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Soil Organic Carbon Stocks with Depth and Land Use at Various U.S. Sites

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Conversion of native grasslands and forest lands to cultivated agricultural soils is reported to have resulted in the loss of 30 to 75% of the soil organic carbon (SOC) pool, with a corresponding loss of soil organic matter (SOM), especially with the use of the conventional-tillage (CT) production system (Haas et al., 1957; Peterson et al., 1998; Lal et al., 2007). Halvorson et al. (2000) showed that after 27 yr of no-tillage (NT) and intensive crop management, SOM levels under NT were 85% of native sod, whereas SOM under the CT crop-fallow production system was 40% of native sod levels at a Nebraska site. More recently Bianco-Canqui and Lal (2008) reported data indicating the total SOC with NT (0–60 cm) did not differ from that with plow tillage (PT) and that SOC under PT was higher in some cases. Farming methods that result in the loss of SOC contribute to increased levels of atmospheric carbon dioxide (CO_2) (Reicosky et al., 2002). Conversely, increasing levels of SOC stored in the soil can help mitigate the greenhouse effects of CO_2 emitted from agricultural systems (Follett, 2001). The Department of Energy (USDOE, 2006) refers to C sequestration as "the provision of long-term storage of carbon in the terrestrial biosphere, underground, or the oceans so that the buildup of CO_2 (the principal greenhouse gas) concentration in the atmosphere will reduce or slow." Future emissions of C as CO_2 to the atmosphere are expected to continue increasing and, along with other greenhouse gases, contribute to the potential for global climate change. The capture and incorporation into plant tissues of atmospheric CO_2 by photosynthesis incorporates

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CO_2 into plant tops and roots. The subsequent sequestration of plant tissue C into SOM-C as SOC is among the best options for C storage in terrestrial ecosystems. Within the United States, the adoption of recommended management practices (RMPs) such as the use of reduced tillage and NT is estimated to lead to the sequestration of 45 to 98 Tg C yr^{-1} (1 teragram = 1 × 10^{12} g = 1 million tonnes) (Lal et al., 2003). With RMPs and other improved practices, total potential of SOC sequestration in the United States is estimated to be 144 to 432 Mt yr^{-1} (average = 288 Mt yr^{-1}) and is composed of 45 to 98 Mt yr^{-1} SOC sequestered in cropland, 13 to 70 Mt yr^{-1} in grazing land, and 25 to 102 Mt yr^{-1} in forestland. In addition, land conversion, soil restoration, and other land uses result in an additional 61 to 162 Mt yr^{-1} of C sequestration (Lal et al., 2003). However, based on their examination of available data, Baker et al. (2007) recently noted that in nearly all cases where reduced tillage was found to sequester C, most soils were sampled to a depth of 30 cm or less, and in those soils that were sampled deeper, reduced tillage showed no consistent accrual of SOC versus CT. Thus, Baker et al. (2007) concluded that there are other good reasons for the use of reduced tillage, but evidence that it promotes C gain was in their opinion not compelling.

Previously, Follett and coauthors (2001) compared the effects of converting cropped land into the Conservation Reserve Program (CRP) on soil C sequestration. Their research showed that at least 5 yr of perennial grass cover provided by CRP had significantly increased SOC stocks across a broad swath of the Great Plains and western Corn Belt of the United States. However, they did not compare the soil C stocks observed under native vegetation to either cropland or CRP sites, nor did they compare tillage practices. This study re-evaluates the sites previously sampled by Follett et al. (2001) and includes additional sites that have since been sampled. The data provided by this study can allow a better understanding of losses in SOC stocks that existed under native vegetation as a result of cultivation and evaluate the SOC stocks for soils that have had vegetation restored to them. Our objectives are to provide a broadly based data set for native, cropped, and revegetated sites at five depth increments ranging within 0 to 100 cm, to determine how the masses of SOC from cultivated soil differ from paired native soils across a wide region of the United States, and to compare the affects of NT and CT on SOC sequestration within the upper 100 cm of the soil.

Materials and Methods

Soil profile properties (i.e., texture and taxonomic classification) for the native and reference soil sites are shown in Table 3–1. Estimates of the extent and mapped acreage of each identified soil series on a soil survey area basis were obtained for site numbers from the original as well as from the additional sites (Fig. 3–1 and 3–2). The site numbering system shown in Table 3–1 and on Fig. 3–1 is used throughout the remainder of this chapter to identify where the data being discussed originated. The Soil Extent Mapping (SEM) Tool was used to obtain both a snapshot, by soil survey area, of where soil series are located and an estimate of the area occupied by a soil series (Fig. 3–2) (NRCS, 2006). The SEM Tool provides web-accessible national maps of individual soil series based on the land area of the series mapped in the SSURGO 2.1 data source as provided by the NRCS Soil Data Mart (http://soildatamart.nrcs.usda.gov/, using an April 2006 data snapshot). Estimated combined acreage of identified soil series is approximately 9 Mha within 18 states. The basic unit shown on the national series extent maps

Table 3–1. Site identification numbers, soil texture, and taxonomic classification of native and reference sites.

