Soil organic carbon and change in soil organic carbon

Modeling the carbon cycle

Plants gather and package energy from the sun through photosynthesis, the process in which plants trap light energy and convert it to chemical energy. Through photosynthesis, plants take in carbon dioxide (CO_2) from the atmosphere and water from the soil, split off the oxygen atom from water, release oxygen gas back to the atmosphere, and combine the carbon atom with other carbon atoms and minerals, including nitrogen and phosphorus, to produce plant tissue and crop yield.

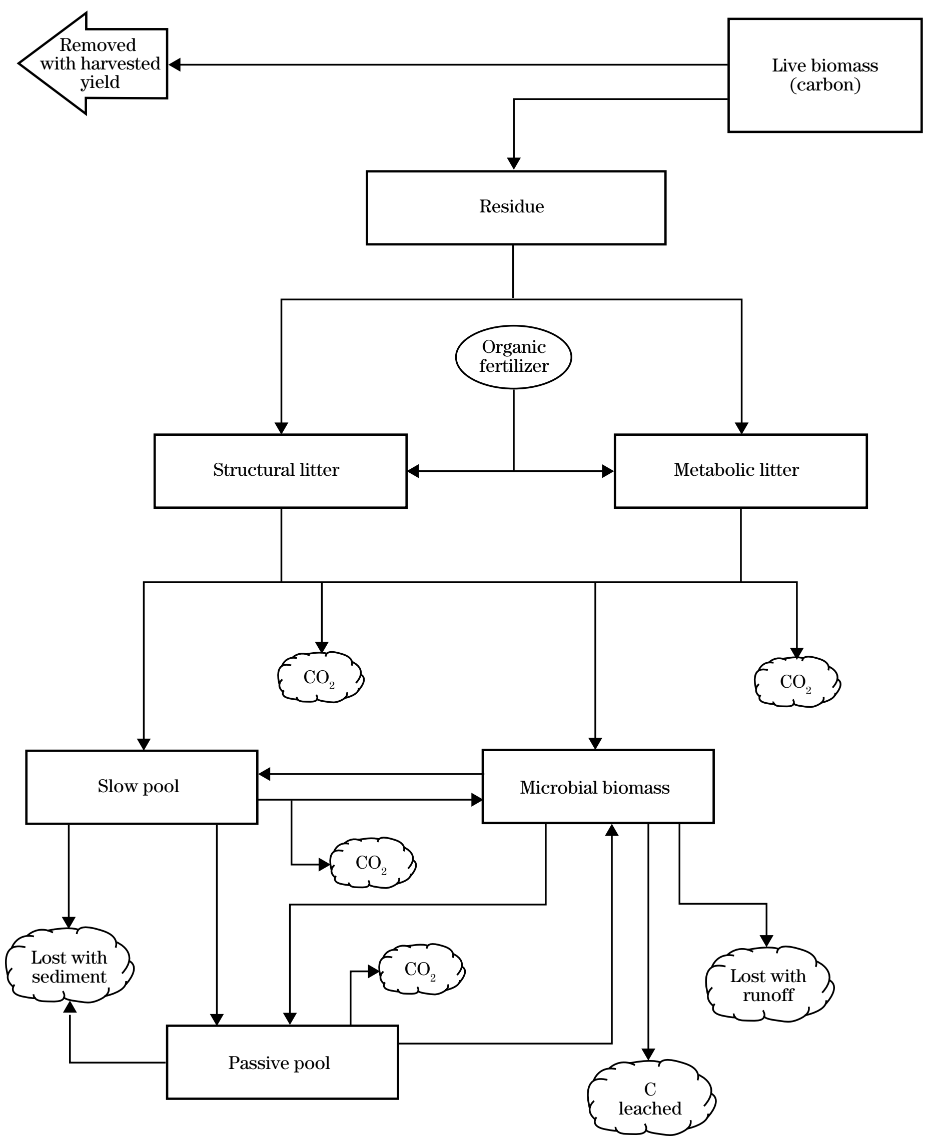
Part of the plant is removed from the field when the crop is harvested. Other plant material on the surface remains in the field as crop residue. Crop residue includes plant stems, leaves, and roots. Over time the plant material decomposes. Some molecules, those most readily decomposable, are quickly incorporated into microorganisms and other soil biota that use it as an energy source. Other plant materials, made of less easily decomposed materials such as lignin, become structural or metabolic litter. As the litter decomposes into compounds like CO_2 and NH_4, its identity as plant material disappears. Some molecules remain resistant to decomposition for thousands of years. In some systems used by soil scientists to describe soil organic matter, including the EPIC model, the most highly resistant fractions of organic material are classified as passive humus. Other materials, resistant for up to 20 years or so, are classified as slow humus. Fractions that decompose faster are part of the biomass, structural litter, or metabolic litter and are often labeled as active or labile organic material. All non-living organic material in the soil not readily identifiable as plant parts comprise that soil component called soil organic matter. The buildup of soil organic matter in the soil results in enhanced soil quality.

EPIC simulates dynamic carbon processes using carbon routines conceptually similar to those in the Century model (Izaurralde et al. 2001; Izaurralde et al. 2005). In EPIC, carbon processes are coupled to the hydrology, erosion, soil temperature, plant growth, nutrient cycling, and tillage components (fig. 33). EPIC tracks the residue and calculates the mass of carbon in the soil. The organic material is apportioned into any of five pools: metabolic litter, structural litter, microbial biomass, slow humus, and passive humus depending on its inherent decomposition rate as estimated by the lignin composition. The model tracks and reapportions the pools over time using a daily mass balance. Decomposition rates are influenced by various environmental factors including climate and soil characteristics. EPIC represents these factors using transformation rate controls exerted by the soil temperature and soil water equations. Tillage and other management operations are simulated to represent affects on decomposition rates. EPIC includes leaching equations that move soluble carbon down through the soil profile. Other equations capture the effects of soil texture on the stabilization of soil organic matter.

