	Wetland	31.5	97	224	393	9.4	3	7	11	1.6
	Total††	737.4	1 158	2 379	3 919	100.0	182	413	706	100.0
0–1.0	Agriculture	132.6	735	1 565	2 561	24.5	253	644	1 121	22.9
	Forest	228.1	647	1 815	3 393	28.4	103	244	433	8.7
	Grass	124.7	308	802	1 402	12.6	330	726	1 221	25.8
	Pasture	72.9	271	651	1 123	10.2	86	207	357	7.4
	Shrub	142.6	203	590	1 091	9.2	405	925	1 602	32.9
	Wetland	31.5	301	788	1 446	12.3	22	62	112	2.2
	Total	737.4	2 539	6 388	11 315	100.0	1 203	2 814	4 842	100.0
0–2.0	Agriculture	132.6	839	1 957	3 306	23.7	590	1 509	2 638	27.9
	Forest	228.1	765	2 312	4 406	28.0	181	455	815	8.4
	Grass	124.7	353	1 016	1 823	12.3	580	1 289	2 172	23.8
	Pasture	72.9	318	840	1 492	10.2	183	463	808	8.5
	Shrub	142.6	237	752	1 418	9.1	668	1 540	2 667	28.4
	Wetland	31.5	411	1 127	2 096	13.6	43	123	226	2.3
	Total	737.4	3 016	8 260	14 992	100	2 261	5 414	9 374	100.0

† Area calculated after overlaying NLCD with STATSGO.
‡ Minimum.
§ Midpoint.
¶ Maximum.
\# Percentage of national totals using midpoint approach.
†† Total soil area in the conterminous USA excludes water, urban, bare rock, and other non-soil bodies.

pasture the values are 38.3, 39.0, and 38.6%, respectively. Agriculture ecosystems have 37.0% of the total SOC of the upper 1 m in the surface layer. In contrast, for wetland ecosystems most of total SOC is in the subsurface layers.

The pattern of SIC by ecosystem is different from that of SOC. The shrub ecosystem has the highest SIC stock in any of the depths studied. However, the relative amount contained in shrublands decreases as soil depth increases. The total U.S. shrub ecosystem contributes 45.5, 32.9, and 28.4%, respectively, to the upper 0.2, 1, and 2 m of the national SIC stock. The decline in relative SIC storage with depth is also observed for grass and forest natural ecosystems. The grassland ecosystem contains 27.2, 25.8, and 23.8%, while the forest ecosystem contains 10.4, 8.7, and 8.4% of the nation's total 0.2, 1, and 2 m SIC stocks, respectively. The amount stored by managed ecosystems increases with depth, and the agriculture ecosystem has 13.1, 22.9, and 27.9%, respectively, while the pasture system has 5.5, 7.4, and 8.4% of the nation's total SIC for 0.2, 1, and 2 m, respectively. Next to the shrub ecosystem, the grass ecosystem is the second largest contributor to the national SIC stock in the upper 0.2 and 1 m. However, for the upper 2 m of soil, the second largest contributor to the national SIC stock is the agriculture ecosystem. This is likely due to the fact that while this region has much of its carbonate removed from its upper meter by leaching, it still retains some combination of both pedogenic and lithologic carbonate at greater depths. As we discuss below, the presence of deep carbonate is particularly well correlated with the presence of young glacial deposits which still retain a significant pool of geologically derived carbonate (Guo et al., 2006). For the upper 2 m, the amount of SIC sequestrated under shrub lands is 668 to 2667 $\times$ 10^7 Mg, while for the agriculture lands (cropland) it is 590 to 2638 $\times$ 10^7 Mg. These quantities are closely followed by that stored in grasslands (580–2172 $\times$ 10^7 Mg).

The SOC and SIC contents (midpoint values) for each terrestrial ecosystem are presented in Fig. 1. For SOC, the wetland (35.8 kg m^{-2}) and agriculture (14.8 kg m^{-2}) ecosystems have the greatest contents in the upper 2 m. These are followed by pasture (11.5 kg m^{-2}), forest (10.1 kg m^{-2}), grass (8.1 kg m^{-2}), and shrub (5.3 kg m^{-2}) ecosystems. In terms of SIC content, agricultural land (11.4 kg m^{-2}), shrub (10.8 kg m^{-2}), and grassland (10.3 kg m^{-2}) have the greatest amounts in the upper 2 m, followed by pasture (6.3 kg m^{-2}), wetland (3.9 kg m^{-2}), and forest (2.0 kg m^{-2}) ecosystems. No linear relationship between SOC and SIC was found for any ecosystem at any soil depth. Most of the agriculture (row crops) in the Midwest and Northern plains regions is located on soils originating from calcareous latest Pleistocene/early Holocene glacial geological substrates, which explains the high SIC content that remains in the deeper layers even though the high MAP has stripped most of the carbonate from the upper 1 m (Jenny and Leonard, 1934).

Soil organic C originates primarily from plants, thus vegetation and land-use history is one of the most important driving factors of SOC. We used the NLCD to represent the current land-covers/uses in the conterminous USA to analyze SOC and SIC by ecosystem. There is no digital database of land-use history currently available, and we are therefore must recognize that present land cover does not necessarily represent long-term history.