Site	Location	Native/reference vegetation	Soil series	Texture	Taxonomic classification
1, 2	Circleville, OH	Orchard	Miamian	Silt loam	Fine, mixed, active, mesic Oxyaquic Hapludalfs
3, 4	Circleville, OH	Forest	Ross	Silt loam	Fine-loamy, mixed, superactive, mesic Cumulic Hapludolls
5, 6	Circleville, OH	Native prairie	Warsaw	Loam	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiudolls
7, 8, 9	Romney, IN	Native prairie	Millbrook	Silt loam	Fine-silty, mixed, superactive, mesic Udollic Endoaqualfs
10, 11	Overton, NE	Native prairie	Uly/Coly	Silt loam	Fine-silty, mixed, superactive, mesic Typic Haplustolls
12, 13	Idaho Falls, ID	Native prairie	Ririe	Silt loam	Coarse-silty, mixed, superactive, frigid Calcic Haploxerolls
14, 15, 16	Clay Center, KS	Native prairie	Crete	Silt loam	Fine, smectitic, mesic Pachic Argiustolls
17	Akron, CO	Native prairie	Weld	Silt loam	Fine, smectitic, mesic Aridic Argiustolls
18	Lincoln, NE	Native prairie	Crete	Silt loam	Fine, smectitic, mesic Pachic Argiustolls
19	Indianola, IA	Native prairie	Macksburg	Silty clay loam	Fine, smectitic, mesic Aquic Argiudolls
20	Bushland, TX	Restored prairie	Pullman	Clay loam	Fine, mixed, superactive, thermic, Torrertic Paleustolls
21	Dalhart, TX	Native prairie	Dallam	Fine sandy loam	Fine-loamy, mixed, superactive, mesic Aridic Paleustalfs
22	Sidney, MT	Native prairie	Bryant	Loam	Fine-silty, mixed, superactive, frigid Typic Haplustolls
23	Columbia, MO	Native prairie	Mexico	Silt loam	Fine, smectitic, mesic Aeric Vertic Epiaqualfs
24	Glencoe, MN	Native prairie	Nicollet	Clay loam	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
25	Dorothy, MN	Native prairie	Radium	Loamy sand	Sandy, mixed, frigid Oxyaquic Hapludolls
26	Roseau, MN	Native prairie	Percy	Loam	Coarse-loamy, mixed, superactive, frigid Typic Calciaquolls
27	Vinson, OK	Native prairie	Madge	Loam	Fine-loamy, mixed, superactive, thermic Typic Argiustolls
28	Boley, OK	Native prairie	Stephenville	Loamy fine sand	Fine-loamy, siliceous, active, thermic Ultic Haplustalfs
29	Mandan, ND	Native prairie	Farnuf	Loam	Fine-loamy, mixed, superactive, frigid Typic Argiustolls
30	Medina, ND	Native prairie	Barnes	Loam	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls

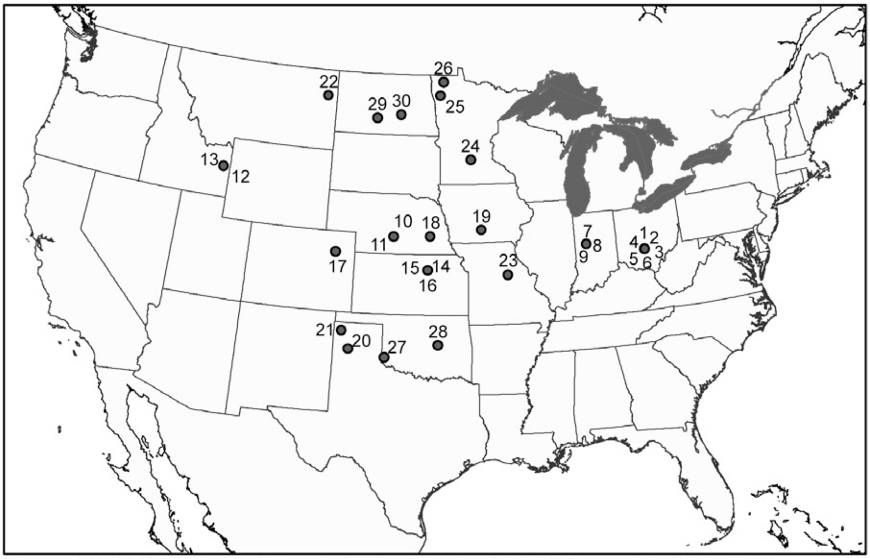

Fig. 3–1. Coterminous U.S. map showing location of soil organic carbon sampling sites.

is a soil survey area (generally a county unit). Figure 3–2 identifies the counties within the various states where individual soil series are located, and the total land area (hectares) mapped for each series. The different shades represent quartile categories for the mapped extent or area of each soil series ranging from light to dark shades, with hatch-marked sections indicating that the soil series is newly included, and data has not yet been reported.

Soil samples were collected from soil pits at depths of 0 to 5 and 5 to 10 cm and by genetic soil-horizon thereafter, with the data reported to a depth of 1 m. Soil pits were dug by backhoe or in a few cases by hand. Soil bulk densities (33 kPa of moisture tension) were determined for each soil layer on clods collected from the face of the excavation and coated with Saran F-310 (Dow Chemical, Midland, MI) for transport (NRCS, 2004).[1] Samples from each soil layer were processed through a 2-mm sieve, ground, and the organic C and inorganic C present measured, but only SOC is reported here. Soils were oven dried (55°C), weighed, and analyzed for C using a Carlo Erba C/N analyzer (Haake Buchler Instruments, Saddle Brook, NJ). Alternatively, soil C analyses were determined using an Elementar varioEL (Elementar Analysensysteme GmbH, Hanau, Germany) (procedure number 4H2a1) (NRCS, 2004). Soil bulk densities were determined using the clod method (procedure number 3B1) (NRCS, 2004). The weights of SOC by soil profile layer were calculated using thicknesses, bulk densities, and C analyses data. Recalculation from the horizon data was necessary to statistically analyze and report the SOC data for discrete depth increments that were deeper than 10 cm. Bulk density and SOC concentration were not recalculated for discrete depth increments from the soil profile. The data reported is for depth increments of 0 to 100, 0 to 10, 10 to 20, 20 to 30, 30 to 60, and 60 to 100 cm. Statistical analyses were performed using SigmaStat 3.0 (SPSS, 2003).

[1] Trade and company names are included for the benefit of the reader and do not imply endorsement or preferential treatment of the product by the authors or the USDA.

