Soil Carbon Stocks in the U.S.: Current Data and Future Inventories

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Abstract. There is an urgent need for site and condition specific soil carbon inventories to increase the reliability of estimates of total national stocks and the amount of carbon that can be practically stored in soil by changing land uses and/or management systems. The objectives of this paper are 1) to report total U.S. C stocks derived from existing soil survey and land cover data, 2) estimate potential increases in soil C that could be achieved with changes in land cover and agricultural management, and 3) to outline current efforts to improve soil survey estimates of U.S. soil C stocks through a scientifically-based and statistically valid inventory. The soil survey for non-federal lands in the U.S. at scales of 1:12,000 to 1:24:000 is essentially complete and is available as the Soil Survey Geographic database (SSURGO). In addition to the spatial database, SSURGO includes soil attribute data, including organic C, $CaCO_3$ equivalent, bulk density, and fragment content, for layers of components of each map unit. In areas of federal land yet to be mapped, less precise (1:250,000 compilation scale) data are available in the State Soil Geographic (STATSGO) database. The SSURGO and STATSGO databases include a representative value (RV) and high and low values for each attribute. The RV represents for soil conditions under the dominant land cover and management system for the map unit in the area of interest. The low value for each map unit component represents soil conditions where the value for the attribute would be expected to be lower than the RV with the high value representing the opposite. The current soil C stock inventory was based on an overlay of National Land Cover Data on SSURGO and STATSGO data expressed in a 30 m grid for the nation. From the combined data, dominant land cover for each soil map unit was evaluated. For areas of map units with the dominant land cover, RV of organic C was applied for calculations of soil C stocks. For areas with land cover that would be expected to result in less soil organic C than the dominant cover, soil C stock calculations were based on the low value in the SSURGO and STATSGO databases, with the high value used for areas with land cover expected to result in higher organic C than the dominant use. For example, if the dominant land use for the map unit was forest, the low attribute value was used for C stock calculations for areas of the map unit used for cropland. These data were combined with bulk density and fragment content data (not adjusted for land cover) and used to calculate soil C stocks for each map unit. Results from the calculations indicate that the U.S. currently has about 65 Pg of soil organic C to 100 cm depth and that by changing land use, an additional 1 Pg of organic C can be stored in the nation's soils. These data will be validated against soil carbon stocks calculated from measured data for 10,000+ pedons sampled from across the nation. The second phase of the NRCS effort to evaluate U.S. carbon stocks will be measurement of soil C and related data major land uses and agricultural management systems within soil groups expected to have similar C dynamics. For this inventory, soils will be sampled to 1 m at about 30,000 points at 6,000 locations. At each sample point, the soil described, and for each horizon, bulk density will be measured by appropriate techniques and total C and $CaCO_3$ equivalent will be estimated from Visible and Near Infra-Red spectra. The goal of this phase is to collect scientifically defensible and statistically valid data for soil C stocks that can be used to guide policy decisions and conservation planning for the nation.

Keywords:

1.Introduction

Elevated concentrations of carbon dioxide (CO_2) and other greenhouse gases in the earth's atmosphere that have resulted from anthropogenically-derived emissions is one of the most pressing environmental issues today (IPCC, 2007). Without mitigation, the rise in CO_2 and other greenhouse gas concentrations in the atmosphere could result in a global average temperature increase of 2° C or greater by 2100 (IPCC, 2007). Such an increase in global temperature can result in increased duration and intensity of extreme climatic events that impact food, fiber, and energy security. As such, natural resource managers and policy makers will need new and reliable information to aid in decisions that will help to minimize negative impacts of climate change.

Organic carbon sequestered in soils can contribute to mitigation of greenhouse gas emissions. To evaluate this potential, however, baseline data on soil carbon stocks are critical for understanding current conditions and how much soil carbon that could be sequestered both in natural and managed agricultural systems (Follett et al., 2009). Over the past 110 years, soils of the U.S. have been inventoried through efforts of a host of federal and state agencies through efforts of the National Cooperative Soil Survey (NCSS) which is a nationwide partnership of federal, regional, state and local agencies; and private entities and institutions lead by the USDA-Natural Resources Conservation Service (NRCS). (Soil Survey Staff, 1993).

The soil survey for non-federal lands in the U.S. at scales of 1:12,000 to 1:24:000 is essentially complete and is available as the Soil Survey Geographic (SSURGO) database. In addition to the spatial database, SSURGO includes soil attribute data, including organic C, $CaCO_3$ equivalent, bulk density, and fragment content, for layers of the different soil components of each map unit. In areas of federal land yet to be mapped similar, less precise (1:250,000 compilation scale) data are available in the State Soil Geographic (STATSGO) database.

In addition to the map unit data in the SSURGO database, the NCSS pedon database contains measured soil property data for horizons to 1 m or greater depth for more than 30,000 pedons (sites) from across the country. These pedons were sampled and analyzed over the last 60 years during the U.S. soil survey, primarily to support classification and interpretation of the soils, and serve as the basis for aggregated values in the SSURGO database. Although land cover and/or agricultural management were not criteria considered in site selection for the NCSS database nor assignment of values in the SSURGO database, these data are well suited to nationwide assessments of U.S. soil organic carbon (SOC) concentrations and stocks.

Use of digital soil survey spatial data and associated estimated attributes for carbon inventories is not a new concept and SOC inventories for the U.S. are available (Bliss et al., 1995; Lacelle et al., 2000; Bliss et al., 2002; Grossman et al., 1992). These earlier efforts, however, focused on limited extents or used generalized soil geographic databases, such as the State Soil Geographic (STATSGO).

The objectives of this paper are 1) evaluate SOC concentration and SOC stocks for the 0 to 5 cm and 0 to 100 cm depths from the SSURGO database, 2) evaluate SOC concentration and SOC stocks for the 0 to 5 cm and 0 to 100 cm depths from the NSSC pedon database, 3) compare results from the two databases, and 4) present current NSSC activities designed to enhance SOC data for the U.S. soil survey.