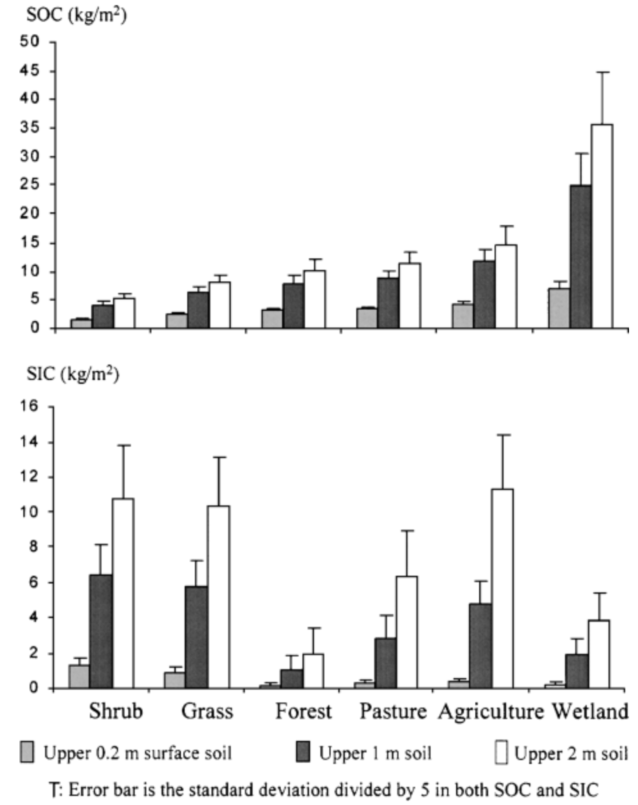


Fig. 1. Soil organic and inorganic C contents in each terrestrial ecosystem (midpoint value).

Soil organic C pools within terrestrial ecosystems in the conterminous USA have been quantified for the upper 1 m in forest ecosystems (Wisniewski et al., 1993; Dixon et al., 1994; Turner and Koepper, 1995, Turner et al., 1998) using different data sources. Forest land in previous work was estimated to have an area of 241.9 $\times$ 10^4 km^2 (including forest, woodland, and woody wetlands) and a total SOC storage of 21.5 $\times$ 10^9 Mg based on USDA Forest Inventory data and soil pedon data (Turner et al., 1998; Kern, 1994). In the NLCD (used here), forestlands were divided into two parts: forested upland and woody wetlands. The former has an area of 228.1 $\times$ 10^4 km^2, and the later 21.1 $\times$ 10^4 km^2 (area estimated after an overlaying of NLCD on STATSGO), which when combined are similar to the area used in previous estimations. We estimated that 6.5 $\times$ 10^9 to 33.9 $\times$ 10^9 (midpoint 18.1 $\times$ 10^9) Mg of SOC are sequestrated in the forested uplands, and 2.0 $\times$ 10^9 to 8.6 $\times$ 10^9 (midpoint 4.9 $\times$ 10^9) Mg of SOC in the upper 1 m of woody wetlands, which when combined yield midpoint estimates of 23.0 $\times$ 10^9 Mg, similar to the earlier results described above.

Topographic Effects on Soil Carbon

The total SOC and SIC in different elevation zones of the conterminous USA is shown in Table 2. Most of the SOC (72.8%) and half of the SIC (46.2%) is sequestrated below 600 m in elevation. The SOC and SIC contents in each elevation zone are presented in Fig. 2. There is a decrease in SOC contents as elevation increases, and the <600-m zones have the highest SOC contents. Our results differ from those of local to regional studies, such as Garten et al. (1999) and Bolstad and Vose (2001), showing that SOC increases with elevation in the southern Appalachian Mountains (as an example). Local trends are usually explained by the fact that increases in soil C with increasing elevation are probably related to decreases in decomposition relative to production, and hence higher long-term accumulation of C in the forest floor at higher elevations (Bolstad and Vose, 2001). Those trends, which are repeatable in many locations, do not appear in our data for possibly two reasons. First, our study includes the entire range of elevations in the USA across a broad range of latitudes. Second, litter or "O" horizons, a substantial C store in many forests, is not included in STATSGO, which might be a reason why SOC does not systematically increase with elevation in our study. Amichev and Galbraith (2004) have developed FIA (Forest Inventory data) as a means to add the forest litter data to STATSGO. The STATSGO database will update this missing litter carbon in later version, thus allowing a better assessment of liter layers, which were not evaluated here.

In terms of the SOC content vs. depth ratio (0.2 m/2 m), the portion of SOC sequestrated in the surface layer increases with increasing elevation: 23.1, 30.6, 31.6,

Table 2. Total soil C sequestrated in each elevation zone.

		Organic C, 10^7 Mg				Inorganic C, 10^7 Mg			
Elevation zone†	**Area‡**	**Min§**	**Mid¶**	**Max#**	**%††**	**Min**	**Mid**	**Max**	**%**
100 m	**$\times 10^4$ km^2**								
<2	**169.8**	**895**	**2 716**	**5 048**	**32.4**	**220**	**591**	**1 049**	**10.6**
[2–4)	**169.0**	**1 002**	**2 329**	**4 035**	**27.8**	**489**	**1 329**	**2 385**	**23.8**
[4–6)	**81.4**	**399**	**1 059**	**1 919**	**12.6**	**272**	**661**	**1 149**	**11.8**
[6–8)	**54.6**	**150**	**456**	**848**	**5.4**	**221**	**496**	**848**	**8.9**
[8–10)	**43.3**	**107**	**319**	**581**	**3.8**	**210**	**459**	**772**	**8.2**
[10–12)	**35.5**	**85**	**254**	**463**	**3.0**	**182**	**407**	**689**	**7.3**
[12–14)	**42.9**	**90**	**273**	**502**	**3.2**	**267**	**577**	**956**	**10.3**
≥14	**168.3**	**315**	**985**	**1 873**	**11.7**	**484**	**1 063**	**1 810**	**19.0**

† Bracket means the point is included and close parenthesis indicates the point is not included.
‡ Area calculated after overlaying terrain database (DEM) with STATSGO.
§ Minimum.
¶ Midpoint.
 # Maximum.
†† Percentage of midpoint value.