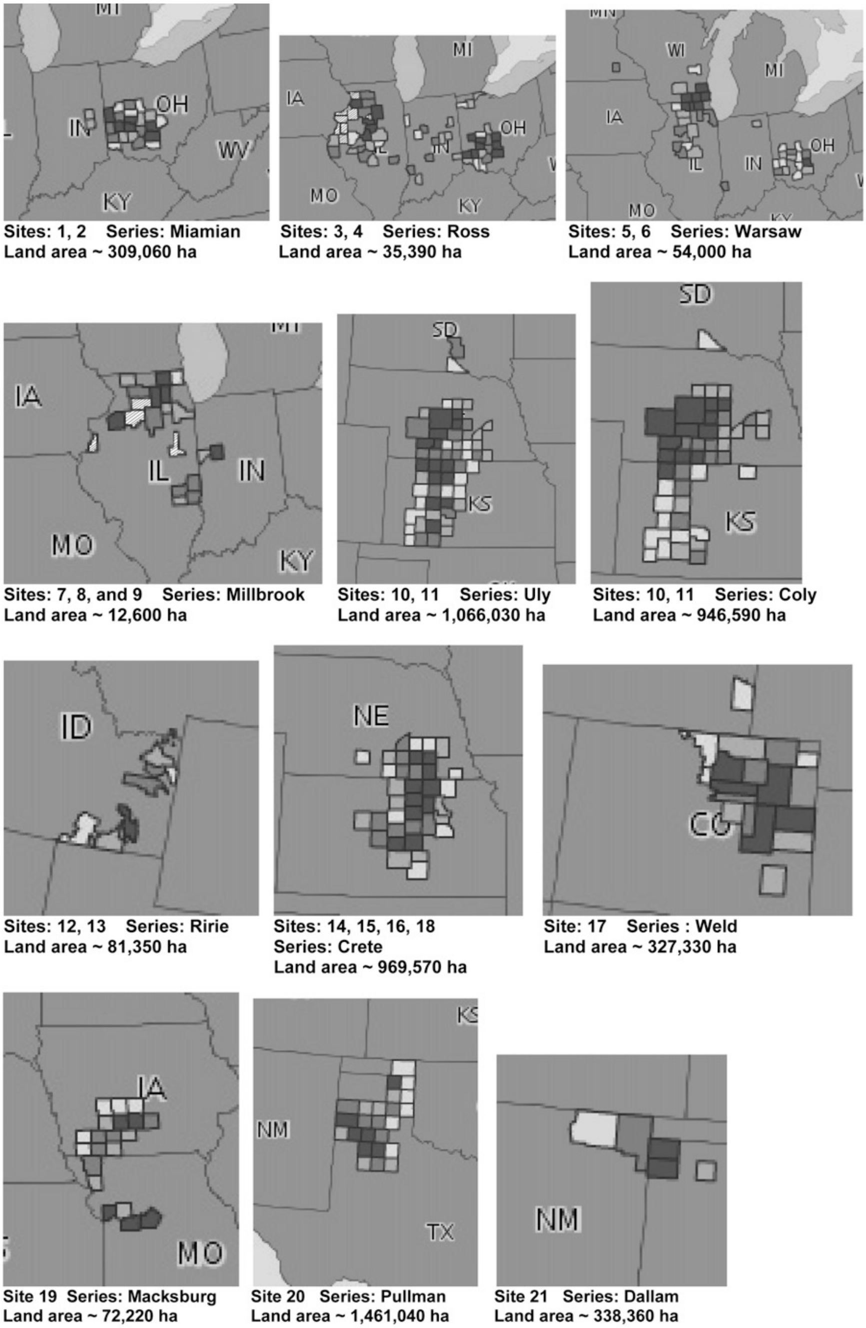

Fig. 3–2. Extents of sampled soil series mapped within various states and counties. Extent of soil series is expressed in hectares as determined by the Soil Extent Mapping Tool (NRCS, 2006). Figure continued on next page.

Total SSA = 8,986,120 ha

Fig. 3–2. Continued.

Results and Discussion

The 67 total sets of data reported here are from a wide region of the United States and include those from native (Table 3–2), cropped (Table 3–3), and revegetated (Table 3–4) treatments. These three tables show the mass of SOC (in kg SOC ha^{-1}) found in the top 100 cm of soil and within five individual depth increments to the depth of 100 cm. In each table, including subsequent tables, the site identification numbers are the same as those shown in Table 3–1 and Fig. 3–1 and 3–2. Average treatment values and of the population standard deviation are shown near the bottom of the tables. The values provided in these first three tables occasion a re-evaluation of the statement that conversion of native grass and forested lands to cultivated agricultural soils have generally resulted in the loss of 30 to

Table 3–2. Mass of soil organic carbon by soil depth increment for native and reference sites.

Site	Location	Native/reference vegetation	Soil series	Depth increment (cm)					
				0–100	0–10	10–20	20–30	30–60	60–100
				kg C ha^{-1}					
1, 2	Circleville, OH	Orchard	Miamian	139,476	40,955	25,944	16,497	24,975	31,105
3, 4	Circleville, OH	Forest	Ross	223,196	42,902	19,530	43,324	71,066	46,374
5, 6	Circleville, OH	Native prairie	Warsaw	183,429	40,786	26,775	25,459	40,424	49,985
7, 8, 9	Romney, IN	Native prairie	Millbrook	143,678	44,208	6,224	43,103	26,802	23,340
10, 11	Overton, NE	Native prairie	Uly/Coly	94,758	34,740	13,888	10,000	24,594	11,536
12, 13	Idaho Falls, ID	Native prairie	Ririe	150,190	26,822	21,771	21,123	45,370	35,104
14, 15, 16	Clay Center, KS	Native prairie	Crete	184,754	38,032	21,887	24,428	59,046	41,360
17	Akron, CO	Native prairie	Weld	88,028	22,719	12,303	11,184	25,989	15,833
18	Lincoln, NE	Native prairie	Crete	109,679	39,387	4,178	36,669	27,812	1,633
19	Indianola, IA	Native prairie	Macksburg	103,199	34,719	16,987	16,987	23,384	11,122
20	Bushland, TX	Restored prairie	Pullman	81,714	15,845	13,221	10,951	23,493	18,204
21	Dalhart, TX	Native prairie	Dallam	65,307	11,387	5,438	5,235	19,776	23,471
22	Sidney, MT	Native prairie	Bryant	136,631	34,646	19,962	16,938	35,065	30,021
23	Columbia, MO	Native prairie	Mexico	103,093	28,790	15,967	10,428	28,583	19,325
24	Glencoe, MN	Native prairie	Nicollet	192,639	46,172	47,702	39,326	43,247	16,192
25	Dorothy, MN	Native prairie	Radium	58,374	19,181	14,314	7,131	13,720	4,027
26	Roseau, MN	Native prairie	Percy	99,561	46,644	19,085	9,426	13,700	10,705
27	Vinson, OK	Native prairie	Madge	65,263	12,874	8,452	7,096	19,376	17,465
28	Boley, OK	Native prairie	Stephenville	54,076	14,105	7,555	6,340	13,029	13,047
29	Mandan, ND	Native prairie	Farnuf	119,220	28,831	17,254	16,702	33,775	22,657
30	Medina, ND	Native prairie	Barnes	149,055	57,786	21,817	21,817	24,146	23,488
			Average	127,671	33,614	16,746	20,976	32,557	23,779
			SD	45,105	11,583	8,922	12,482	15,069	12,640

Table 3–3. Mass of soil organic carbon by soil depth increment for cropped sites.†