EPIC calculates soil organic carbon by summing the products of layer thickness, bulk density, and proportion of soil organic carbon in the soil for each layer in the soil profile. Soil organic carbon includes the microbial biomass and slow and passive humus pools, but not residue or litter. The calculation is very sensitive to the bulk density estimate, as there are large differences in the mass per volume between organic material and mineral material. Considering the soil in the example below, the multiple of columns 1, 2, and 3 times 100 results in metric tons of soil organic carbon per 100 square meters for each soil layer. This is then converted to metric tons per hectare for each layer by multiplying by 100 square meters per hectare (col. 5) and then converted to tons per acre by multiplying by the product of 1.1023 metric tons per ton and 0.4047 hectares per acre (col. 6). Total soil organic carbon for the soil profile is obtained by summing over the layers. In the following example, soil organic carbon in the soil profile is 58.7 tons per hectare, or 26.2 tons per acre:

Soil layer	Layer thickness (m)	Bulk density (metric ton/m³)	Proportion of soil organic carbon	Metric tons of soil organic carbon per 100 square meters	Metric tons of soil organic carbon per hectare	Tons of soil organic carbon per acre
	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
1	0.01	1.56	0.0231	0.036	3.604	1.608
1	0.29	1.56	0.0074	0.335	33.478	14.934
2	0.16	1.44	0.0025	0.058	5.760	2.540
3	0.73	1.55	0.0014	0.158	15.841	7.067

Figure 33 Carbon cycle as modeled in EPIC



Model simulation results for soil organic carbon

Soil organic carbon

In these model simulations, the initial soil organic carbon is the soil organic carbon input derived from the soil properties database associated with the representative soil for each soil cluster. As described earlier in this report, a 40-year simulation was conducted with the first 10 years serving as the equilibration period for the model to adjust to the various default starting values, including the initial value for soil organic carbon. Annual model output was used for reporting beginning with the 11th year of the simulation and ending with the 40th year of the simulation, providing 30 annual estimates of soil organic carbon. Year 1 results correspond to the 11th year of the simulation, and year 30 results correspond to the last year. Over this simulation period, soil organic carbon changes depending on climatic factors, erosion rates, amount of crop residue generated each year, annual organic carbon additions such as manure application, and tillage intensity. The same crop was grown in each year of the simulation with the same management activities each year; crop rotations were not simulated. Weather was simulated using a weather generator; resulting estimates, therefore, do not represent any specific historical time period. Soil organic carbon estimates presented in this report are calculated as the annual average for the 30-year period.

For the 15 specific crops included in the study, model simulations estimated an average of 58 tons of soil organic carbon per cropland acre (table 66). The largest amount of soil organic carbon associated with cropland acres was in the Upper Midwest region, which also had the highest per-acre amount—71 tons per cropland acre on average. The lowest per-acre soil organic carbon levels were in the Southern Great Plains and South Central regions, averaging 43 and 44 tons per acre, respectively. The soil organic carbon content of cropland soils in the West and the Southeast regions was, on average, only slightly higher (table 66).

The spatial distribution of soil organic carbon on a per-acre basis is shown in map 35 and as total tons of soil organic carbon in map 36. It is clear from map 35 that soil organic carbon levels vary considerably among cropland acres. Cropland with the highest organic carbon content—including soils in the organic soil texture class—are shown in the highest category (dark brown colored areas). These acres have an average soil organic carbon content of over 150 tons per acre and represent about 3 percent of the cropland acres included in the study. The few acres that have organic carbon levels this high tend to be concentrated in Minnesota, Iowa, eastern Wisconsin, northern Indiana, and eastern North Carolina. Most cropland acres with soil organic carbon levels averaging 100 to 150 tons per acre are concentrated in Iowa and Minnesota, and represent about 7 percent of the cropland acres. Cropland acres with the lowest soil organic carbon levels—less than 25 tons per acre and representing about 14 percent of the acres—primarily are scattered throughout the southern half of the country.

Soil organic carbon levels also varied by crop within regions, as shown in table 66. Legume hay consistently had the highest or among the highest soil organic carbon levels in every region. Cotton and peanuts had the lowest soil organic carbon levels in regions where those crops were grown. The highest soil organic carbon level when averaged by crop within region was for spring wheat in the Upper Midwest region—123 tons per acre. The lowest was for cotton in the West—16 tons of soil organic carbon per acre.

Soil organic carbon levels and soil texture are inter-related in these model simulations, as shown in figure 34 and table 67. Soil organic carbon content was highest for fine textured soils and decreased as the soils became coarser in texture, with the exception of the soils in hydrologic soil group D. Coarse soils in hydrologic soil group D had among the highest levels of soil organic carbon. Organic soils, which represent less than 0.5 percent of cropland acres, averaged over 600 tons per acre of soil organic carbon.

Change in soil organic carbon

Under the assumptions of the model simulation, nearly three-fourths of the cropland acres lost soil organic carbon over the 30 years (table 68). However, many of these losses were very small. About half of the acres losing carbon in these model simulations lost less than 3 tons per acre over the 30 years, equivalent to only about 0.1 tons per acre per year or less. Gains and losses this small are difficult to detect in an actual farm field setting, and may represent a steady state condition where small carbon gains occur in some years that are mostly offset by small carbon losses in other years.