2. Methods

2.1. Soil C stock development from the Soil Survey Geographic (SSURGO) database

To date, soil inventories have been completed for more than 95% of the private and tribal lands in the conterminous U.S. as well as an appreciable areas of public lands. Mapping scales for these inventories generally ranged from 1:12,000 to 1:63,360. All map data is available in electronic format in the Soil Survey Geographic (SSURGO) database (Soil Survey Staff, 2009). In addition to the spatial soil data, this database contains attribute data for each map unit including aerial extent of the map units, estimates of the relative proportion of the soil components (soil series) that comprise the map unit, and estimates of the physical and chemical properties for major horizons of each map unit component including organic C concentration, bulk density, and coarse fragment content. The estimated properties are based on a data collected from one or more pedons representing the soil series or a similar soil that occurs on similar landscapes. The SSURGO database includes the estimated range in for each property, represented as low, representative, and high values, that is expected over the aerial extent and range of land covers expected for the soil component.

Surface horizon SOC concentrations were summarized from a December 2009 edition of the SSURGO database of existing soil survey inventories for the United States (USDA, 2009). In addition, SOC, bulk density, and coarse fragment contents from this database were used to develop estimates of SOC stocks at two depths, 0 to 5cm (to approximate shallow samples and remotely-sensed estimates), and 0-100cm (as a baseline). This edition of the National SSURGO collection contains 285,496 map units expressed as 35,715,241 polygon features. The map units are composed of 765,569 components and 1,831,072 horizons. Our method was developed as a MS SQL Server 2005 script and adapted to the SSURGO 2.1 data structure (USDA, 2009) from the method by Bliss et al. (1995) and Lacelle et al., (2000). Water bodies and miscellaneous areas were excluded from the calculation. For calculation of total mass, the geometry of the SSURGO map unit polygon vector features in an Albers Equal Area Conic Projection were used to determine area in square meters. Where digital soil surveys were not available, published reports and General Soil Map of the US information was substituted. Our calculations did not use soil map units that contain null value records providing a conservative soil organic carbon content and mass estimate.

The SSURGO data were stratified into four land cover categories derived from the National Land Cover Database (NLCD) (USGS, 2001). The 21 land cover categories identified in this database were reduced to four categories by grouping NLCD categories. The four land cover categories were cropland (cultivated crops), forestland (deciduous forest, evergreen forest, and mixed forest); grassland (grassland/herbaceous and pasture hay), and other which contains all remaining NLCD categories. SOC concentrations and stocks were summarized by land cover and spatially by Land Resource Region (Fig. 1) (USDA, 2006)

The land cover adjusted SOC content was based on a 12/30/2009 snapshot of the SSURGO database combined with the 2001 NLCD and the application of expert rules to adjust the SSURGO map unit SOC content based upon map unit dominant NLCD category and pixel level NLCD land cover condition. SOC content calculations use the methodology of Waltman et al., 2010. The SSURGO vector map layer was projected to an Albers Equal Area projection and gridded at 10 meter resolution. The 10 meter grid was then resampled to a 30 meter grid and composited with the 2001 NLCD grid. Area estimates are based on the assumption that each 30 meter pixel contains 900 sq meters.

The current soil C stock inventory was based on a composite of the 2001 NLCD on SSURGO data expressed in a 30 m grid for the nation. From the combined data, dominant land cover for each soil map unit was calculated. An NLCD adjusted estimate of SOC was prepared at the 30 meter pixel level by applying expert rules that used SSURGO database representative organic C values for the dominant land cover and those land covers that were expected to have SOC concentrations similar to the dominant land cover. For those pixel land cover categories where SOC concentration was expected to be greater than that for the dominant land cover, the high soil C value from the SSURGO database was used to calculated SOC stocks. For those pixel land cover categories where organic carbon was expected to be less than that for the dominant land cover, the low SOC from the SSURGO database was used. For example, if the dominant land cover for the map unit was forest, the low SOC concentration value was used for SOC stock calculations for areas of the map unit used for cropland. If the dominant land cover for the map unit was cropland, the high SOC concentration value was used for SOC stock calculations for areas of the map unit under grassland. These pixel level land cover data were combined with bulk density and fragment content data (not adjusted for land cover) and used to calculate soil C stocks for each map unit.

2.2. Soil C stock development from the National Cooperative Soil Survey (NCSS) pedon database

During the course of the soil survey, horizons from selected pedons were described and sampled, and physical, chemical, and mineralogical properties evaluated by standard methods (Burt, 2004). These data, collected over the past 60 years, have been assembled into a single pedon database (NCSS, 2010).

Surface horizon SOC concentrations from pedons that included land cover were summarized from the NCSS pedon database. Soil C stocks for the 0 to 5 cm and 0 to 1 m depths were calculated from SOC concentrations, bulk density, and coarse fragment content for the same pedons using the calculation method outlined in Waltman et al. (2010). Bulk density data were not available for all horizons from these pedons. If bulk density data were missing a value of 1.45 g cm^{-3} was assumed for mineral horizons and a value of 0.25 g cm^{-3} was assumed for O horizons. These assumed values for missing bulk density may result in overestimation or underestimation of SOC stocks calculated from the pedon data.

The locations of the pedons were overlain on the SSURGO spatial data (soil map) for comparison between SOC concentrations from SSURGO and the NCSS pedon databases. If the soil identified for sampled pedon was not one of the components of the map unit at the pedon location, the data were omitted from the analysis. Comparisons were also made for SSURGO derived and pedon derived SOC stocks. It should be noted that the SOC concentrations are for data from a single pedon, and the SSURGO concentrations and stocks represent spatially weighted averages for soil map units.