Site	Location	Tillage and crop	Soil series	Depth increment (cm)					
				0–100	0–10	10–20	20–30	30–60	60–100
				kg C ha^{-1}					
1	Circleville, OH	NT corn, 50-cm rows	Miamian	107,798	18,530	13,940	11,182	29,067	35,099
2	Circleville, OH	CT corn, 76-cm rows	Miamian	104,997	18,802	17,094	12,999	27,528	28,574
3	Circleville, OH	NT soybeans, 50-cm rows	Ross	307,560	28,796	32,802	32,802	41,861	112,906
4	Circleville, OH	CT soybeans, 50-cm rows	Ross	291,699	28,134	26,296	27,541	110,756	98,972
5	Circleville, OH	NT corn, 76-cm rows	Warsaw	188,203	26,127	25,384	23,495	57,219	55,978
6	Circleville, OH	CT corn, 76-cm rows	Warsaw	175,458	26,333	21,021	19,774	56,194	52,166
7	Romney, IN	NT corn/soybeans, 76-cm rows	Millbrook	85,482	23,265	5,742	20,299	18,376	17,800
8	Romney, IN	NT corn/injected hog manure	Millbrook	117,560	27,002	5,544	18,480	45,408	21,126
9	Romney, IN	CT corn/soybeans, 76-cm rows	Millbrook	69,076	15,836	12,683	10,296	5,140	25,120
10	Overton, NE	NT irrigated corn, 6 yr	Uly/Coly	43,726	15,712	8,768	4,347	7,915	6,984
11	Overton, NE	CT soybeans	Uly/Coly	44,330	16,732	6,106	2,982	9,901	8,609
12	Idaho Falls, ID	NT irrigated barley	Ririe	123,141	27,507	14,342	14,059	30,671	36,562
13	Idaho Falls, ID	CT irrigated barley	Ririe	79,906	14,854	11,039	7,927	22,122	23,964
14	Clay Center, KS	NT irrigated sorghum/hog manure, 5 yr	Crete	103,951	21,810	18,834	10,496	29,457	23,355
15	Clay Center, KS	NT corn/wheat/injected hog manure, 2 yr	Crete	133,127	24,423	25,662	18,689	40,320	24,033
16	Clay Center, KS	CT wheat	Crete	94,943	17,390	14,577	13,015	25,466	24,496
17	Akron, CO	CT wheat/fallow	Weld	58,998	11,532	9,976	9,031	18,621	9,839
18	Lincoln, NE	CT wheat/fallow	Crete	63,890	14,563	15,628	11,670	13,460	8,569
19	Indianola, IA	CT corn/soybean	Macksburg	103,924	28,251	19,831	15,182	26,233	14,427
20	Bushland, TX	CT wheat/fallow	Pullman	71,447	8,992	11,497	11,078	20,357	19,523
21	Dalhart, TX	CT sorghum/wheat	Dallam	28,874	3,257	4,536	3,767	8,204	9,110
22	Sidney, MT	CT spring wheat/barley	Bryant	139,068	20,477	13,687	15,347	47,322	42,235
23	Columbia, MO	NT double crop soybeans	Mexico	73,935	27,530	6,261	10,566	16,267	13,312
24	Glencoe, MN	CT peas (corn/soybeans)	Nicollet	167,849	33,537	33,604	30,940	45,034	24,735
25	Dorothy, MN	CT barley/corn	Radium	77,154	21,180	22,506	14,027	12,078	7,363
26	Roseau, MN	CT wheat	Percy	90,277	15,475	15,635	15,635	31,185	12,347
27	Vinson, OK	CT cotton/wheat	Madge	41,207	5,367	6,503	6,634	14,766	7,936
28	Boley, OK	CT winter wheat	Stephenville	32,113	4,444	2,925	3,741	10,609	10,393
29	Mandan, ND	CT wheat	Farnuf	110,498	26,484	21,295	18,818	26,726	17,176

Site	Location	Tillage and crop	Soil series	Depth increment (cm)					
				0–100	0–10	10–20	20–30	30–60	60–100
				kg C ha−1					
30	Medina, ND	CT clover/barley/wheat	Barnes	106,743	35,567	11,648	11,648	27,508	20,371
			Average	107,898	20,264	15,179	14,216	29,192	27,103
			SD	64,771	8,195	8,195	7,448	20,653	24,538

† CT, conventional tillage; NT, no-tillage.

Table 3–4. Mass of soil organic carbon by soil depth increment and the plant cover on revegetated sites.

Site	Location	Revegetated/plant cover	Soil series	Depth increment (cm)					
				0–100	0–10	10–20	20–30	30–60	60–100
				kg C ha^{-1}					
7, 8, 9	Romney, IN	Reinvasion by native trees	Millbrook	127,280	31,571	19,434	14,523	27,204	34,548
10, 11	Overton, NE	Alfalfa	Uly/Coly	69,695	23,088	5,376	5,376	14,009	21,846
17	Akron, CO	Bromegrass, intermediate wheat grass	Weld	47,915	12,552	6,193	7,414	12,882	8,874
18	Lincoln, NE	Mostly bromegrass	Crete	66,751	20,105	15,737	7,909	13,538	9,462
19	Indianola, IA	Bromegrass, clover, alfalfa	Macksburg	102,156	31,177	21,623	16,206	22,073	11,077
20	Bushland, TX	Plains bluestem	Pullman	72,934	16,050	10,318	8,950	20,074	17,543
21	Dalhart, TX	Plains bluestem	Dallam	61,843	15,781	5,609	5,645	19,561	15,247
22	Sidney, MT	Bromegrass	Bryant	110,823	19,070	16,122	14,085	34,436	27,109
22	Columbia, MO	Orchard grass, alfalfa	Mexico	69,189	17,904	12,270	9,399	18,556	11,061
24	Glencoe, MN	Orchard, bromegrass, alfalfa	Nicollet	153,004	34,248	25,033	25,033	50,752	17,939
25	Dorothy, MN	Bromegrass	Radium	147,294	47,579	33,844	20,192	36,231	9,446
26	Roseau, MN	Alfalfa, timothy	Percy	99,859	32,929	26,683	22,566	10,201	7,480
27	Vinson, OK	Bermuda grass	Madge	48,905	9,635	6,771	6,469	14,402	11,628
28	Boley, OK	Broomsedge, annual weeds	Stephenville	38,100	7,833	4,073	4,062	11,539	10,594
29	Mandan, ND	Intermediate wheat grass	Farnuf	100,211	27,668	19,150	12,767	23,299	17,328
30	Medina, ND	Alfalfa, bromegrass	Barnes	138,575	32,118	27,919	22,282	35,163	21,094
			Average	65,881	17,242	11,126	8,789	16,012	12,712
			SD	51,888	13,913	10,262	7,806	13,546	11,089