Table 66 Soil organic carbon estimates–by region and by crop within regions

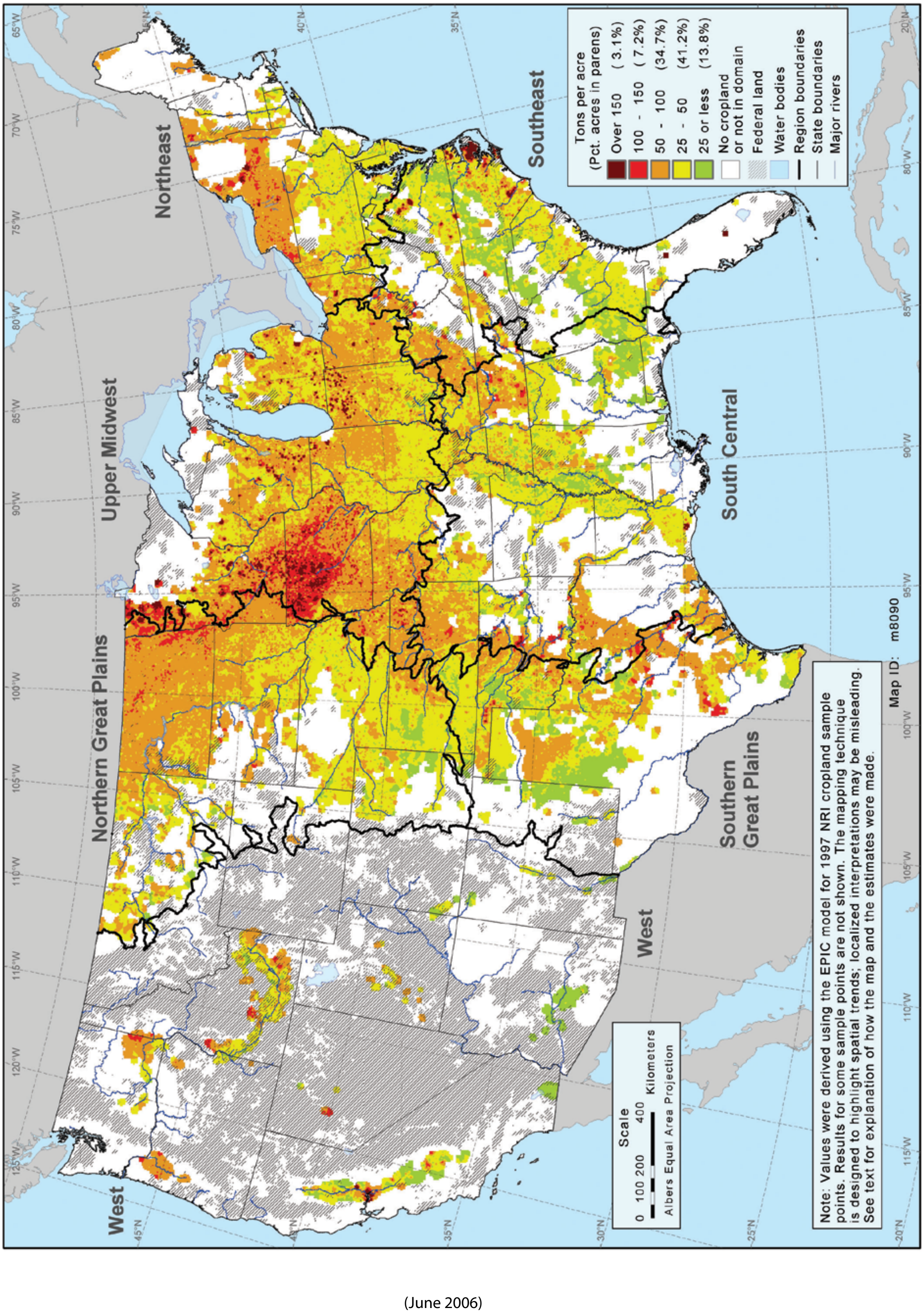
Region	Crop	Acres (1,000s)	Tons (1,000s)	30-year change in tons (1,000s)	Tons per acre	30-year change in tons per acre	30-year percent change in tons per acre
By region							
Northeast	All crops	13,642	743,013	191,270	54.5	14.0	28.7
Northern Great Plains	All crops	72,397	4,081,437	-94,257	56.4	-1.3	-2.3
South Central	All crops	45,350	2,000,380	4,282	44.1	0.1	0.2
Southeast	All crops	13,394	628,985	8,049	47.0	0.6	1.3
Southern Great Plains	All crops	32,096	1,392,353	-105,340	43.4	-3.3	-7.3
Upper Midwest	All crops	112,581	8,029,824	29,188	71.3	0.3	0.4
West	All crops	9,018	417,195	22,693	46.3	2.5	5.6
All regions	All crops	298,478	17,293,187	55,886	57.9	0.2	0.3
By crop within region*							
Northeast	Corn	2,943	121,919	-10,979	41.4	-3.7	-8.6
	Corn silage	1,482	56,510	-11,401	38.1	-7.7	-18.1
	Grass hay	2,369	115,664	650	48.8	0.3	0.6
	Legume hay	4,052	343,888	223,074	84.9	55.1	89.7
	Oats	362	15,460	-1,916	42.7	-5.3	-11.6
	Soybeans	1,305	46,746	-3,531	35.8	-2.7	-7.2
	Winter wheat	853	30,291	-2,785	35.5	-3.3	-8.8
Northern Great Plains	Barley	3,243	229,224	-3,368	70.7	-1.0	-1.4
	Corn	15,466	784,030	-42,844	50.7	-2.8	-5.3
	Corn silage	810	37,291	-3,888	46.1	-4.8	-9.8
	Grass hay	2,443	149,209	12,607	61.1	5.2	8.8
	Legume hay	6,152	362,445	58,582	58.9	9.5	17.3
	Oats	1,255	70,065	-3,605	55.8	-2.9	-5.0
	Spring wheat	18,916	1,234,053	-47,102	65.2	-2.5	-3.7
	Sorghum	1,595	66,388	-3,567	41.6	-2.2	-5.2
	Soybeans	9,562	611,474	-45,596	64.0	-4.8	-7.1
	Winter wheat	12,748	522,517	-13,319	41.0	-1.0	-2.5
South Central	Corn	5,956	249,374	-10,294	41.9	-1.7	-4.0
	Cotton	5,487	159,940	-27,435	29.1	-5.0	-15.7
	Grass hay	3,347	153,638	3,234	45.9	1.0	2.1
	Legume hay	1,630	153,452	128,389	94.1	78.7	129.0
	Peanuts	880	22,721	-1,952	25.8	-2.2	-8.2
	Rice	3,004	108,803	-14,825	36.2	-4.9	-12.7
	Sorghum	2,729	160,825	-13,890	58.9	-5.1	-8.3
	Soybeans	14,083	580,697	-22,291	41.2	-1.6	-3.8
	Winter wheat	7,896	395,855	-34,709	50.1	-4.4	-8.4

Table 66 Soil organic carbon estimates–by region and by crop within regions—Continued

Region	Crop	Acres (1,000s)	Tons (1,000s)	30-year change in tons (1,000s)	Tons per acre	30-year change in tons per acre	30-year percent change in tons per acre
By crop within region*							
Southeast	Corn	3,028	184,211	-21,771	60.8	-7.2	-11.1
	Corn silage	412	15,624	-1,776	37.9	-4.3	-10.7
	Cotton	2,422	77,859	-14,874	32.1	-6.1	-17.4
	Grass hay	2,000	80,660	77	40.3	<0.1	0.1
	Legume hay	1,183	92,145	73,208	77.9	61.9	120.7
	Peanuts	479	13,708	-1,619	28.6	-3.4	-11.1
	Soybeans	2,419	100,666	-14,570	41.6	-6.0	-13.4
	Winter wheat	1,216	51,716	-8,802	42.5	-7.2	-15.6
Southern Great Plains	Corn	2,665	122,199	-10,379	45.9	-3.9	-8.1
	Cotton	7,316	239,430	-41,400	32.7	-5.7	-15.8
	Legume hay	677	40,861	16,340	60.3	24.1	48.2
	Oats	503	29,756	-2,908	59.1	-5.8	-9.3
	Peanuts	484	9,732	-1,198	20.1	-2.5	-11.5
	Sorghum	4,895	222,676	-22,970	45.5	-4.7	-9.8
	Winter wheat	15,037	702,914	-42,355	46.7	-2.8	-5.8
Upper Midwest	Corn	47,941	3,430,754	-215,962	71.6	-4.5	-6.1
	Corn silage	1,947	104,537	-10,555	53.7	-5.4	-9.6
	Grass hay	4,044	260,068	7,996	64.3	2.0	3.1
	Legume hay	9,233	806,086	484,358	87.3	52.5	80.0
	Oats	1,388	77,389	-8,378	55.8	-6.0	-10.2
	Spring wheat	815	100,110	-5,916	122.8	-7.3	-5.7
	Sorghum	1,604	96,759	-7,479	60.3	-4.7	-7.4
	Soybeans	40,049	2,822,992	-204,019	70.5	-5.1	-6.9
	Winter wheat	5,147	286,890	-7,279	55.7	-1.4	-2.5
West	Barley	958	45,836	-1,891	47.9	-2.0	-4.0
	Corn silage	297	16,695	-1,063	56.2	-3.6	-6.1
	Cotton	1,631	26,687	-2,463	16.4	-1.5	-8.8
	Legume hay	1,847	99,887	38,218	54.1	20.7	46.2
	Potatoes	329	11,036	-841	33.5	-2.6	-7.3
	Rice	599	22,307	-3,982	37.2	-6.6	-16.3
	Spring wheat	772	32,954	-846	42.7	-1.1	-2.5
	Winter wheat	2,118	124,725	-3,201	58.9	-1.5	-2.5

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.
Note: A 40-year simulation was conducted. The first 10 years served as the equilibration period for the model to adjust to the various default starting values. The 30-year period from which these carbon estimates were derived started on the 11th year of the simulation and ended with the 40th year of the simulation. Tons reported here are the annual average for the 30-year period.