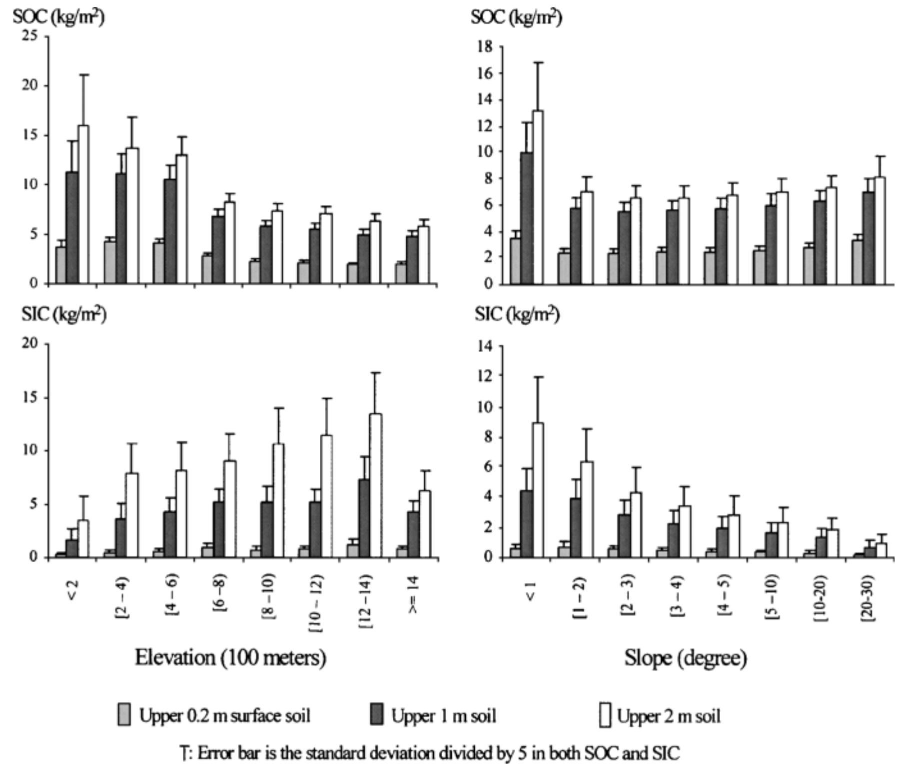


Fig. 2. Soil organic and inorganic C contents in each elevation zone and slope class (midpoint value).

33.9, 31.2, 30.3, 30.7, and 34.2% in the <200-, 200- to 400-, 400- to 600-, 600- to 800-, 800- to 1000-, 1000- to 1200-, 1200- to 1400-, and >1400-m elevation zones, respectively. Low elevations have the lowest SOC content (0.2 m/2 m) ratio. For SIC, there was no pattern in SIC content vs. elevation.

The total SOC and SIC in each slope class is presented in Table 3. Almost four fifths of both SOC (76.5%) and SIC (77.9%) in the USA are sequestrated in level areas. Soil organic C and SIC contents in each slope class are presented in Fig. 2. The effect of topography on SOC is complex (Yoo et al., 2005a, 2005b), and depends on not only slope but also aspect (Miller et al., 2004). Aspect effects on SOC and SIC are not explicitly evaluated here due to the scale limitations of the database. Our result shows that SOC contents on level topography are almost double that in the other slope classes. In terms of the SOC content vs. depth ratio (0.2 m/2 m), the portion of SOC sequestrated in the surface layer increases with increasing slope: for example, 26.8, 34.2, 36.7, 37.1, 37.3, 37.7, 38.5, and 42.1% in the <1, 1 to 2, 2 to 3, 3 to 4, 4 to 5, 5 to 10, 10 to 20, and 20 to 30° slope classes, respectively. This trend is expected in that soil erosion rates increase with increasing slope curvature (the first derivative of slope) (Yoo et al., 2005a, 2005b). Increasing erosion rates result in thinner soils, less C storage, and a greater fraction of total storage in shallow depth increments. The effect of slope on SIC is even more obvious than that on SOC, and there is also a decrease in SIC contents as slope becomes steeper.

Table 3. Total soil C sequestrated in each slope class.

		Organic C, 10^7 Mg				Inorganic C, 10^7 Mg			
Slope class†	Area‡	Min§	Mid¶	Max#	%††	Min	Mid	Max	%
Degree	×10^4 km²								
<1	484.8	2 406	6 418	11 468	76.5	1 806	4 359	7 526	77.9
[1–2)	109.3	254	777	1 472	9.3	309	701	1 201	12.5
[2–3)	47.2	98	312	605	3.7	91	207	359	3.7
[3–4)	30.2	64	201	391	2.4	45	103	182	1.8
[4–5)	21.9	48	149	289	1.8	28	64	113	1.1
[5–10)	54.2	127	383	745	4.6	54	127	233	2.3
[10–20)	18.7	45	138	272	1.6	14	34	66	0.6
[20–30)	1.0	3	8	16	0.1	0	1	2	0.0

† Bracket means the point is included and close parenthesis indicates the point is not included.
‡ Area calculated after overlaying terrain database (DEM) with STATSGO.
§ Minimum.
¶ Midpoint.
# Maximum.
†† Percentage of midpoint value.

Climatic Effects on Soil Carbon

The total SOC and SIC in each MAP zone are estimated in Table 4. It is obvious that most SOC is sequestrated in zones having adequate precipitation for plant production. Areas with less than 400 mm MAP, which occupy 25.4% of the conterminous USA, have only 11.6% of the total SOC. In contrast, low SIC exists in high precipitation zones. Only 4.1% of the total SIC in the USA is located in the >1000 mm MAP zones. Although SIC indeed occurs in arid and semiarid regions as might be expected, there is also a large portion of SIC (to 2 m) in areas of moderate MAP.

The SOC and SIC contents by MAP zone are shown in Fig. 3. Soil organic C content increases as MAP in-

Table 4. Total soil C sequestrated in each precipitation zone.