75% of the SOC pool (Haas et al., 1957; Peterson et al., 1998; Lal et al., 2007). However, there is some ambiguity concerning the above statement relative to the depth increment in which the 30 to 75% loss was estimated to have occurred (i.e., only 25 to 70% of the original mass of SOC remaining). We calculated the effect of the cropped versus the revegetated treatments, compared to the native treatments, by subtracting the mass of SOC for each treatment (Tables 3–3 and 3–4, respectively) from the mass of SOC found in the corresponding native treatments (Table 3–2) for each depth increment.

We recognize the large amount of variance that exists in the data we report here. Such variation is expected because of the large region from which the data were collected. Irrespectively, data in Tables 3–2 and 3–3 can be used to calculate masses of SOC across this broad sampling region. Cropping had lowered the SOC in especially the 0- to 10- and to a lesser degree in the 0- to 30-cm depths, where the masses of SOC remaining are 59 ± 20% and 68 ± 21% (±1 SD), respectively, across all cropped sites, compared to the corresponding depths for their paired native sites as calculated from Tables 3–2 and 3–3. The cropped sites when paired with comparable native sites have a mass of SOC present to a depth of 100 cm that averages 78% ± 25% of that found in the native sites, and these values are larger than the 25 to 70% indicated to remain by the literature. By comparison, the effect of revegetation on SOC (Table 3–4) shows a restoration of SOC, particularly at the 0- to 10- and the 0- to 30-cm depths, where the masses of SOC averaged 83 ± 44% and 86 ± 43%, respectively, across all sites, of that observed to the same depths for the corresponding paired native sites. Certainly, these data do not represent all regions of the United States but may indicate that previously reported losses are greater than they should be or that presently used farming practices can maintain and perhaps restore SOC levels in many U.S. soils to near their native levels. Regardless, these data are consistent with those of Follett et al. (2001) who observed that revegetation (CRP) compared to the cropped treatments had resulted in a greater mass of SOC (equivalent to 740 and 910 kg ha^{-1}) in the 0- to 10- and 0- to 20-cm depths, respectively. The data are also consistent with results reported by Novak et al. (2007) who found that when soil cores were collected to a depth of 90 cm after 24 yr, the only significant change (an increase) in SOC occurred under CT (reduced) at the 0- to 5-cm depth when compared to disk-tillage management.

For each soil series at each location, we established an index based on the mass of SOC present in the native treatment, from which we were able to measure management-induced change in SOC (Tables 3–5 and 3–6). A paired *t*-test for a selected data subset was used to compare differences between the mass of remaining SOC in cropped sites to the mass of remaining SOC in revegetated sites (Table 3–6). The *p* value was significant for the 0- to 10-cm depth increment, a result consistent with observations by both Follett et al. (2001) and Novak et al. (2007). The value of *p* was not significant for the 10- to 20-cm depth increment (p = 0.12), and the value of *p* did not improve sufficiently to be significant for any of the other depth increments. However, the average differences between the native and the cropped treatments were greater than for the difference between the SOC in the native minus the revegetated treatments for all increments except the 60- to 100-cm depth. The relationship of mass of SOC in native treatments minus revegetated treatments (increment a, Fig. 3–3) versus the native treatment minus the cropped treatment (increment b, Fig. 3–3) illustrates that the mass of SOC in the

Table 3–5. Difference in mass of soil organic carbon by soil depth increment of native minus cropped sites.†

Site	Location	Soil series	Tillage and crop	Depth increment (cm)					
				0–100	0–10	10–20	20–30	30–60	60–100
				kg C ha^{-1}					
1	Circleville, OH	Miamian	NT corn, 50-cm rows	31,678	22,425	12,004	5,335	−4,092	−3,994
2	Circleville, OH	Miamian	CT corn, 76-cm rows	34,479	22,153	8,850	3,498	−2,553	2,531
3	Circleville, OH	Ross	NT soybeans, 50-cm rows	−84,364	14,106	−13,272	10,552	−41,840	−53,880
4	Circleville, OH	Ross	CT soybeans, 50-cm rows	−68,502	14,768	−6,766	15,783	−39,690	−52,598
5	Circleville, OH	Warsaw	NT corn, 76-cm rows	−4,774	14,659	1,391	1,964	−16,795	−5,993
6	Circleville, OH	Warsaw	CT corn, 76-cm rows	7,971	14,453	5,754	5,715	−15,770	−2,181
7	Romney, IN	Millbrook	NT corn/soybeans, 76-cm rows	58,196	20,943	482	22,804	8,426	5,541
8	Romney, IN	Millbrook	NT corn/injected hog manure	26,118	17,206	680	24,623	−18,606	2,214
9	Romney, IN	Millbrook	CT corn/soybeans, 76-cm rows	74,602	28,372	−6,459	32,807	21,662	−1,780
10	Overton, NE	Uly/Coly	NT irrigated corn, 6 yr	51,032	19,028	5,120	5,653	16,679	4,552
11	Overton, NE	Uly/Coly	CT soybeans	50,428	18,008	7,782	7,018	14,693	2,927
12	Idaho Falls, ID	Ririe	NT irrigated barley	27,049	−685	7,429	7,065	14,698	−1,458
13	Idaho Falls, ID	Ririe	CT irrigated barley	70,284	11,968	10,732	13,197	23,247	11,140
14	Clay Center, KS	Crete	NT irrigated sorghum/hog waste, 5 yr	80,802	16,222	3,053	13,932	29,590	18,005
15	Clay Center, KS	Crete	NT corn/wheat/injected hog waste, 2 yr	51,627	13,609	−3,775	5,739	18,726	17,327
16	Clay Center, KS	Crete	CT wheat	89,811	20,642	7,311	11,413	33,581	16,864
17	Akron, CO	Weld	CT wheat/fallow	29,029	11,187	2,327	2,153	7,368	5,994
18	Lincoln, NE	Crete	CT wheat/fallow	45,789	24,824	−11,450	24,999	14,351	−6,936
19	Indianola, IA	Macksburg	CT corn/soybean	−725	6,468	−2,844	1,805	−2,849	−3,305
20	Bushland, TX	Pullman	CT wheat/fallow	10,267	6,852	1,724	−127	3,137	−1,319
21	Dalhart, TX	Dallam	CT sorghum/wheat	36,433	8,131	901	1,468	11,572	14,361
22	Sidney, MT	Bryant	CT spring wheat/barley	−2,437	14,169	6,274	1,591	−12,257	−12,214
23	Columbia, MO	Mexico	NT double crop soybeans	29,158	1,261	9,706	−138	12,316	6,013

Table continued.