Map 35 Estimated per-acre soil organic carbon



Map 36 Estimated tons of soil organic carbon for cropland acres

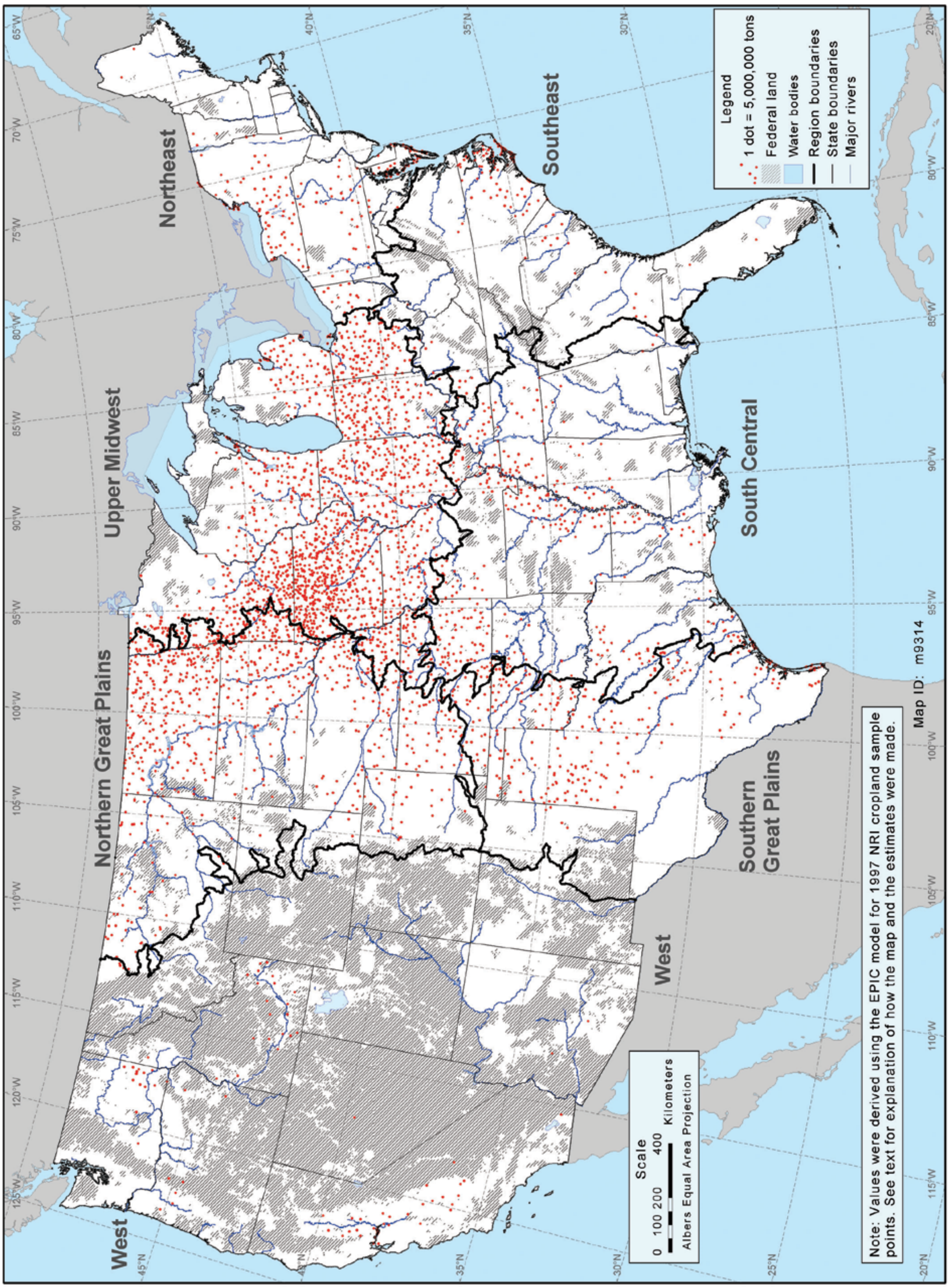


Figure 34 Per-acre soil organic carbon–by soil texture class and hydrologic soil group