3. Results

3.1. Spatial Distribution of Surface Horizon SOC Concentrations and SOC Stocks

Estimates from SSURGO: Mean estimated SOC concentration for the surface horizon derived from SSURGO ranged from less than 1% in LRRs C, D, H, J, and P to more than 10% in LRRs A, K, and R (Table 1). The three LRRs with high SOC are heavily forested and are at relatively high latitudes (Fig. 1). Additionally, LRR K has low relief and associated poorly drained soils. LRRs C, D, H, and J are relatively dry areas with aridic, ustic, or xeric soil moisture regimes (Soil Survey Staff, 2010), and the soils were developed under mid to short grass prairies. LRR P, in the southeast U.S., is dominated by Ultisols developed under forest vegetation. This region was extensively used for crop production during the 1800's and early 1900's, and soil erosion was common. Much of the region has been converted to pastures and forests over the last 30 to 40 years, but the residual effects of past management are reflected in low SOC contents.

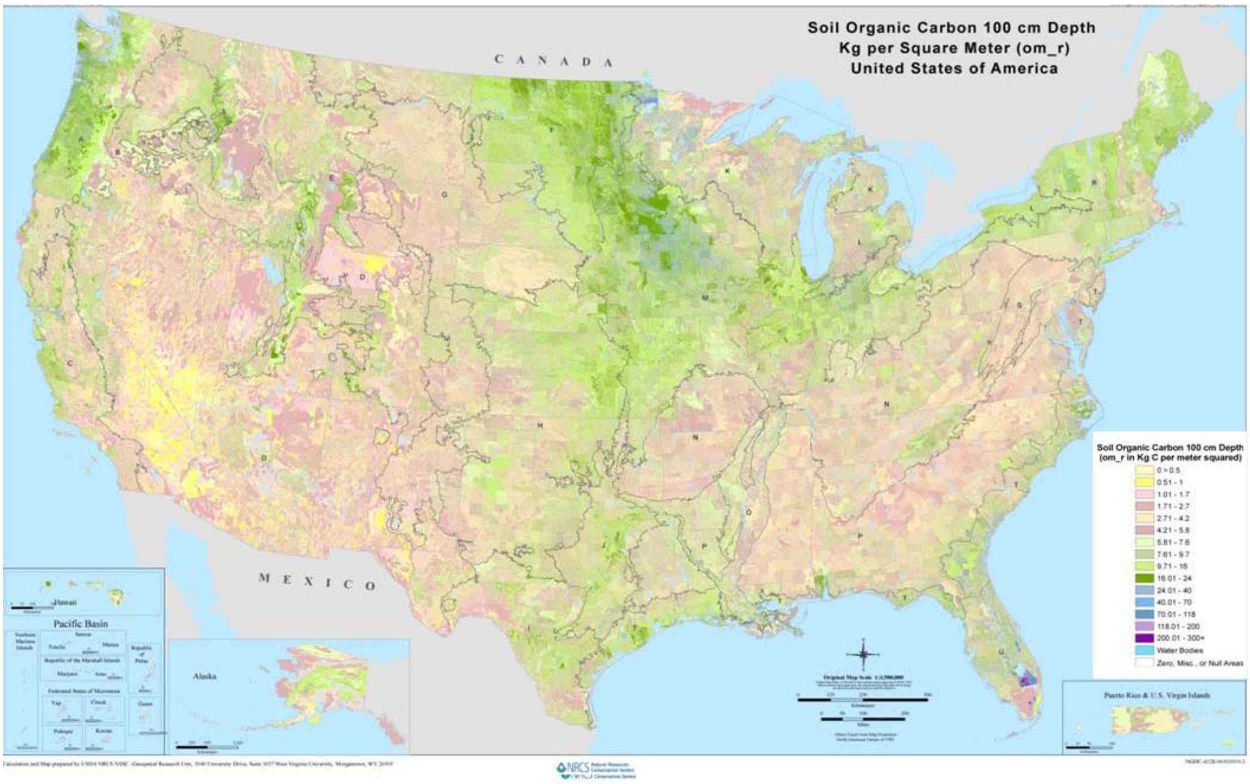

Figure 1. SOC stocks for 0 to 1 m depth derived from SSURGO representative SOC values.

For the conterminous U.S., the total SOC stock for the 0 to 1 m depth is about 65 Pg (Table 2). Like surface horizon SOC concentration, the SOC stocks vary considerably across the U.S. The highest mean SOC stocks for the 0 to 1 m depth are found in LRRs K (22 kg m^{-2}) and U (20 kg m^{-2}) (Fig. 1; Table 1). As previously discussed, LRR K is heavily forested with low relief. LRR U which occurs in peninsular Florida has large areas of low relief along coastlines with associated poorly drained soils. This LRR also contains the Florida Everglades and an extensive area of Histosols associated with this large swamp.

LRRs A, F, L, M, R, and T have mean SOC mass stocks of 12 to 15 kg m^{-2} to 1 m (Table 1, Fig. 1). Although the SOC stocks are similar among these LRRs, climate, relief, and soils vary considerably. LRRs F and M are dominated by Mollisols developed under prairie vegetation. Aquolls are common as are depressional wetlands with Histosols in LRR F. LRR A contains mountainous landscapes with abundant Andisols developed from volcanic parent materials. LRRs L and R are dominantly forested with mesic and frigid soil temperature regimes. LRR T has a thermic soil temperature regime, but is dominantly forest and has many coastal wetlands.

Table 1. Mean SOC concentration, mass, and stocks for U.S. Land Resource Regions. Data derived from SSURGO database.