		Organic C, 10^7 Mg				Inorganic C, 10^7 Mg			
Precipitation†	Area‡	Min§	Mid¶	Max#	%††	Min	Mid	Max	%
10 mm	$\times 10^4$ km^2								
<10	2.8	1	7	15	0.1	5	18	35	0.3
[10–25)	58.4	44	208	412	2.4	260	568	953	10.1
[25–40)	135.4	264	777	1416	9.1	629	1406	2388	25.0
[40–55)	112.3	388	1120	2023	13.1	554	1265	2155	22.5
[55–70)	68.7	330	858	1527	10.0	347	833	1444	14.8
[70–85)	73.9	594	1309	2224	15.3	279	725	1290	12.9
[85–100)	76.9	464	1026	1735	12.0	206	584	1054	10.4
[100–115)	80.0	245	789	1535	9.2	56	164	299	2.9
[115–130)	70.2	316	1003	1902	11.7	8	28	53	0.5
≥1300	95.0	442	1447	2785	16.9	11	37	71	0.7

† Bracket means the point is included and close parenthesis indicates the point is not included.
‡ Area calculated after overlaying precipitation database (MAP) with STATSGO.
§ Minimum.
¶ Midpoint.
# Maximum.
†† Percentage of midpoint value.

creases up to MAP 700 to 850 mm, then, SOC content fluctuates as MAP continues to increase, a pattern consistent with observations in the Central Plains grasslands by Burke et al. (1989). In terms of SIC, there is no obvious pattern of SIC content versus MAP until MAP exceeds 1000 mm, at which point SIC drops dramatically. This is expected based on previous work. The amount of SIC in soils is partially dictated by parent material (not explicitly evaluated here) and at MAP's < 1000 mm, the recorded variation in SIC likely reflects both parent materials and climate. At precipitation levels > 1000 mm, Jenny and Leonard (1934) and Retallack (1994) have shown that precipitation generally removes carbonate from the upper 1 m of soils. In the USA, 60.24% of the forests exist in the >1000-mm MAP zones, which explains why the SIC content in forests is low (Fig. 1).

The total SOC and SIC in each MAT zone is presented in Table 5. Only 0.6% of SOC was sequestrated at temperatures <0°C MAT. Most (54.2%) of the