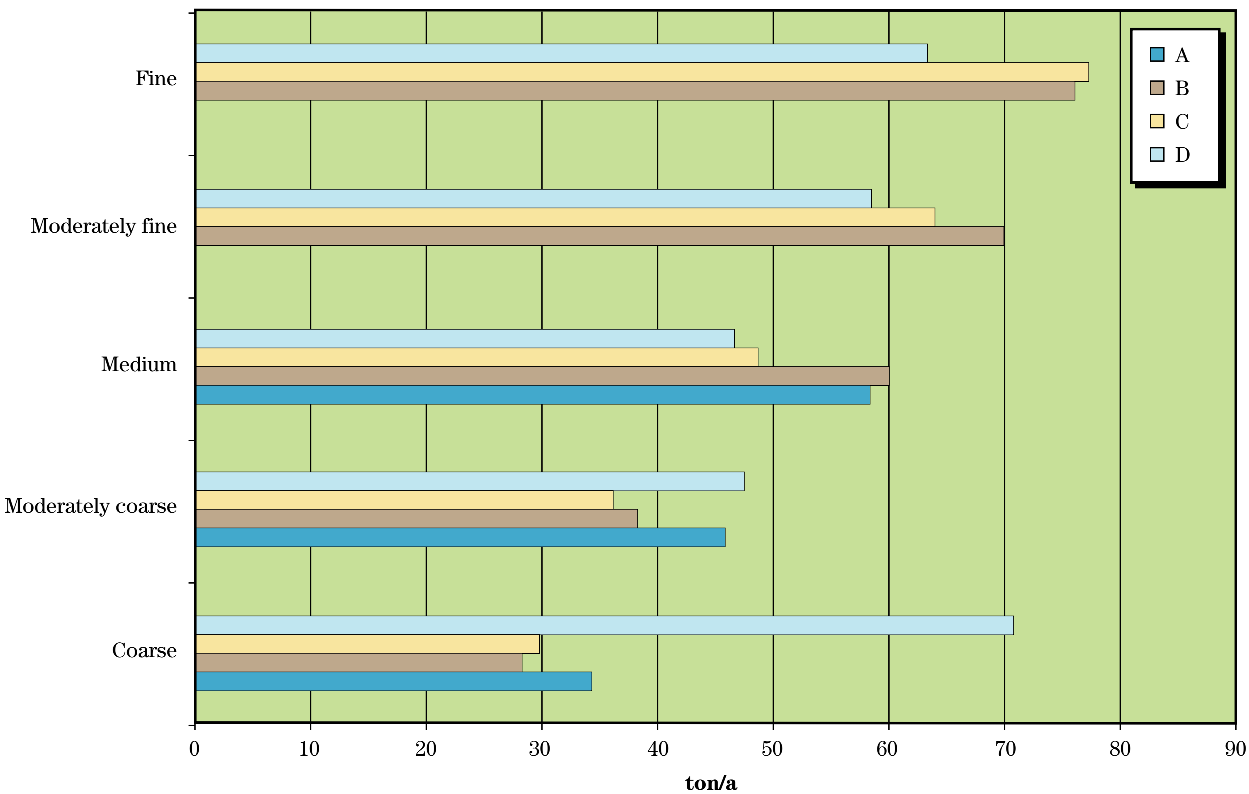


Table 67 Soil organic carbon levels–by soil texture class

Soil texture class	Acres (1,000s)	Percent of total acres	Soil organic carbon (ton/a)	30-year change in soil organic carbon (ton/a)	30-year percent change in soil organic carbon
Coarse	15,152	5.1	32.2	-0.9	-2.7
Moderately coarse	32,452	10.9	38.8	1.4	3.5
Medium	153,484	51.4	55.2	2.3	4.2
Moderately fine	78,249	26.2	66.5	-2.6	-3.8
Fine	17,950	6.0	65.6	-3.5	-5.1
Organic	1,142	0.4	606.8	-52.1	-8.3
Other	49	<0.1	33.0	5.2	16.8
All	298,478	100.0	57.9	0.2	0.3

Table 68 Percentage of acres gaining and losing soil organic carbon over the 30-yr simulation

		Acres loosing soil organic carbon over 30-year period				Acres gaining soil organic carbon over 30-year period			
	Acres (1,000s)	Percent loosing more than 3 tons per acre	Percent loosing 1 to 3 tons per acre	Percent loosing 0 to 1 tons per acre	Sum of percent acres	Percent gaining 0 to 1 tons per acre	Percent gaining 1 to 3 tons per acre	Percent gaining more than 3 tons per acre	Sum of percent acres
Northeast	13,642	31.4	16.9	9.7	58.0	5.4	5.5	31.1	42.0
Northern Great Plains	72,397	27.3	34.0	16.7	78.1	8.6	2.9	10.5	21.9
South Central	45,350	40.4	25.5	9.9	75.8	9.1	8.5	6.6	24.2
Southeast	13,394	38.3	27.0	9.1	74.4	5.4	7.7	12.5	25.6
Southern Great Plains	32,096	52.1	31.3	10.3	93.7	2.7	1.3	2.2	6.3
Upper Midwest	112,581	38.3	20.7	10.4	69.4	12.1	8.4	10.1	30.6
West	9,018	20.3	13.0	15.8	49.1	18.5	13.0	19.5	50.9
All regions	298,478	36.6	25.7	11.9	74.2	9.4	6.3	10.1	25.8

Overall gains in soil organic carbon outweighed overall losses for the acres included in the study. When aggregated over all cropland acres, the change in soil organic carbon averaged only 0.2 tons per acre over the 30-year simulation (table 66). Only the Northern and Southern Great Plains regions had overall soil organic carbon losses on cropland acres (table 66). In the Southern Great Plains region, 94 percent of the cropland acres had decreasing soil organic carbon (table 68), over half of which lost more than 3 tons per acre over the 30-year period. In the Northeast region, the average per-acre soil organic carbon level increased 14 tons per acre over the 30-year simulation, equivalent to about 0.5 tons per acre per year. On average, soil organic carbon gain occurred for only two crops—grass hay and alfalfa hay; other crops had average losses of soil organic carbon in every region (table 66).

The spatial distribution of the changes in tons per acre of soil organic carbon over the 30-year model simulation is shown in map 37. The green areas on the map had increases in soil organic carbon and the red areas had losses. The lightest red and lightest green colored areas represent very low levels of gains and losses, and probably reflect more of a steady state condition. Broad areas with these low levels of gains and losses occurred in Illinois, Indiana, and western Ohio and in the Northern Great Plains region. The highest losses of soil organic carbon (losses of more than 10 ton/a over the 30-yr period) occurred predominantly in Iowa, southern Minnesota, and eastern North Carolina primarily where soil organic carbon levels were relatively high. These areas represent about 7 percent of the cropland acres included in the study. The spatial distribution and regional differences are largely the result of differences in decomposition rates driven by climate and the crop mix. Higher decomposition rates in the warm humid climates lead to low organic carbon accrual.