Table 3–5. Continued.†

Site	Location	Soil series	Tillage and crop	Depth increment (cm)					
				0–100	0–10	10–20	20–30	30–60	60–100
24	Glencoe, MN	Nicollet	CT peas/corn/soybeans	24,790	12,635	14,098	8,386	−1,786	−8,543
25	Dorothy, MN	Radium	CT barley/corn	−18,779	−1,999	−8,192	−6,896	1,643	−3,336
26	Roseau, MN	Percy	CT wheat	9,283	31,169	3,450	−6,209	−17,486	−1,642
27	Vinson, OK	Madge	CT cotton/wheat	24,056	7,506	1,949	462	4,610	9,528
28	Boley, OK	Stephenville	CT winter wheat	21,963	9,661	4,630	2,598	2,420	2,654
29	Mandan, ND	Farnuf	CT wheat	8,721	2,347	−4,041	−2,115	7,049	5,481
30	Medina, ND	Barnes	CT clover/barley/spring wheat	42,313	22,219	10,169	10,169	−3,362	3,117
			Average	25,210	14,144	2,301	7,506	4,658	−1,453
			SD	37,392	8,083	6,836	9,166	16,265	17,329

† CT, conventional tillage; NT, no-tillage.

Table 3–6. Difference in mass of soil organic carbon by soil depth increment of native minus cropped versus native minus revegetated sites.

Site	Location	Soil series	Tillage and plant cover	Depth increment (cm)					
				0–100	0–10	10–20	20–30	30–60	60–100
				kg C ha^{-1}					
7	Romney, IN	Millbrook	Reinvasion by native trees	16,398	12,638	−13,210	28,580	−402	−11,208
10	Overton, NE	Uly/Coly	Alfalfa	25,063	11,652	8,512	4,624	10,585	−10,310
17	Akron, CO	Weld	Bromegrass/intermediate wheat grass	40,113	10,167	6,110	3,770	13,107	6,959
18	Lincoln, NE	Crete	Switchgrass/predominantly bromegrass	42,927	19,281	−11,559	28,760	14,274	−7,829
19	Indianola, IA	Macksburg	Bromegrass, switchgrass, clover, alfalfa	1,043	3,542	−4,636	781	1,311	45
20	Bushland, TX	Pullman	Plains bluestem	8,780	−205	2,903	2,001	3,420	661
21	Dalhart, TX	Dallam	Plains bluestem	3,464	−4,393	−171	−410	215	8,224
22	Sidney, MT	Bryant	Bromegrass	25,809	15,576	3,839	2,853	628	2,913
23	Columbia, MO	Mexico	Orchard grass/alfalfa	33,904	10,887	3,697	1,029	10,027	8,264
24	Glencoe, MN	Nicollet	Orchard grass/bromegrass/alfalfa	39,635	11,924	22,669	14,293	−7,504	−1,747
25	Dorothy, MN	Radium	Brome	−88,920	−28,398	−19,530	−13,061	−22,511	−5,420
26	Roseau, MN	Percy	Alfalfa/timothy	−298	13,716	−7,598	−13,140	3,499	3,225
27	Vinson, OK	Madge	Bermuda grass	16,358	3,239	1,681	627	4,975	5,837
28	Boley, OK	Stephenville	Broomsedge/annual weeds	15,976	6,272	3,482	2,278	1,490	2,453
29	Mandan, ND	Farnuf	Alfalfa, intermediate wheat grass	19,008	1,163	−1,896	3,936	10,477	5,329
30	Medina, ND	Barnes	Alfalfa, wheat grass, clover, bromegrass	10,480	25,668	−6,102	−465	−11,016	2,395
			Average	13,109	7,045	−738	4,154	2,036	612
			SD	29,556	11,769	9,606	11,142	9,251	6,111
Paired *t* test, 16 native cropped vs. 16 native revegetated (Table 3–5 vs. 3–6): value of p =				0.13	0.02	0.12	0.99	0.64	0.74

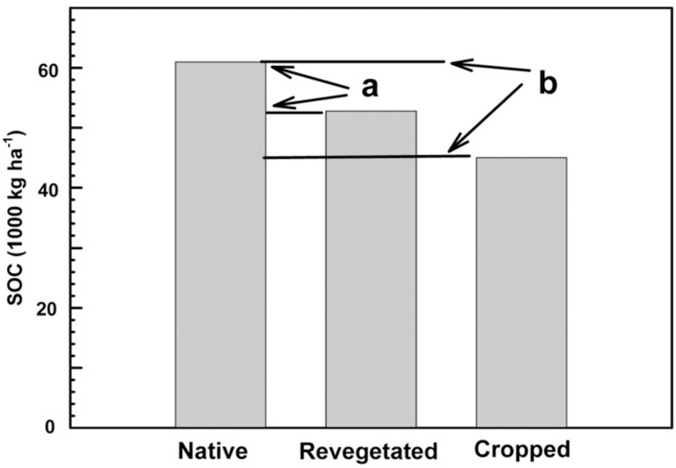

Fig. 3–3. When the mass of soil organic carbon (SOC) from comparable sites (0–30 cm depth) of revegetated and cropped treatments is subtracted from the mass of SOC in the corresponding native treatment, smaller resulting values indicate larger masses of SOC. Data are from sites 17 through 30, which provided a complete data set of all three treatments.

native treatment minus the treatment with the lowest mass of SOC (cropped) will have a larger difference (increment b, Fig. 3–3) than will a treatment with a somewhat larger mass of SOC (revegetated), as shown by the size of increment a (Fig. 3–3). This illustration applies to the values expressed in Tables 3–5, 3–6, and 3–7.