Land Resource Region (LRR)	Area	Surf. Hor. SOC Conc.	SOC Mass 0-5 cm	SOC Mass 0-1 m	SOC Stock 0-5 cm	SOC Stock 0-1 m	SOC Stock 0-5 cm Proportion of 0-1 m
	km^2	%	Mg X 10^{-6}	Mg X 10^{-6}	kg m^{-2}	kg m^{-2}	%
A	233,635	11.51	535	2,908	2.3	12.4	18.4
B	210,555	1.87	236	1,402	1.1	6.7	16.8
C	161,570	0.84	166	995	1.0	6.2	16.7
D	1424,480	0.87	691	4,933	0.5	3.5	14.0
E	612,875	7.54	1,031	4,435	1.7	7.2	23.3
F	368,535	2.32	1,358	4,633	3.7	12.6	29.3
G	554,395	1.11	532	2,681	1.0	4.8	19.8
H	569,420	0.95	972	4,194	1.7	7.4	23.2
I	187,460	1.19	170	1,259	0.9	6.7	13.5
J	154,695	0.90	212	1,212	1.4	7.8	17.5
K	307,795	11.70	1,539	6,894	5.0	22.4	22.3
L	118,460	4.32	509	1,789	4.3	15.1	28.5
M	731,905	2.02	2,564	10,287	3.5	14.1	24.9
N	612,645	1.33	522	2,962	0.9	4.8	17.6
O	100,710	1.11	206	789	2.0	7.8	26.2
P	684,340	0.90	939	3,976	1.4	5.8	23.6
R	312,625	10.91	974	3,993	3.1	12.8	24.4
S	105,905	1.95	125	550	1.2	5.2	22.8
T	240,055	3.00	731	3,604	3.0	15.0	20.3
U	92,275	5.86	378	1,880	4.1	20.4	20.1

The other LRRs, with the exception of LRR D, have a mean SOC stocks for the 0 to 1 m depth that range from 5 to 8 kg m^{-2} to 1 m (Table 1; Fig. 1). Climate, relief, and parent materials vary widely among these LRRs. In general, soil moisture regimes are ustic, xeric, or aridic and soil temperature regimes are thermic and mesic. Pre-European settlement vegetation was either mid to short grass prairie or forested. LRR D in the arid southwest U.S. has the lowest mean SOC mass concentration, 3 kg m^{-2} to 1 m. This region is dominantly Aridisols and arid Entisols.

The distribution of SOC stocks for the 0 to 5 cm depth is similar to that observed for the 0 to 1 m depth (Table 1). For this depth increment, LRRs K (5.0 kg m^{-2}), L (4.3 kg m^{-2}) and U (4.1 kg m^{-2}) have the highest mean SOC stocks among the LRRs. LRR L has similar soils relief as LRR K. LRRs D, I, and N have SOC 0 to 5 SOC stocks less than 1 kg m^{-2}. Other LRRs have 0 to 5 cm SOC stocks between 1 and 4 kg m^{-2}.

Estimates from NCSS pedon data: Data were available for about 12,000 georeferenced pedons that had land cover identified. SSURGO estimates of SOC concentration and stocks for map units are based on a spatially weighted average of all components in the map unit. The pedons sampled, in many cases, may have represented a minor component of the map unit instead of the one that was most extensive. Because of unknown extensiveness of the component sampled in the map unit, SOC concentration and stock estimates derived from the measurements on the pedons sampled may not be directly comparable to estimates from SSURGO data.

Table 2. Mean SOC concentration, mass, and stocks for U.S. Land Resource Regions. Data derived from measured values from NCSS pedon database.

Land Resource Region (LRR)	N	Surface Horizon SOC Concentration	SOC Stock 0-5 cm	SOC Stock 0-1 m	SOC Stock 0-5 cm: Proportion of 0-1 m
		%	kg m^{-2}	kg m^{-2}	%
A	662	13.47	3.6	19.8	18.1
B	365	3.27	1.5	10.2	15.0
C	437	2.62	1.2	7.8	15.0
D	1,753	2.96	1.2	8.0	15.2
E	804	11.17	2.8	13.1	21.7
F	543	3.40	1.8	13.5	13.4
G	826	2.10	1.2	8.8	13.6
H	1,302	1.38	0.9	8.8	10.5
I	131	1.42	0.8	8.0	10.3
J	149	1.45	1.0	9.2	10.9
K	598	9.17	3.2	16.5	19.6
L	240	10.85	3.2	25.1	12.7
M	2,329	2.39	1.5	12.6	11.6
N	728	11.73	2.7	11.2	23.6
O	111	3.90	1.3	14.1	9.3
P	692	2.41	1.3	7.1	18.3
R	549	17.95	4.2	18.0	23.4
S	196	6.55	2.4	9.9	24.7
T	332	4.67	1.8	14.1	13.1
U	11	8.17	3.5	15.4	22.5

Data for the pedon were omitted from the analysis if the component represented by the pedon was not part of the map unit at the sample location, but the data for the pedon might not reflect the properties of the dominant soil within the map unit. Even with these limitations, comparisons between measured and estimated SOC concentrations and stocks were considered to be useful.

Mean measured surface horizon SOC concentration among the LRRs ranged from 1.4 to 18.0% (Table 2). LRRs with the highest surface horizon SOC concentrations were heavily wooded and most were mountainous with high relief. The LRRs with low surface horizon SOC concentrations (LRRs H, I, and J) occurred in the central and southern Great Plains. In 19 of the 20 LRRs, measured surface horizon SOC concentration was greater than the estimated value in the SSURGO database (Tables 1 and 2), and mean SSURGO surface horizons SOC concentrations was 42% less than the mean of measured values. Reasons for this discrepancy are unclear from this analysis, but may include limited data from which to base estimates for extensive soils and extrapolation of data for a map unit component from and areas of land cover with low SOC to other land covers than promote organic C accumulation.

The mean SOC stocks derived from the pedon data ranged from 1.2 to 3.6 kg m^{-2} for the 0 to 5 cm depth and 7.1 to 25.1 kg m^{-2} for 0 to 1 m (Table 2). For the 0 to 5 cm depth, nine of the LRRs had SOC stock estimates from the pedon data that were higher than those derived from SSURGO. In comparison, 19 of the LRRs had greater measured surface horizon SOC concentrations than the SSUGO estimates. This suggests that bulk density estimates in the SSURGO database are higher than bulk density values in the pedon database or estimated coarse fragment contents are lower.