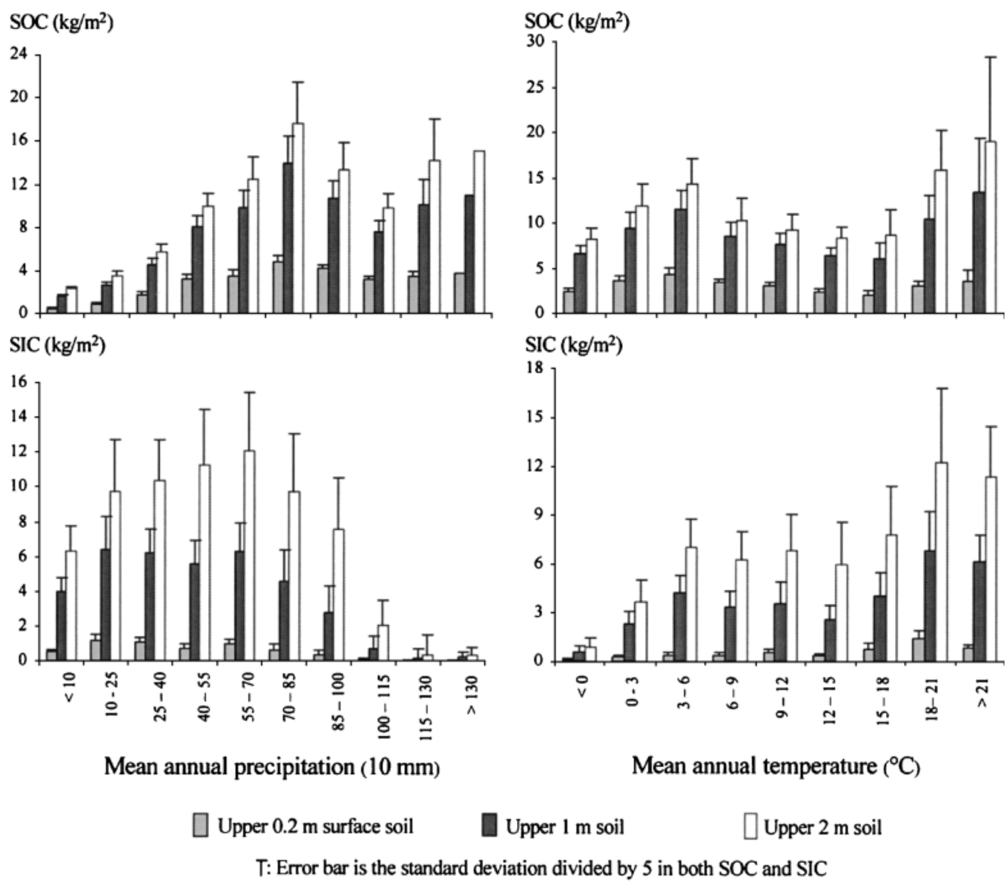


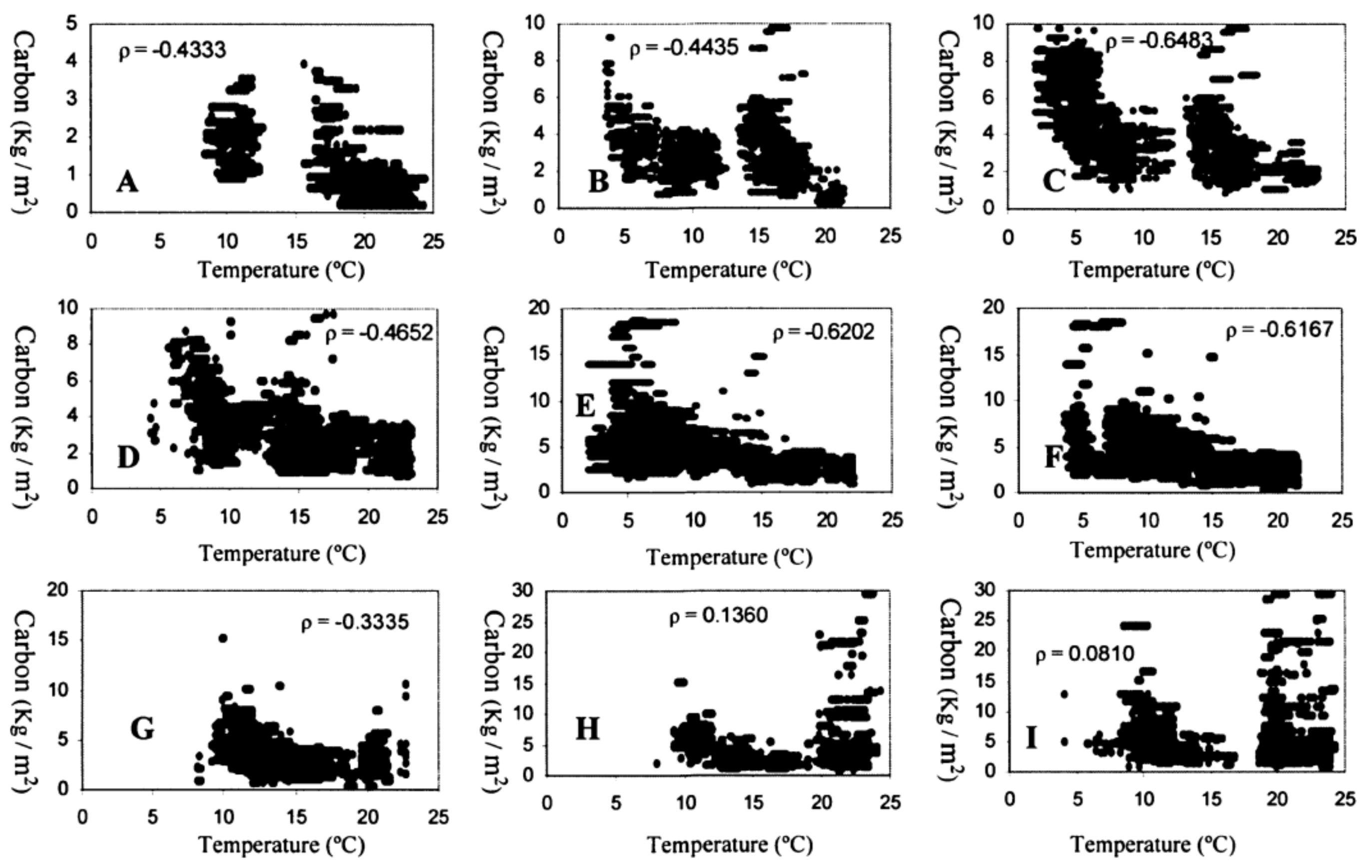
Fig. 3. Soil organic and inorganic C contents in each precipitation and temperature zone (midpoint value).

Table 5. Total soil C sequestrated in each temperature zone.

		Organic C, 10^7 Mg				Inorganic C, 10^7 Mg			
Temperature†	Area‡	Min§	Mid¶	Max#	%††	Min	Mid	Max	%
°C	$\times 10^4$ km^2								
0	6.2	17	52	102	0.6	2	6	14	0.1
[0–3)	17.0	65	202	396	2.3	23	63	121	1.1
[3–6)	99.7	516	1426	2655	16.5	286	707	1254	12.2
[6–9)	176.1	768	1827	3187	21.2	441	1106	1942	19.1
[9–12)	151.9	572	1421	2479	16.5	417	1038	1784	17.9
[12–15)	113.0	299	957	1790	11.1	305	676	1132	11.7
[15–18)	141.9	400	1255	2310	14.6	484	1118	1920	19.3
[18–21)	64.8	314	1030	1985	11.9	366	799	1353	13.8
≥21	23.9	155	456	831	5.3	90	274	508	4.7

† Bracket means the point is included and close parenthesis indicates the point is not included.
‡ Area calculated after overlaying temperate database (MAT) with STATSGO.
§ Minimum.
¶ Midpoint.
# Maximum.
†† Percentage of midpoint value.

SOC is located in the 3 to 12°C MAT temperature zones. The SOC and SIC contents vs. MAT are presented in Fig. 3. A nonlinear relationship between SOC and MAT was observed, indicating that the effect of temperature on SOC is complicated or compounded by other factors. In terms of the SOC content vs. depth ratio (0.2 m/2 m), the portion of SOC sequestrated in the surface layer is 30.5, 31.4, 31.3, 33.0, 33.6, 29.9, 24.2, 19.5, and 19.1% in the <0, 0 to 3, 3 to 6, 6 to 9, 9 to 12, 12 to 15, 15 to 18, 18 to 21, and >21°C temperature zones, respectively. This illustrates a trend of low ratios in high MAT zones, as has been observed and discussed by Trumbore (2000).



A: Region with MAP <250 mm. **B:** Region with MAP [250-400) mm. **C:** Region with MAP [400-550) mm.
D: Region with MAP [550-700)mm. **E:** Region with MAP[700-850) mm. **F:** Region with MAP[850-1000) mm.
G: Region with MAP [1000-1150) mm. **H:** Region with MAP [1150-1300) mm. **I:** Region with MAP (>=1300) mm.

Fig. 4. Soil organic C response to the mean annual temperature (MAT) in the upper 0.2 m of grassland soils.

Table 6. The response of soil organic C (*y*, kg m^{-2}) to mean annual temperature (*x*, °C) under grassland in different precipitation zones.