As mentioned earlier, Baker et al. (2007) concluded that, while there may be other good reasons for the use of reduced tillage, the evidence that it promotes C gain was in their opinion not compelling. Recently Blanco-Canqui and Lal (2008) found that in 8 of their 11 profile comparisons there was no significant difference in amount of SOC stored between paired NT and PT treatments to a depth of 60 cm (defined by Blanco-Canqui and Lal as the entire profile). Certainly it is an appropriate challenge to soil scientists to sample deeper, include comparisons for depths below 30 cm, and evaluate in their studies whether reduced tillage does or does not sequester more SOC than CT. The database we have assembled here was not designed to compare SOC sequestration of reduced tillage to CT at depths below 30 cm. However, we can analyze the data that we do have to see if it can in part address the issue raised by Baker et al. (2007) and more recently by Blanco-Canqui and Lal (2008). Table 3–7 shows differences in mass of SOC increment of native minus cropped data from paired sites where CT versus NT data could be compared to a depth of 100 cm and at increments in between. The site ID numbers from Table 3–7 can be used to find the mass of SOC by site and by depth increment from Table 3–5. Sites 9 and 16 were repeated in Table 3–7 and served for comparison with sites 7 and 8 and 14 and 15, respectively, thus facilitating the use of the paired *t*-test. Treatments were compared with their paired native site by subtracting the mass of SOC in the treatments from the mass of SOC for the same depths measured at the native site. Thus, as illustrated in Fig. 3–3, the larger the difference of the native minus the cropped treatment, the less SOC was present at the cropped site (increment b), whereas a smaller difference (increment a) of

Table 3–7. Difference in mass of soil organic carbon by soil depth increment of native minus cropped sites under conventional tillage (CT) versus no-tillage (NT) management. Probability levels by *t* test and by one-way analysis of variance are shown in the bottom row.

Site	Location	Soil series	Treatments	Depth increment (cm)					
				0–100	0–10	10–20	20–30	30–60	60–100
				kg C ha^{-1}					
Conventional									
2	Circleville, OH	Miamian	Corn, 76-cm rows	34,479	22,153	8,850	3,498	−2,553	2,531
4	Circleville, OH	Ross	Soybeans, 50-cm rows	−68,502	14,768	−6,766	15,783	−39,690	−52,598
6	Circleville, OH	Warsaw	Corn, 76-cm rows	7,971	14,453	5,754	5,715	−15,770	−2,181
9	Romney, IN	Millbrook	Corn/soybeans 76-cm rows	74,602	28,372	−6,459	32,807	21,662	−1,780
9	Romney, IN	Millbrook	Corn/soybeans 76-cm rows	74,602	28,372	−6,459	32,807	21,662	−1,780
11	Overton, NE	Uly/Coly	Soybeans	50,428	18,008	7,782	7,018	14,693	2,927
13	Idaho Falls, ID	Ririe	Irrigated barley	70,284	11,968	10,732	13,197	23,247	11,140
16	Clay Center, KS	Crete	Wheat	89,811	20,642	7,311	11,413	33,581	16,864
16	Clay Center, KS	Crete	Wheat	89,811	20,642	7,311	11,413	33,581	16,864
			Average	47,054	19,931	3,117	14,847	10,046	−890
			SD	48,032	5,500	6,959	10,254	23,267	19,659
No-tillage									
1	Circleville, OH	Miamian	Corn, 50-cm rows, NT = 20 yr	31,678	22,425	12,004	5,335	−4,092	−3,994
3	Circleville, OH	Ross	Soybeans, 50-cm rows, NT = 20 yr	−84,364	14,106	−13,272	10,552	−41,840	−53,880
5	Circleville, OH	Warsaw	Corn, 76-cm rows, NT = 19 yr	−4,774	14,659	1,391	1,964	−16,795	−5,993
7	Romney, IN	Millbrook	Corn/soybean, 76-cm rows, 15y	58,196	20,943	482	22,804	8,426	5,541
8	Romney, IN	Millbrook	Corn/injected hog waste, NT ≤ 3yr	26,118	17,206	680	24,623	−18,606	2,214
10	Overton, NE	Uly/Coly	Irrigated corn, NT = 6 yr	51,032	19,028	5,120	5,653	16,679	4,552
12	Idaho Falls, ID	Ririe	Irrigated barley, NT = 18 yr	27,049	−685	7,429	7,065	14,698	−1,458
14	Clay Center, KS	Crete	Irrigated sorghum/hog waste, NT = 5 yr	80,802	16,222	3,053	13,932	29,590	18,005
15	Clay Center, KS	Crete	Corn/wheat/injected hog waste, NT = 2 yr	51,627	13,609	−3,775	5,739	18,726	17,327
			Average	26,374	15,279	1,457	10,846	8,648	−3,371
			SD	45,317	6,335	6,739	7,596	17,050	23,709
Comparison of CT and NT data by paired *t* test: value of *p* =				0.01	0.03	0.44	0.02	0.25	0.33

the native minus the NT treatment would indicate more SOC was present. Paired *t*-tests between CT and NT treatments were conducted on data collected from sites extending from Indiana through Kansas and Nebraska, and into Idaho. The average difference in the 0- to 100-cm depth between the native minus cropped values was 47,000 kg ha^{-1} m^{-1} for the CT treatments. However, the average corresponding difference between native and cropped values for NT treatments was only 26,400 kg ha^{-1} m^{-1}, thus indicating that on average the NT treatments have a mass of SOC nearer to that in the native sites and that the amount in the NT treatment averaged 20,600 kg SOC ha^{-1} greater than in the CT treatment.

The next question that can be addressed to some degree by the data in Table 3–7 is, at what depths, under NT, is the mass of SOC less than, the same, or greater than for the CT treatments? A paired *t*-test was conducted, and the results are reported in Table 3–7. Differences ($P \leq 0.05$) were significant at the $P \leq 0.05$ level for the 0- to 100-, 0- to 10-, and 20- to 30-cm depths. There were no significant differences for the 10- to 20-, 30- to 60-, or the 60- to 100-cm depths. Interestingly, at all depths except at 60 to 100 cm, the average value for the native treatment minus the CT treatment was always greater than for the average for the native treatment minus the NT treatment, thus indicating that overall there was more SOC in the NT than in the CT treatments (Fig. 3–3). Also indicated is that the NT treatments in this study had as much SOC at depths below 30 cm as did the corresponding CT treatments for the soils and cropping systems used for the fields studied.