3.2. Land Cover Effects on Surface Horizon SOC Concentrations and SOC Stocks

Estimates from SSURGO data: Of the four general land cover categories evaluated in this study, forestland had the highest mean surface horizon SOC concentration (4.71%) (Table 3). Surface horizon SOC concentrations were 2.03 and 2.02%, for cropland and grassland, respectively. It was hypothesized that surface horizon SOC concentrations for grassland would be more similar to forestland than cropland. This was not the case, however.

The mean SOC stocks for the 0 to 5 cm depth increment were 1.0, 1.7, and 2.6 kg m^{-2} for cropland, forest, and grassland, respectively (Table 3). The relative magnitude of SOC stocks for these land covers at the shallow depth did not reflect the relative magnitude of surface horizon SOC concentrations. Grassland with the lowest mean surface horizon SOC concentration had the highest SOC stocks, and forestland with the highest mean surface horizon SOC concentration had an intermediate mean SOC stock. The discrepancy between these two data sets is, at least, partially due to high surface horizon bulk density for large areas with grassland cover in the semi-arid and arid western U.S.

Surprisingly, cropland had the greatest mean SOC stocks for the 0 to 1 m depth, 10.7 kg m^{-2} (Table 3). Forest and grassland had similar mean SOC mass concentrations which were about 70% of that found in cropland. SOC concentration did not follow the SOC stock trends. SOC stocks for 0 to 1 m varied considerably among the LRRs with no consistent trends in relative amounts among the three land covers. In general, forestland in LRRs in the northwestern U.S. (LRRs A, B, E, F, and G) and New England (LRR R) tended to have higher surface horizon SOC concentrations than cropland and rangeland, but this difference was not consistently found for SOC stocks for 0 to 1 m (data not shown). These LRRs are mountainous with a large proportion of the forestland occurring on steep slopes. Thus, although surface horizon SOC is high under forest cover, this is not consistently reflected in 0 to 1 m SOC stocks because of shallow soil depths, coarse fragments in the subsoils, and relatively low bulk density in surface horizons.

Table 3. Mean SOC concentration, mass, and stocks for different land cover classes for the conterminous U.S. Data derived from SSURGO database.

Land Cover	Area	Prop. of Total Area	Surf. Hor. SOC Conc.	SOC Mass 0-5 cm	SOC Mass 0-1 m	SOC Stock 0-5 cm	SOC Stock 0-1 m	SOC Stock 0-5 cm Proportion of 0-1 m
	km^2	%	%	Mg X 10^{-6}	Mg X 10^{-6}	kg m^{-2}	kg m^{-2}	%
Cropland	1,245,429	16	2.03	1,282	13,347	1.0	10.7	9.6
Forestland	1,891,581	24	4.71	3,158	14,494	1.7	7.7	21.8
Grassland	1,839,414	24	2.02	4,758	13,732	2.6	7.5	34.6
Other	2,807,910	36	4.41	5,194	23,805	1.8	8.5	21.8
Total	7,784,335	100		14,392	65,377			

Estimates from NCSS pedon data: For the conterminous U.S., forestland had the highest mean surface horizon SOC concentration, 12.4%, with cropland and grassland having considerably lower measured concentrations; 2.2 and 2.6%, respectively (Table 4). High SOC concentrations under forest as was observed in these data have often been often reported (Follett et al., 2009). SOC concentrations that are similar for cropland and grassland land covers have been less commonly observed. The number of pedons analyzed from arid and semi-arid rangelands with associated relatively low biomass inputs and potential for rapid organic matter decomposition is hypothesized to reduced the nationwide average for grassland.

Table 4. Mean SOC concentration, mass, and stocks for land cover classes for the conterminous U.S. Data derived from measured values from NCSS pedon database.

Land Cover	N	Surface Horizon SOC Concentration	SOC Stock 0-5 cm	SOC Stock 0-1 m
		%	kg m^{-2}	kg m^{-2}
Cropland	3,430	2.20	1.3	11.5
Forestland	2,346	12.41	3.2	14.4
Grassland	3,390	2.59	1.4	10.3
Other	3,620	4.63	1.7	11.7
Total	12,786			

The relative magnitude of cropland and rangeland SOC concentrations are similar to those in the SSURGO database. Measured values for forestland, however, are considerably higher than the estimated SSURGO values (Table 3 and 4). The discrepancy between the measured and estimated values may have resulted from omission of O horizons in the SSURGO database because the SSURGO data are not varied by land cover. If O horizons are not found under cropland and grassland, presence and attribute data for these horizons would probably not be included in the SSURGO database. In addition, sampled pedons on which the SSURGO estimates are based may not have included O horizons.

For the 0 to 5 cm depth, mean measured SOC stocks were 1.3, 3.2, and 1.4 kg m^{-2} for cropland, forestland, and grassland, respectively (Table 4). These values reflect the relative magnitude of the measured surface horizon SOC concentrations. The SOC stocks for cropland calculated from measured data were similar to those derived from SSURGO data (Table 3 and 4). The SOC stocks from measured data for forestland, however, were considerably higher than those from SSURGO data which reflects the difference in surface horizon SOC concentration as discussed above. The SOC stocks for grasslands derived from the pedon data were similar to those for cropland, but were considerably lower than grassland SOC stocks calculated from SSURGO data. Overestimation of bulk density for map unit components in extensive rangeland areas may have contributed to this discrepancy.

Mean measured SOC stocks for 0 to 1 m were 11.5, 14.4, and 10.3 kg m^{-2}, for cropland, forestland, and grassland, respectively (Table 4). Again, these SOC stocks reflect the surface horizon SOC concentrations although the magnitude of the difference between forestland and the other land covers is less than was observed for SOC concentration and SOC stocks for 0 to 5 cm. Shallow depth to bedrock and high coarse fragment content in soils with forest cover in high relief areas may have reduced forestland SOC stocks relative to the other land covers.