		Top 0.2 m soil		Top 1.0 m soil		Top 2.0 m soil	
MAP†	Number of cells‡	Empirical equation	ρ§	Empirical equation	ρ§	Empirical equation	ρ§
<250	3 368 434	Y = 6.5875exp(−0.1135x)	−0.5411	Y = 9.0956exp(−0.0682x)	−0.4111	Y = 8.3873exp(−0.0447x)	−0.2994
[250–400)	6 751 911	Y = 6.2138exp(−0.0709x)	−0.5531	Y = 14.2774exp(−0.0645x)	−0.5046	Y = 15.9655exp(−0.0605x)	−0.4644
[400–550)	47 179 844	Y = 7.2049exp(−0.0727x)	−0.7348	Y = 16.9670exp(−0.0638x)	−0.6673	Y = 19.0220exp(−0.0571x)	−0.5870
[550–700)	53 415 212	Y = 4.9370exp(−0.0471x)	−0.4579	Y = 9.3965exp(−0.0212x)	−0.1945	Y = 9.2374exp(−0.0017x)	−0.0144
[700–850)	59 881 198	Y = 9.1432exp(−0.0765x)	−0.6093	Y = 25.0806exp(−0.0708x)	−0.5297	Y = 28.0264exp(−0.0605x)	−0.4518
[850–1000)	57 355 633	Y = 10.8792exp(−0.0851x)	−0.5986	Y = 22.4141exp(−0.0602x)	−0.4257	Y = 21.5433exp(−0.0401x)	−0.2789
[1000–1150)	10 940 357	Y = 6.6090exp(−0.0593x)	−0.3196	Y = 9.5128exp(−0.0165x)	−0.0806	Y = 8.9644exp(0.0064x)	0.0277
[1150–1300)	10 071 121	Y = 1.0898exp(0.0620x)	0.2441	Y = 2.7178(exp0.0691x)	0.2509	Y = 2.8693exp(0.0856x)	0.3006
≥1300	7 885 885	Y = 2.0247exp(0.0269x)	0.0855	Y = 11.6565exp(−0.0044x)	0.0127	Y = 22.8632exp(−0.0210x)	0.0608

† Bracket means the point is included and close parenthesis indicates the point is not included.
‡ Cell resolution 30 m.
§ Linear correlation coefficient between X and ln(Y).

For SIC contents, there is a trend of increasing SIC as MAT increases (Fig. 3).

Soil Organic Carbon Along Temperature Gradients

A nonlinear relationship between SOC and MAT was found in the analysis made above. We further examined the relationship of SOC versus MAT for two natural ecosystems (grass, or forest), at elevations <600 m, on level topography, within each MAP zone. The SOC (kg m^{-2}) versus MAT for the upper 0.2 m of grassland is presented in Fig. 4. There is a negative correlation between SOC and MAT in all MAP zones of <1150 mm. The correlation of SOC vs. MAT under grassland (upper 1 m) or forestland (upper 0.2, 1, and 2 m) is similar to that found for the upper 0.2 m of the grassland. The relationship between SOC and MAT was further explored through linear and exponential regression analyses. 70% of the pairs of datasets in each MAP zone of a given land-cover fit an exponential model better than a linear model (Tables 6 and 7). This matches the type of function that is widely used to describe the response of SOC decomposition to changes in MAT, for example the so-called Q_{10} function (Kawahara et al., 1981; Raich and Schilesinger, 1992; Lloyd and Taylor, 1994; Buchmann 2000). The constant β, in a exponential model $Y = ce^{\beta x}$, indicates sensitivity of Y on X and Tables 6 and 7 suggest that SOC is more sensitive in the surface layer than that in the deeper layers ($|\beta_{0.2\ m}| > |\beta_{1\ m}|$ and $|\beta_{2\ m}|$), especially in grassland.

The coefficient of determination ($R^2 = \rho^2$) describes the portion of variation in a dependant variable (Y) that is captured by an independent variable (X). Most of the coefficients of determination (SOC vs. MAT) in Tables 6 and 7 are small, indicating that there are other factors affecting SOC. To avoid the effect of other factors, the analysis of SOC should be focused on average trends. The means of surficial SOC (kg m^{-2}) averaged for every 0.1°C increment in each MAP zone of both grasslands and forestlands are presented in Fig. 5 and 6. The relationship of mean SOC vs. MAT is described by an exponential model in all zones with <1000 mm MAP. In grasslands, the response of SOC to temperature varies with MAP, and the sensitivity ($|\beta|$) of SOC to increasing temperature decreases as MAP increases. When MAP exceeds 1000 mm, the response of mean SOC to MAT gradually changes from exponential to polynomial (Fig. 5).

Soil organic C is less sensitive to increasing temperature in forests than that in grasslands. However, this result does not include the O horizons, which are a substantial C store in many forests. A more sensitive response of SOC to MAT for forests might be expected if O horizons are considered, since SOC at the surface is more sensitive to temperature than subsurface horizons (Tables 6 and 7).

Soil parent material (or geological substrates) and time (e.g., age of geomorphic surface) are two important additional factors that have strong controls on soil C. However, we could not analyze the effect of these two factors since digital spatial data for the nation are not

Table 7. The response of soil organic C (y, kg m^{-2}) to mean annual temperature (x, °C) under forestland in different precipitation zones.