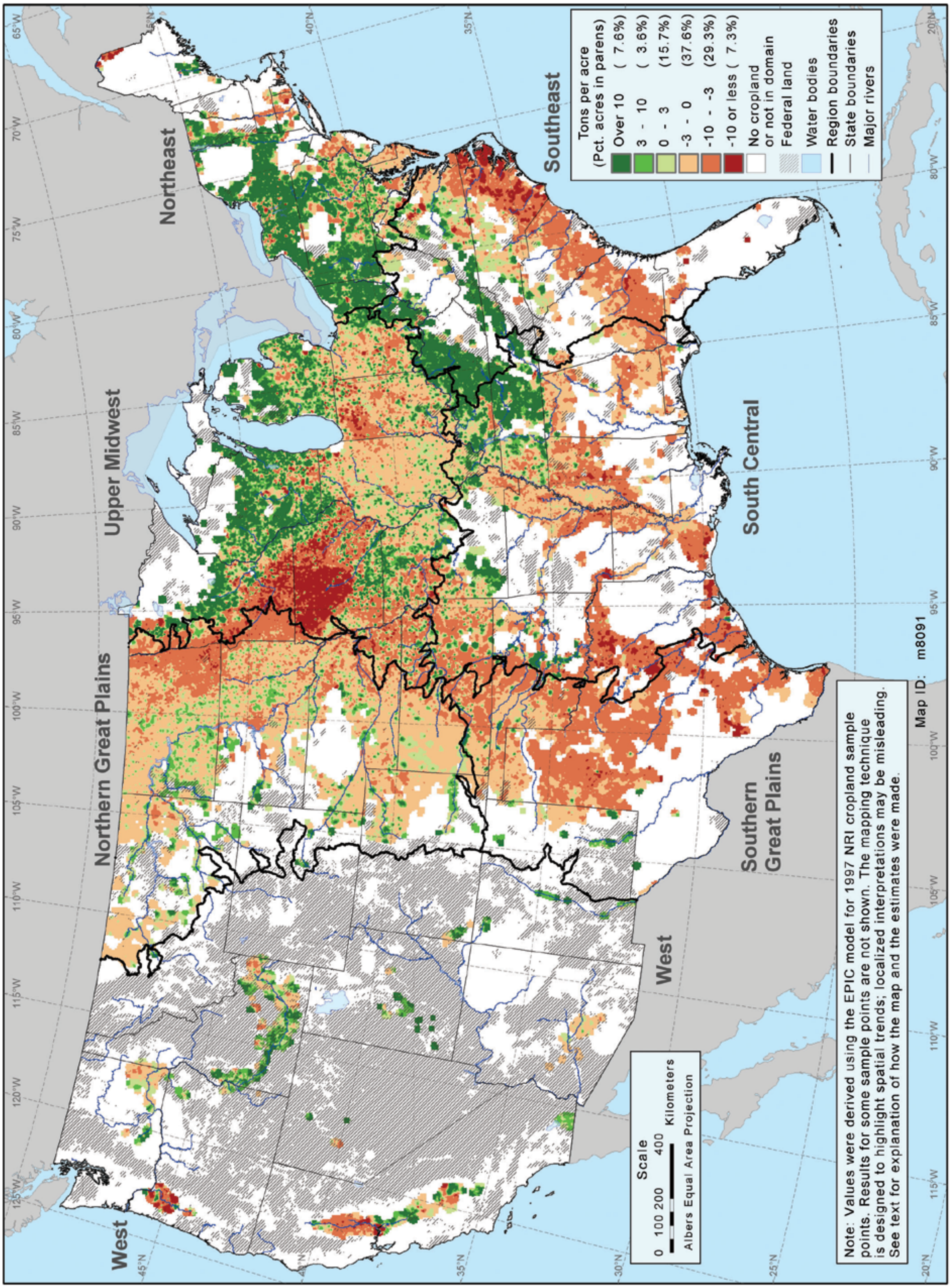
The percent change in soil organic carbon is presented in map 38. This map shows the percent change in soil organic carbon relative to the level of soil organic carbon in year 1 of the 30-year model output series. Thus, areas with low soil organic carbon levels but large changes in soil organic carbon are more pronounced in map 38 than in map 37. Soil organic carbon decreased more than 10 percent on about 17 percent of the acres over the 30-year simulation (darkest red color), and increased more than 10 percent on about 10 percent of the acres (darkest green color). Cropland in the southern states generally had the highest losses of soil organic carbon in terms of percent change.

Results in terms of the percent change in soil organic carbon also showed patterns related to soil texture (table 67). Cropland acres with medium and moderately coarse soil textures had, on average, about a 4 percent increase in soil organic carbon over the 30-year simulation, whereas other soil textures were associated with carbon losses, on average. Medium textured soils represent over half of the cropland acres included in the study.

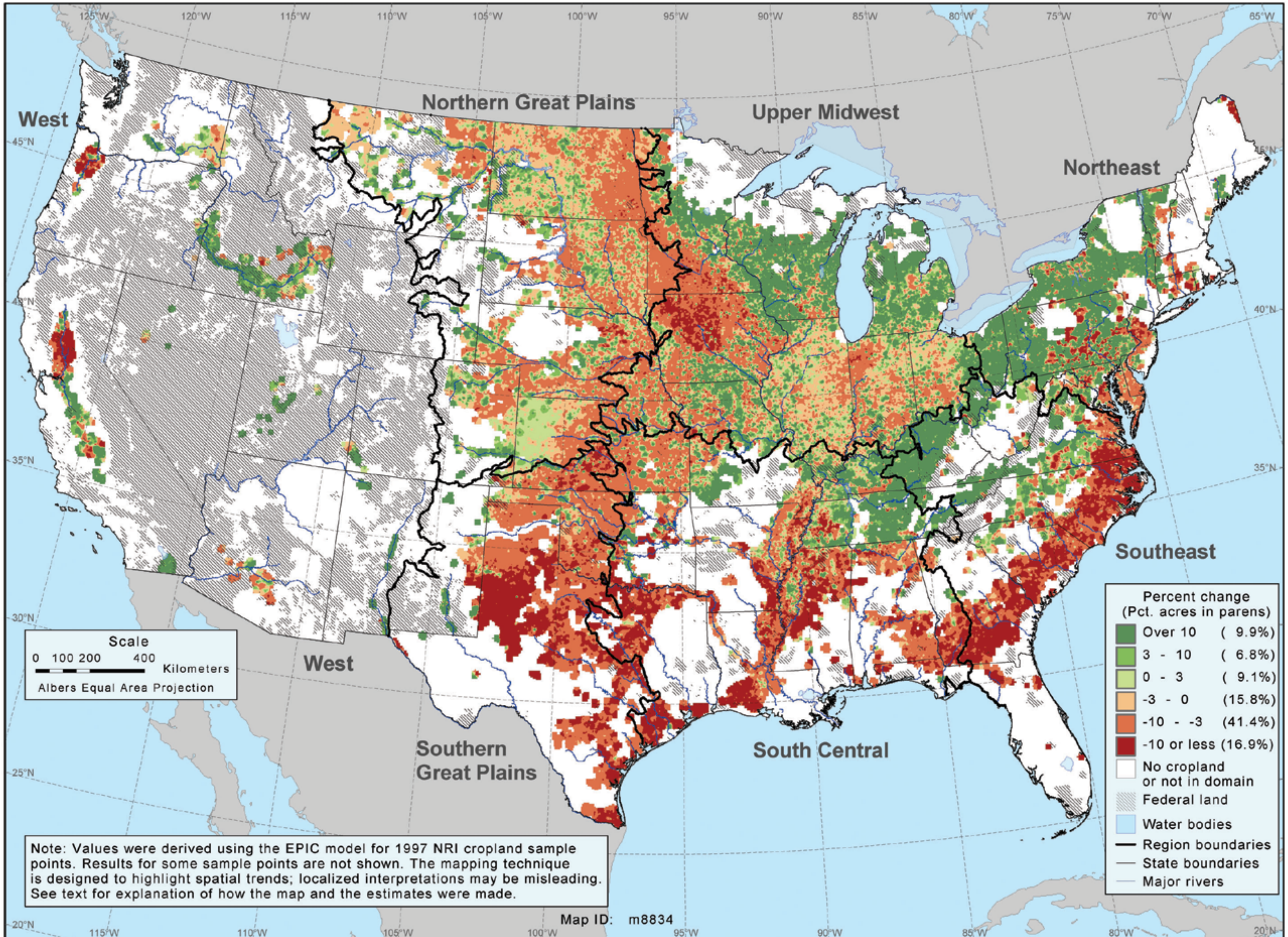
Recent modeling studies using the Century model have reported an accretion in soil organic carbon for common cropping systems in Iowa, Nebraska, and Indiana (Brenner et al. 2001; Brenner et al. 2002; Smith et al. 2002). In contrast, model simulations in this study found that the bulk of the acres in Nebraska and Indiana had very small net losses in soil organic carbon over the 30-year simulation; although, some areas within the states had significant losses while other areas had significant gains (map 37). Most cropland acres in Iowa had significant loss of carbon in this study. Without attempting to make a detailed comparison between the two modeling efforts, there are five main reasons why this study would be expected to estimate higher losses of soil organic carbon than some other studies.