3.3. Relation of SSURGO and Pedon Data

The overall relationship between SOC stocks for the 0 to 1 m depth derived from measured pedon data and those in the SSURGO database is poor (Fig. 2). This relationship suggests that SOC stocks calculated from SSURGO estimates were considerably less than those calculated from measured data. Many properties of map unit components can be estimated with reasonable accuracy from a combination of data collected for a few pedons and field observations over the larger area in which the soil occurs. These data, however, suggest that organic C cannot be consistently estimated by these methods. This is because SOC content is strongly influenced by land cover, agricultural management, and other disturbances in addition to soil properties such as texture and drainage. Although soil color is generally related to SOC content, differences in soil color among land covers and managements are not great enough to allow reliable prediction of SOC content.

During the early stages of the U.S. National Cooperative Soil Survey, the emphasis was to map and collect data for soils used for crop production. Thus, a large amount of the SOC data in the NCSS pedon database reflects cropland management, and in many cases, the management system included intensive tillage. These are the data that served as the basis for SOC estimates in SSURGO for many of the soils.

The SSURGO database allows entry of a low, representative, and high value for soil properties to accommodate the range of property values that may occur over the aerial extent of a soil. Without data to support estimates of the range or viable relationships to predict a property value, however, the property estimates may have considerable error. Data to accurately reflect the effect of land cover and management on SOC content are available for a few soils but the number is small compared to the number of soils recognized in the U.S. Thus, data used as the basis for SSURGO SOC concentrations may have been from a single land cover and in many cases, may have been from a different soil in the area that had similar properties. The combination of limited data, preponderance of data from cropland management, and lack of a reliable method to estimate SOC from other soil properties appears to have resulted in the low estimates of SOC content in the SSURGO database.

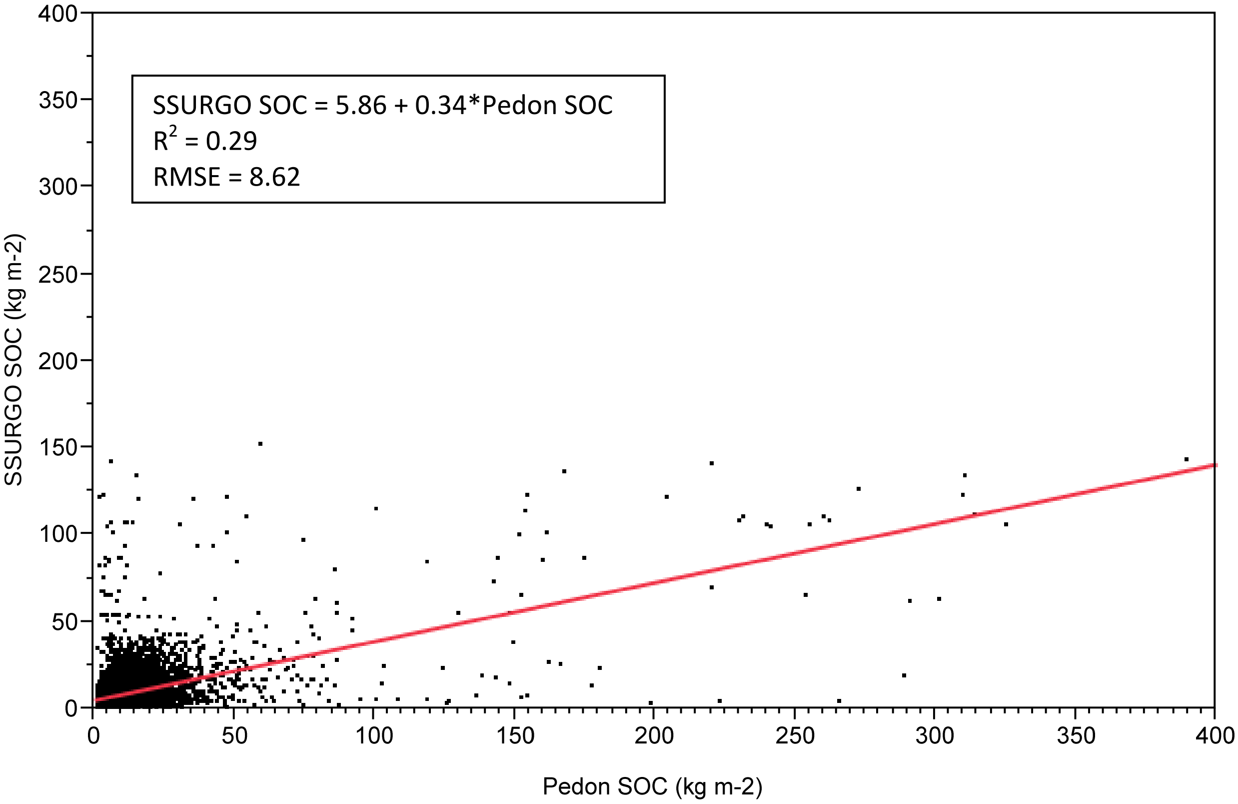

Figure 2. Relation between 0 to 1 m SOC stocks derived from measured pedon and SSURGO databases.

Proportion of SOC stocks at Shallow Depth: SOC stocks were calculated from both SSURGO and pedon data of the 0 to 5 and 0 to 100 cm depths to better understand the depth distribution of SOC, especially as it relates to shallow sampling and carbon predictions from remotely sensed data and imagery. The proportion of the 0 to 1 m SOC stocks that occurred in the shallow, 0 to 5 cm, depth increment was less than 35% independent of land cover, LRR, or database from which the SOC stocks were calculated (Tables 1, 2, 3, and 4). These data emphasize the fact that most soils have a considerable amount of SOC below the upper few centimeters. The deeper organic C may occur in A horizons that are thicker than 5 cm or in subsoil C accumulations in spodic horizons or buried A horizons. Even if the soil has a typical depth distribution of SOC, small concentrations of SOC in the large volume of soil to a 1 m depth result in large amounts of SOC stocks compared to that contained in a thin surface layer.