		Top 0.2 m soil		Top 1.0 m soil		Top 2.0 m soil	
MAP†	Number of cells‡	Empirical regression	ρ§	Empirical regression	ρ§	Empirical regression	ρ§
<250	218 355	Y = 11.1313exp(−0.1248x)	−0.6281	Y = 14.2922exp(−0.0799x)	−0.4777	Y = 13.1532exp(−0.0596x)	−0.3733
[250–400)	535 912	Y = 2.2124exp(0.0052x)	0.0542	Y = 5.8971exp(0.0037x)	0.0312	Y = 7.8466exp(−0.0014x)	−0.0107
[400–550)	4 405 858	Y = 9.2315exp(−0.0725x)	−0.6957	Y = 20.5230exp(−0.0588x)	−0.5562	Y = 23.0659exp(−0.0515x)	−0.4807
[550–700)	34 231 869	Y = 6.0763exp(−0.0527x)	−0.6439	Y = 17.3029exp(−0.0483x)	−0.5449	Y = 21.4768exp(−0.0432x)	−0.4606
[700–850)	135 949 610	Y = 6.6890exp(−0.0532x)	−0.4135	Y = 18.3180exp(−0.0545x)	−0.3564	Y = 23.1887exp(−0.0539x)	−0.3380
[850–1000)	123 248 965	Y = 7.6755exp(−0.0739x)	−0.6331	Y = 13.2936exp(−0.0427x)	−0.3565	Y = 14.0750exp(−0.0265x)	−0.2148
[1000–1150)	229 473 835	Y = 7.4929exp(−0.0869x)	−0.6446	Y = 12.9210exp(−0.0638x)	−0.4174	Y = 13.0661exp(−0.0432x)	−0.2794
[1150–1300)	241 200 561	Y = 4.4123exp(−0.0384x)	−0.2451	Y = 7.5017exp(−0.0123x)	−0.0685	Y = 7.7489exp(0.0062x)	0.0339
≥1300	319 840 339	Y = 2.6501exp(−0.0044x)	−0.0209	Y = 2.8557exp(0.0472x)	0.1864	Y = 2.5910exp(0.0734x)	0.2740

† Bracket means the point is included and close parenthesis indicates the point is not included.
‡ Cell resolution 30 m.
§ Linear correlation coefficient between X and ln(Y).

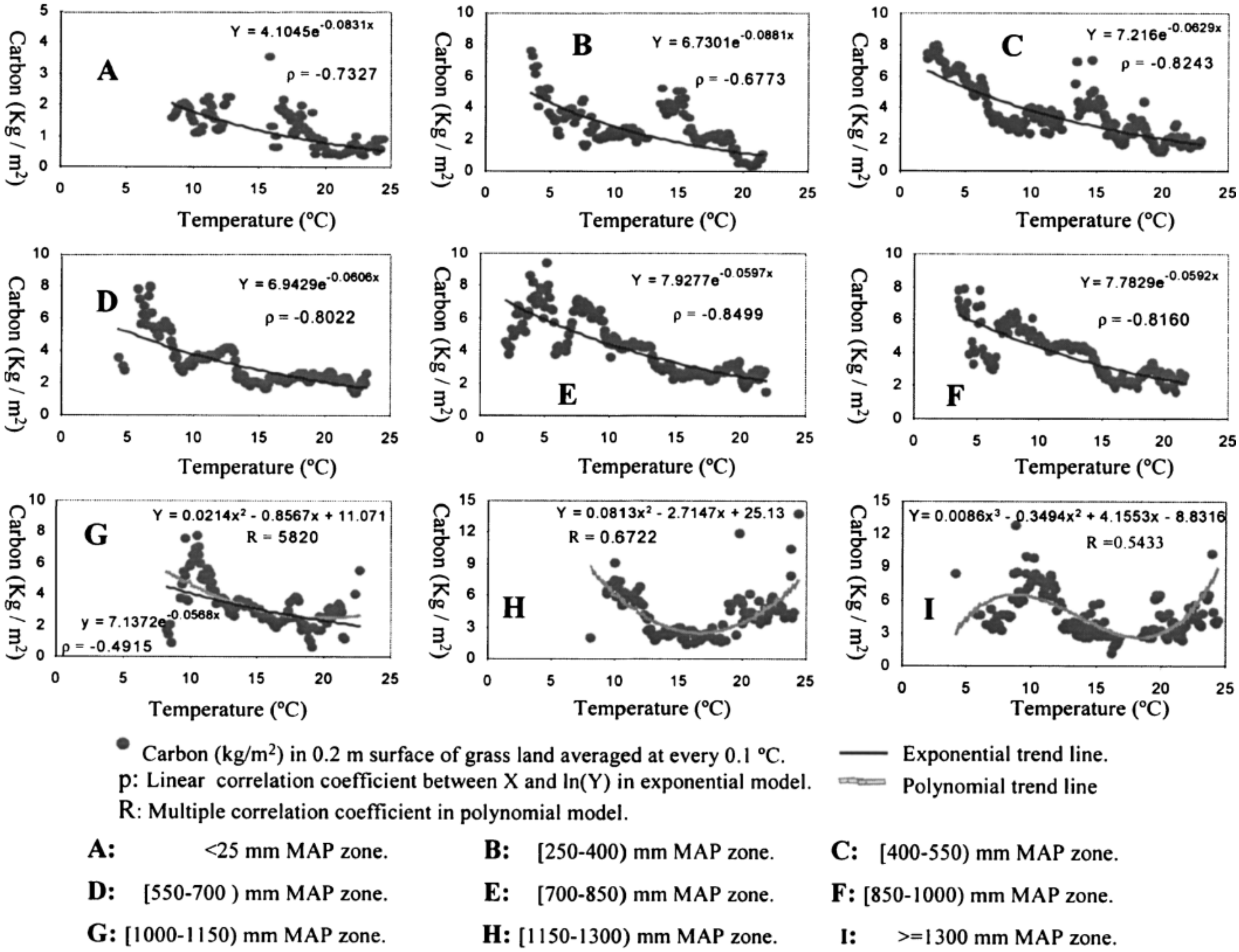


Fig. 5. Mean soil organic C (kg m^{-2}) response to mean annual temperature in the upper 0.2 m of grassland soils.

available. It is very likely that unexplained variations in SOC/SIC vs. the factors we have considered are due to variations in these two remaining variables. However, despite these problems or deficiencies in the available data, our analysis clearly reveals important environmental patterns in the national soil C pools.