The above results provide evidence that reduced tillage has resulted in a larger mass of sequestered SOC to a depth of 100 cm in these soils and under these management and cropping conditions than has the CT treatments. However, the authors recognize that sites 8, 14, and 15 (Table 3–7) received hog wastes that could potentially confound the interpretation of the results by providing an additional C source to the NT treatments compared to the CT treatments. To evaluate this effect, the data in Table 3–7 were analyzed with sites 8, 14, and 15 and their CT pairs removed. The subsequent analysis decreased the degrees of freedom for the paired *t*-test, but the total SOC in all increments, except in the 30- to 60-cm depth, still remained larger under NT than under CT, with the amount of SOC in the 0- to 100-cm depth under NT exceeding that under CT by an average of 15,000 kg ha^{-1} ($P = 0.06$). Thus, even though the hog waste may have contributed to the SOC in the NT treatments in Table 3–7, removing those treatment pairs from the analysis of the remaining NT treatments still showed NT to exceed CT pairs by an average 15,100 kg ha^{-1} within the 0- to 100-cm depth increment. Including the hog waste pairs increased the difference between NT and CT treatments to 20,680 kg ha^{-1}.

Summary and Conclusions

The data provided by this study were collected from a total of 67 soil pits representing 21 soil series that were sampled from across a wide region of the United States. These data provide a broadly based data set of SOC measurements. Sampling was designed to compare individual treatments (native, cropped, or revegetated) on the same geomorphic unit, mapped series, slope, and aspect. The results were analyzed based on the differences in masses of SOC with depth among treatments at each site.

Cropped treatments paired across all soil series with native sites had a mass of SOC present in the top 100 cm that averaged 78% of that found in the native sites. Certainly, these data do not represent all regions of the United States and, because of differences in climate and overall management across the extensive sampling area, have a large variance. However, they likely indicate that the farming practices that are presently used do maintain and possibly restore SOC levels in many U.S. soils to nearer to their native levels than is reported in the literature. Regardless, cropping has lowered the SOC in the 0- to 10- and to a lesser degree in the 0- to 30-cm depths, where the masses of SOC remaining are 59 and 68%, respectively, across all cropped sites, compared to the corresponding depths for the native sites. By comparison, the effect of revegetation on the mass of SOC present shows a restoration of SOC, particularly at the 0- to 10- and the 0- to 30-cm depths, where the masses of SOC averaged 83 and 86%, respectively, of the amounts of native SOC.

Sites that allowed the comparison of CT versus NT treatments using a paired *t*-test were selected from the data set. These sites extended from Indiana through Kansas and Nebraska, and into Idaho. Within this subset of data, the NT treatment averaged 20,680 kg ha^{-1} greater mass of SOC within the top 100 cm than did the CT treatment. After removing sites from the analysis that may have been affected by the application of hog waste, NT treatments still averaged 15,100 kg ha^{-1} more SOC within the 0- to 100-cm depth than did the CT treatments. This result offers good evidence that NT and likely reduced-tillage treatments result in a larger mass of sequestered SOC to a depth of 100 cm than do CT treatments. In conclusion, there still exists the issue of where in the soil profile SOC is sequestered, especially under reduced tillage when compared to CT systems. The amount of SOC being sequestered in the top 30 cm of the soil, and its vulnerability to loss, must not be undervalued. However, to more fully understand C storage and sequestration in agricultural systems, soil scientists need to collect data on the mass of SOC at incremental depths to 100 cm. Such data are especially needed from sites that have long-term management records and where NT, CT, or other management treatments can be compared.

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References

Baker, J.M., T.E. Oschner, R.T. Venterea, and T.J. Griffis. 2007. Tillage and soil carbon sequestration: What do we really know? Agric. Ecosyst. Environ. 118:1–5.

Blanco-Canqui, H., and R. Lal. 2008. No-tillage and soil-profile carbon sequestration: On-farm assessment. Soil Sci. Soc. Am. J. 72:693–701.

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 61:77–92.

Follett, R.F., S.E. Samson-Liebig, J.M. Kimble, E.G. Pruessner, and S.W. Waltman. 2001. Carbon sequestration under the Conservation Reserve Program in the historic grassland soils of the United States of America. p. 27–40. *In* R. Lal (ed.) Soil carbon sequestration and the greenhouse effect. SSSA Spec. Publ. 57. SSSA, Madison, WI.

Haas, H.J., C.E. Evans, and E.F. Miles. 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. USDA Technical Bulletin No. 1164. U.S. Gov. Print. Office, Washington, DC.

Halvorson, A.D., C.A. Reule, and L.S. Murphy. 2000. No-tillage and N fertilization enhance soil carbon sequestration. Fluid J. 8(3):8–11.

Lal, R., R.F. Follett, and J.M. Kimble. 2003. Achieving soil carbon sequestration in the United States: A challenge to policymakers. Soil Sci. 168:827–845.

Lal, R., R.F. Follett, B.A. Stewart, and J.M. Kimble. 2007. Soil carbon sequestration to mitigate climate change and advance food security. Soil Sci. 172:943–956.

Novak, J.M., P.J. Bauer, and P.G. Hunt. 2007. Carbon dynamics under long-term conservation tillage and disk tillage management in a Norfolk Loamy Sand. Soil Sci. Soc. Am. J. 71:453–456.

NRCS (Natural Resources Conservation Service). 2004. Soil Survey Laboratory methods manual. Soil Survey Investigations Report No. 42. Version 4.0, November 2004. Rebecca Burt (ed.) Available at http://soils.usda.gov/technical/lmm/ (verified 15 June 2008).

NRCS. 2006. Soil extent mapping tool. Revision 1.2. Available at www.cei.psu.edu/soiltool/ (verified 15 June 2008).

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka. 1998. Reducing tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Tillage Res. 47:207–218.

Reicosky, D.C., S.D. Evans, C.A. Cambardella, R.R. Allmaras, A.R. Wilts, and D.R. Huggins. 2002. Continuous corn with moldboard tillage: Residue and fertility effects on soil carbon. J. Soil Water Conserv. 57:277–284.

SPSS. 2003. SigmaStat, Version 3.0. SPSS Inc., Chicago. Available at www.spss.com (verified 15 June 2008).

USDOE. 2006. Carbon sequestration. Office of Science, DOE. Available at http://cdiac2.esd.ornl.gov/index.html (verified 15 June 2008).