As the data discussed above have illustrated, existing soil survey data do not adequately represent SOC stocks for all soils in the U.S., especially as they are affected by land cover and agricultural management. Thus, the USDA-NRCS and the NCSS have initiated an effort to collect additional soil C data to develop a comprehensive and statistically valid database of soil C stocks for all soils in the country. The following section describes the general protocol for this data collection.

The objectives of this program are 1) to evaluate differences in soil carbon associated with differing soil properties, agricultural management systems, ecosystems, and land uses and apply these differences to improving existing decision support tools, and 2) to develop a scientifically-based and statistically valid baseline inventory of soil C stocks for the U.S.

The initial phase of the project is evaluation of existing SSURGO data for map units and comparison of these data with pedon data to evaluate applicability of the SSURGO estimates of SOC stocks for a national inventory. Results of this evaluation are partially presented above. The second phase of the effort is to collect soil carbon and related data for broad soil groups based on Benchmark and other important soils. This data collection design includes stratification within the soil groups by land cover, steady-state agricultural management, ecosystem, and land use conditions. These data will be extrapolated using statistical and modeling techniques to predict expected trends in estimated carbon sequestration or evolution from the nation’s soils over the next one or two decades.

The protocol used for field evaluation of soil C and related properties, soil morphology, bulk density and coarse fragment content, is based on the concept of substituting space for time. The assumption underlying this technique is that evaluations of different management or ecological conditions on the same soil at a point in time are equivalent to evaluating soil C at a single site over time after a change in land use or agricultural management system. Using this concept, all lands in the U.S. and all ecosystems, including agricultural management systems and minor ecosystems such as wetlands and floodplains, will be evaluated.

Soil grouping: Without extraordinary effort, soil C stocks cannot be evaluated for all soils, ecosystems, land uses, and agricultural management systems that occur in the U.S. Reasonable groupings of soils, ecosystems, and management systems have been developed that are expected to result in similar soil C stocks to a depth of 1 m and were expected to respond to differences in land cover and land use. The soil series or map unit component was chosen as the means to stratify soil sampling and data collection since the map unit component incorporates soil properties, landscape characteristics, and climate. Other variables affecting soil carbon stocks including agricultural management systems, ecosystem types, and land uses, were stratified within the soil groups.

To create the soil groups, properties of each soil series that occurs in the U.S. were evaluated from the NCSS Official Series database. Properties considered included soil Great Group, family particle size class, soil temperature regime, depth to restrictive layer, and drainage class. Each property was assigned a numerical score, and the scores were summed for each soil in a manner similar to the similar-dissimilar soil model proposed by Norfleet and Eppinette (1993). These scores and resulting sums were subjected to multiple reviews by NRCS and academic soil scientists and modified as needed. To create groups of soils with similar expected C dynamics, the overall score for each soil was subjected to a hierarchical clustering analysis.

Agricultural management systems, ecosystems, and land uses: The goal of the Rapid C Assessment is to evaluate carbon stocks for all ecosystems including agricultural management systems, forest, grasslands, wetlands, etc. As with the soils, time and resources available preclude evaluation of all management systems, land uses, and ecological sites that occur within a region. Thus, data collection will focus on management systems, land uses, and/or states of ecological sites that are most common, most degraded, and those considered to be optimal and expected to have the highest soil carbon stocks within the soil grouping. This approach allows current soil carbon stocks to be documented and reasonable estimates of projected carbon stocks if management was changed to one expected to degrade soil carbon or one expected to be optimum for carbon sequestration.

For efficiency, various “minor” permutations of agricultural management systems and ecological sites were grouped into categories expected to result in similar amounts of soil carbon. This approach does not address minor changes in soil carbon that may be due to minor differences in management such as changes in the frequency of crop rotations, differences in fertilizer applications, cover crops, differences in yield, etc. The assumption is that minor changes in soil carbon stocks induced by these types of management differences would not be detectable with the proposed sampling scheme. The proposed scheme, however, will provide statistically valid data for comparison among major management systems, e.g. conventional clean tillage and no-till systems, and major states of ecological sites.

For the space for time method to be effective in evaluating the effect of agricultural management and ecological states on soil carbon stocks, the management system or ecological state must be in a steady-state condition. Otherwise, data collected will represent an unknown point during the transition instead of the condition after soil carbon has equilibrated to the new system. Thus, use of this protocol will provide information on the potential impact of management and ecosystem state changes on soil carbon but will provide no indications of the rate of the change. Rate of change must be evaluated with monitoring studies beyond the scope of this effort.

It is anticipated that ancillary studies to address particular local issues will be incorporated into the larger data collection effort. For example, sites on characteristic hillslopes or map units within a region may be intensively sampled to evaluate differences in organic carbon and bulk density associated with soil parent material, landscape position, or other attributes such as erosion. Relationships developed from these smaller studies can be applied to similar landscapes in the region to enhance relationships or potentially reduce the number of sites needed to adequately describe soil carbon stocks for the map units and/or landscapes, especially in areas lacking SSURGO data.

Sample site selection: An analysis of variability in soil carbon stocks derived from existing NCSS pedon data was used to estimate the number of sample points necessary to achieve a selected error and confidence limit for each soil-land cover category. This analysis indicated about 30,000 sample points would be needed to achieve an average 80% confidence in soil C stocks for the 0 to 1 m depth. Difference in variability among soils and ecosystems will translate to different confidence levels for the data. The goal, however, is an nationwide average confidence of 80%.

To enhance efficiency, a cluster sampling design is being employed (Fig. 3). Independent locations are be distributed across the geographic extent of the soil-ecosystem combination. At each location, five sample points are evaluated in a flexible systematic pattern. In addition to time and cost efficiencies gained, cluster sampling also provides information on short and long range variability of soil C stocks.