- Estimates in this study included loss of carbon with water and wind erosion. In the EPIC model, carbon may be transported off the field as part of soil eroded by wind and water. The model also includes a routine that leaches soluble organic carbon down through the soil profile. The Century model does not account for this loss from the system, assuming instead that these erosion losses of carbon are merely translocated to other areas and, therefore, do not represent a net loss to the total carbon stock.
- Model simulations in this study did not account for crop rotations or cover crops, as all model runs simulated growth of the same crop over the full simulation time period. Soybeans, for example, produces small amounts of crop residue, whereas corn is a high biomass producing crop with much higher crop residues left in the field under conservation tillage and no-till. Soybeans grown in rotation with corn would have had more carbon added to the soil when averaged

Map 37 30-year change in per-acre soil organic carbon



Map 38 30-year percent change in soil organic carbon (30-yr change/soil organic carbon in year 1)



over the 30-year simulation than continuous soybeans. Other crop rotations beneficial to soil carbon accretion are grasses or legume hay in rotation with row crops and small grains in rotation with row crops.

- Soil organic carbon for some model runs was negatively affected by under-fertilization because the fertilizer application rates were not site-specific. Nitrogen is an essential element for the formation of stable soil organic matter. Average application rates by state and sometimes state combinations were applied to all NRI sample points in those states without regard to soil productivity or differing climatic conditions among the NRI points. Relative to the inherent productivity for the sample point, some received too much fertilizer while others received too little. Thus, soils best positioned to gain soil organic carbon with good agricultural management were restricted because less than optimum fertilizer rates resulted in lower biomass production. Similarly, biomass production could have been restricted because of other management activities, such as tillage, that were also not adjusted to reflect site-specific differences in soils and field conditions.
- Initial soil organic carbon settings are also an important factor in estimating gains and losses. How these data inputs are handled can sometimes explain differences between model outputs in similar studies.
- Site-specific information about drainage was not known, therefore, in the EPIC model simulations, we assumed fields had drainage sufficient to keep the water table to the bottom of the root zone for the entire period. Increased decomposition of soil organic carbon resulting from optimum oxygen conditions is a likely effect of such a global assumption.

Soil organic carbon as an indicator of soil quality

Soil quality in its simplest terms is how well a soil is doing what we want it to do. The definition of soil quality adopted by the Soil Science Society of America is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. The definition of soil quality includes two aspects: the inherent properties of soil and the effect of human use and management on the ability of the soil to function. The inherent properties of the soil establish the basis from which to set expectations for a specific soil to function. Evaluation of changes in soil quality is based on whether management has enhanced, sustained, or degraded the ability to provide the chosen service, without adverse effects on its surroundings. Soil provides the following basic functions or services:

- Controlling water flow. Soil helps control where rain, snowmelt, and irrigation water goes. Water and dissolved solutes flow either over the soil surface or into and through the soil profile.
- Sustaining plant and animal productivity. The diversity and productivity of living things depends on soil. This includes not only crops, but also soil biota such as earthworms and microbes that are beneficial for sustained crop production.
- Filtering potential pollutants. The minerals and microbes in soil are responsible for filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposits.
- Cycling nutrients. Carbon, nitrogen, phosphorus, and many other nutrients are stored, transformed, and cycled through the soil.
- Supporting structures. Soils provide a stable medium for plant root growth with sufficient porosity to allow solute flow and aeration. For land uses other than crop production, buildings need stable soil for support, and archeological treasures associated with human habitation are protected in soils.

The key to managing for improved soil quality for purposes of crop production is to manage for soil organic matter. Soil organic matter is the organic faction of the soil including plant and animal residues, soil organisms, and many combinations of chemical elements. Much of the soil organic matter consists of the element carbon. Carbon is key because we have the ability to manipulate it, and it has a major role in physical, chemical, and biological properties of soil.

Managing for carbon includes adding organic material such as manure and managing crop residues through reduced tillage, crop rotations, and cover crops. Through microbial breakdown of residues and other natural processes, soil carbon accumulates in the soil. The soil's structure improves through greater aggregation produced by water insoluble proteins and other organic products from the breakdown of residues that bind smaller particles together. This improved aggregation further resists the impacts of rainfall and enhances infiltration, providing more water for plant growth and less for runoff. The reduction in runoff improves water quality by reducing sediment and nutrient loads and increasing the use of the soil as a natural filter. Organic matter removes contaminants from the environment through strong chemical bonds with the soil, rendering the contaminants harmless, or degrading the contaminants to less toxic forms. A soil's ability to retain water is enhanced by the chemical nature of organic matter, which can hold from 10 to 1,000 times more water than inorganic soil matter.

Change in soil organic carbon is an indicator of soil quality. Cropland soils that are increasing in soil organic carbon over time will have an increased capacity to sustain plant and animal activity, retain and hold water, filter potential pollutants, and cycle nutrients—that is, enhanced soil function. However, not all cropland soils that are losing soil organic carbon are in a degraded state with respect to soil function. Loss of soil organic carbon is much less serious for cropland acres with inherently high levels of soil organic carbon than for acres with inherently low levels of soil organic carbon. Some soils with relatively high percent losses can continue to lose soil organic carbon for many years before soil function is impaired. Other soils, on the other hand, may only be able to tolerate very small percent losses before soil function is impaired.

A soil quality degradation indicator was developed to identify cropland acres where the potential for soil quality degradation is the greatest and, thus, where conservation practices to enhance soil quality would be needed the most. The soil quality degradation indicator was derived from a soil organic carbon indicator that adjusted soil organic carbon estimates to better reflect those cropland acres where soil organic carbon losses have a deleterious affect on soil function.