CONCLUSIONS

The technology now exists to both tabulate the total quantities, and the geographical distribution, of soil properties in the USA and to examine the underlying controls on these patterns. Here we have focused on the organic and inorganic C content of U.S. soils. Here and elsewhere (Guo et al., 2006), we have tabulated the spatial distribution of soil C by USDA Land Resource Region and by Taxonomic grouping. In this paper, we have utilized digital databases to examine the relationship of the soil C to climate, topography, elevation, and soil C partitioning among various ecosystems. Additionally, the data sets provide some opportunities to examine the impact of human disturbance on soil C in a national scale.

The effects of land use, topography (elevation and slope), and MAP are more obvious than that of MAT on SOC. Mean annual temperature appears to interact with other variables at the relatively course scale our analysis provides. However, when other variables are highly restricted, there is clearly a decline in SOC with increasing temperature.

Our investigation of SIC mirrored the long-known effect of MAP on carbonate in the upper 1m, but revealed that substantial SIC exists between 1 and 2 m in many intermediate precipitation zones in the upper Plains and Midwest.

GIS-based analyses of soil C and other properties are a valuable resource, but one that is also somewhat limited by its scale and the generalized nature of the data. As the present STATSGO is gradually replaced by more detailed databases such as SURRGO, the reliability of the data analyses will greatly improve. Additionally, the availability of surficial geology databases will also allow pedologists to examine the effect of the full suite of state factor effects on soil properties. Despite the eventual benefits these new databases will provide, the present

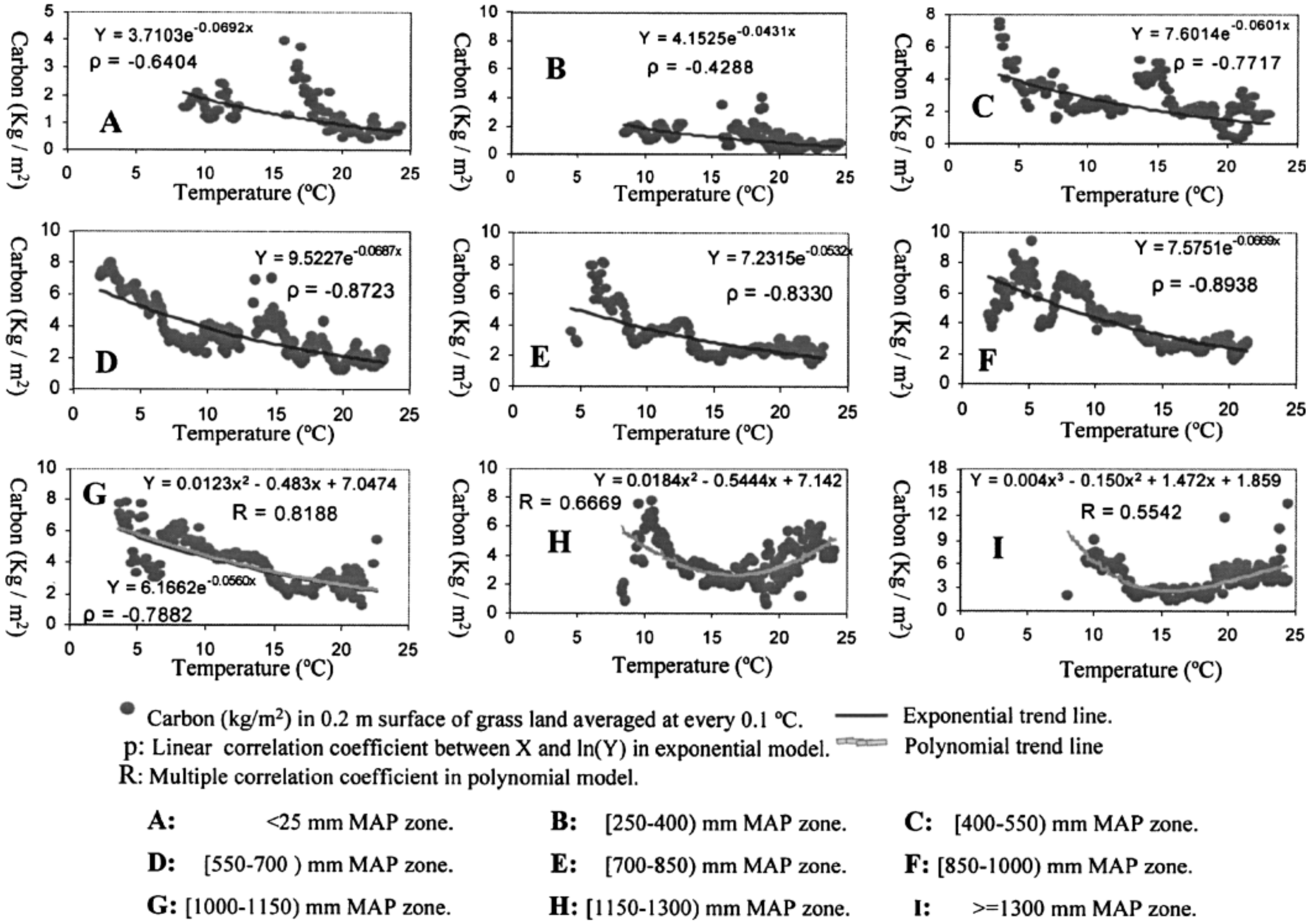


Fig. 6. Mean soil organic C (kg m^{-2}) response to mean annual temperature in the upper 0.2 m of forestland soils.

STATSGO database provides a largely untapped potential for assessing the geographical distribution of soil properties for the nation.

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