The locations being sampled are associated with a national network that has been used for a national resource inventory. To avoid bias, a subset of locations was randomly selected from network, and each location was randomly ordered within administrative regions and is being evaluated in order of random selection. To ensure sufficient locations are available to meet sample requirements, an excess number of locations have been selected. Initial evaluation of a location is to determine if the sample points are 1) accessible, 2) have soil properties consistent with those of the soil group the location represents, and 3) have the desired land cover and/or steady-state management system. If any of these three criteria are not met, the location is rejected, and the next location on the list is evaluated.

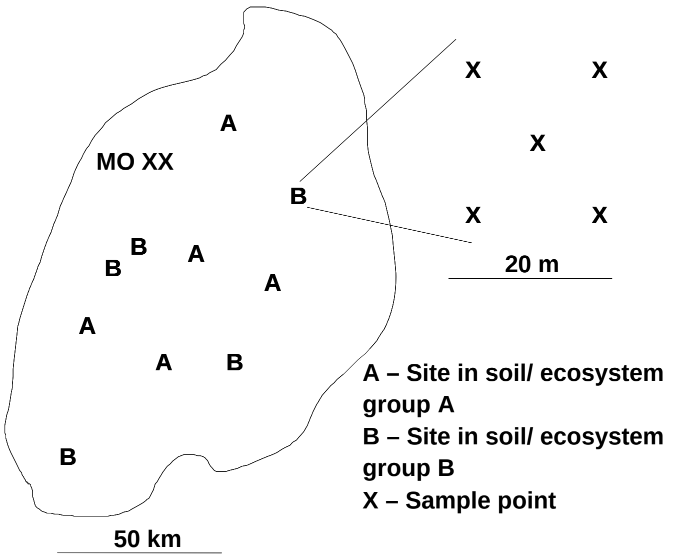

Figure 3. Example of clustered sample design. Sites in two soil-ecosystem/management groups (A and B) are randomly distributed within the region. Sample points (X) are systematically distributed from a central point representing the site.

The total number of locations evaluated in each soil group depends on the areal extent of the group. Each soil group will have a minimum number of locations allocated to ecosystems/management groups occurring in the group. Additional locations will be sampled as area of the soil group increases.

The soil, management, and ecosystem state grouping will result in a matrix similar to the example shown in Table 5. Because soil properties will, in some cases, have an appreciable impact on management systems used and ecosystems present, all soil groups will not have all ecosystem/management groups available for evaluation.

Data Collection: At each sample point, the soil and landscape characteristics will be described to confirm classification and map unit component represented. Soil carbon, bulk density, soil water content, and rock fragment content will be evaluated for each horizon to 1 m. Soil carbon will be estimated from visible and near infrared diffuse reflectance (VNIR) spectra collected in the field or local soil survey office laboratory. The estimates will be based on statistical models developed from spectral libraries collected at the NSSC Soil Survey Laboratory (SSL). Bulk density for each horizon to 50 cm will be determined by appropriate methods that are suitable for site conditions. Bulk density for horizons deeper than 50 cm will be derived from existing data for similar soils or from pedotransfer functions. Rock fragment contents will be measured gravimetrically for fragments <20 mm diameter. For fragments >20 mm diameter, volumetric contents will be estimated visually.

Table 5. Example of soil-ecosystem matrix of the numbers of sample locations.

	Ecosystem A	Ecosystem B	Ecosystem C	Ecosystem D
Soil group S	25*	25	NA	25
Soil group T	25	NA	25	NA
Soil group U	35	35	NA	35
Soil group V	NA	25	NA	25
Soil group W	30	30	NA	30
Soil group X	NA	NA	25	NA

* The number in each block represents the number of sample points that will be evaluated for each soil-ecosystem combination.

Equipment has been purchased, sample locations selected, and sampling has begun for this effort. Expectations are that most samples will be collected over the next year and sample analysis will be completed a few months later. Data will be analyzed and summarized at the National Soil Survey Center, and these data summaries as well as raw data from all locations will be publically available through a web site.

4. Summary

There is an urgent need for site and condition specific soil carbon inventories to increase the reliability of estimates of total national stocks and the amount of carbon that can be practically stored in soil by changing land uses and/or management systems. Results presenter here illustrate the applicability of using detailed soil survey data to meet this need.

Total SOC mass for the conterminous U.S. is about 65 Pg based on data from the SSURGO database, Mean SOC concentrations vary from 0.8 to 11.7%, and mean SOC stocks for the 0 to 1 m depth vary from 3.5 to 22.4 g m^{-2} among U.S. Land Resource Regions. These differences are related to variation in temperature, rainfall, landscape characteristics, and soil properties among the LRRs.

Based on SSURGO data, the nationwide mean surface horizon SOC concentration is 2.0, 2.0, and 4.7% for cropland, forestland, and grassland, respectively. Nationwide mean SOC stocks for the 0 to 1 m depth were 10.7, 7.7, and 7.5 g m^{-2}, for cropland, forestland, and cropland, respectively. The difference in relative magnitude between surface horizon SOC concentration and SOC stock to 1 m illustrates the impact of subsoil horizon properties on SOC stock calculations. Low SOC stocks in forestland as compared to surface horizon SOC concentrations is probably due to more common occurrence of forests in the U.S. on landscapes with high relief and shallow and/or stony soils. The best soils in any region are normally those chosen to grow crops, and as such, are commonly deeper and less stony than soils in areas with rangeland and forestland covers.

SOC concentrations and SOC stocks derived from SSURGO data do not agree well with similar data from measured values in the NCSS pedon database. Reasons for this discrepancy are unclear.

Bias toward cropland land cover, scarcity of pedon data in some regions, and the fact that land cover was not a basis for pedon sampling nor SSURGO estimates probably contribute to this difference.

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