The soil organic carbon indicator

The soil organic carbon (SOC) indicator was calculated using the Soil Management Assessment Framework (SMAF), which was designed to assess the impact of soil management practices on soil function (Andrews et al. 2004; Andrews et al. 2002). While SMAF consists of three steps (indicator selection, interpretation, and integration into an index), only the integration step was used for development of the SOC indicator used in this report. The interpretation step was used to transform EPIC model estimates of SOC into unitless scores based on site-specific relationships between SOC and soil function. The indicator represents the ability of the soil to meet potential soil function to support crop production.

The SOC indicator scoring curve consists of an algorithm with parameters that change based on site-specific environmental factors. The basic curve shape was determined by literature review and consensus of collaborating researchers (Andrews et al. 2004). The scoring curve selected is an ascending logistic S-curve, or more-is-better function, based on the role of soil organic carbon in soil fertility, water partitioning, and structural stability (Tiessen et al. 1994; Herrick and Wander, 1998). A higher score (on a 0 to1 scale) represents greater performance of soil functions such as nutrient cycling and productivity.

Site-specific controlling factors (such as climate or inherent soil properties) are used to define the slope and inflection point of the scoring curve for specific soils. For instance, in a southeastern United States Ultisol, a SOC of 2 percent would be considered a high value because of the high decomposition rates that occur in that climate; this soil would receive a high SOC score. In a Midwestern Mollisol, however, a SOC of 2 percent would be considered a low value, consistent with a degraded soil, because these soils have inherently high SOC levels due to their formation under grasses and their cooler climates that yield lower decomposition rates. It would, therefore, receive a correspondingly low score. The factors controlling these differences include average annual precipitation, average annual temperature, soil texture, and soil taxonomic suborder as a surrogate for inherent soil organic matter.

To model these associations between indicators, function, and controlling factors, one must have knowledge of (or make assumptions about) not only the appropriate curve shape (based on indicator performance of ecosystem function), but also the expected direction of change in curve inflections as major controlling factors change. For instance, as temperature and precipitation increase, expected SOC decreases because of increased decomposition rates. This results in a shift to the left in the inflection point of the scoring curve. For a given SOC value, a shift of the curve to the left produces a higher score compared with the same SOC value in a climate with inherently lower decomposition rates. The same is true for sandy soils versus clays; most sandy soils have inherently less organic matter than clays and the curve shifts to accommodate this phenomenon. Site-specific scoring enables the interpretation to reflect both overall soil function and inherent capabilities of the soil.

The SOC scoring curve used to calculate the SOC indicator is:

$$y = \frac{a}{\left(1 + b \times \exp^{-c \times soc}\right)}$$

The parameter "a" is set to 1.0 and the parameter "b" is set to 50.1 on the basis of empirical testing. The parameter "c" is a function of three factors: inherent organic matter, soil texture (Needelman et al. 1999), and climate (USDA 1966):

$$c = \left(iOM \times txt\right) + \left(iOM \times txt \times clim\right)$$

where:

iOM = a coefficient representing four classes of inherent organic matter grouped by soil suborder (USDA NRCS 1998; C. Seybold, personal communication)

txt = a coefficient for five soil texture levels defined by Quiesenberry et al. (1993)

clim = a coefficient derived from average annual precipitation and degree days above freezing (USDA SCS 1981; Bailey 1995) for major land resource areas

For the inherent organic matter factor, soil suborders were grouped into four classes based on their inherent levels of soil organic matter according to the following table. The "iOM" coefficients are also listed.

Class	Suborder	Coefficient
1	Aquands, Aquods, Aquox, Fibrists, Folists, Hemists, Histels, Saprists, Turbels	0.3
2	Albolls, Aquepts, Aquerts, Aquolls, Aquults, Borolls, Cryolls Muhods, Humolts, Rendolls, Udands, Udolls, Udox, Ustands, Ustolls, Xerests, Xerolls	1.55
3	Andepts, Anthrepts, Aqualfs, Aquents, Boralfs, Cryalfs, Cryands, Cryerts, Cryods, Orthels, Udalfs, Ustalfs, Vitrands, Xeralfs	2.17
4	Arents, Argids, Calcids, Cambids, Cryepts, Cryids, Durids, Fluvents, Gypsids, Ochrepts, Orthents, Orthids, Orthods, Orthox, Perox, Psamments, Salids, Torrands, Torrerts, Torrox, Tropepts, Udepts, Udults, Umbrepts, Ustepts, Ustox, Ustults, Xerands, Xerepts, Xerents, Xerults	3.81

The five soil texture classes used for the texture factor were based on water movement as related to soil particle size. The five classes and coefficients are:

Class	Textures	Coefficient
1	sand, loamy sand, or sandy loam (with <8% clay)	1.6
2	Sandy loam (≥ 8% clay), sandy clay loam, or loam	1.25
3	silt loam, silt	1.1
4	Sandy clay, clay loam, silty clay loam, silty clay or clay (<60% clay)	1.05
5	clay (>60% clay)	1

The four climate classes used for the climate factor were based on average annual degree days above freezing and average annual precipitation. The four classes and coefficients are:

Class	Average annual degree days	Average annual precipitation	Coefficient
1	≥ 170 °days	≥ 550 mm	0.15
2	≥ 170 °days	< 550 mm	0.05
3	< 170 °days	≥ 550 mm	-0.05
4	< 170 °days	< 550 mm	-0.01

The SOC indicator score was calculated for each cropland sample point included in the study for model output for years 1 and 30. Because the above SOC scoring curve is calibrated for percent SOC by weight, the EPIC model estimate of soil organic carbon in units of tons per acre had to be converted. The formula for conversion uses both soil bulk density and sample depth. The initial bulk density value was used for each representative soil cluster and assumed a uniform soil depth of 30 centimeters (11.8 in) for this conversion. The controlling factor information was obtained from the model input parameters for soil and climate.

An SOC indicator score ranging between zero and one was then determined for each modeled NRI point using the scoring curve (above). A SOC indicator score was determined for both the first year in the model simulation output (year 1) and the last year (year 30).

The soil organic carbon indicator score for the last year of the model simulation is shown in map 39. As described previously, the distance-weighted average value over several NRI cropland points is represented in each 25 square kilometer (9.6 mi^2) grid cell on the map. High scores are indicative of soil organic carbon levels that provide nearly full soil function for purposes of crop production, such as nutrient cycling and water partitioning. Similarly, low scores indicate that soils are very low in carbon relative to inherent levels, and thus soil function could be improved with appropriate management. Comparing map 39 to map 35 (average per-acre soil organic carbon) provides an example of what the soil organic carbon indicator represents. Acres with very high soil organic carbon levels tended to score high, and acres with very low soil organic carbon levels tended to score low. In several regions, however, acres with modest levels of soil organic carbon also scored high. About 77 percent of the acres had SOC scores greater than 0.90, indicating they were meeting or nearly meeting the full potential of the soil to support crop production at the end of the 30-year simulation.

The soil quality degradation indicator

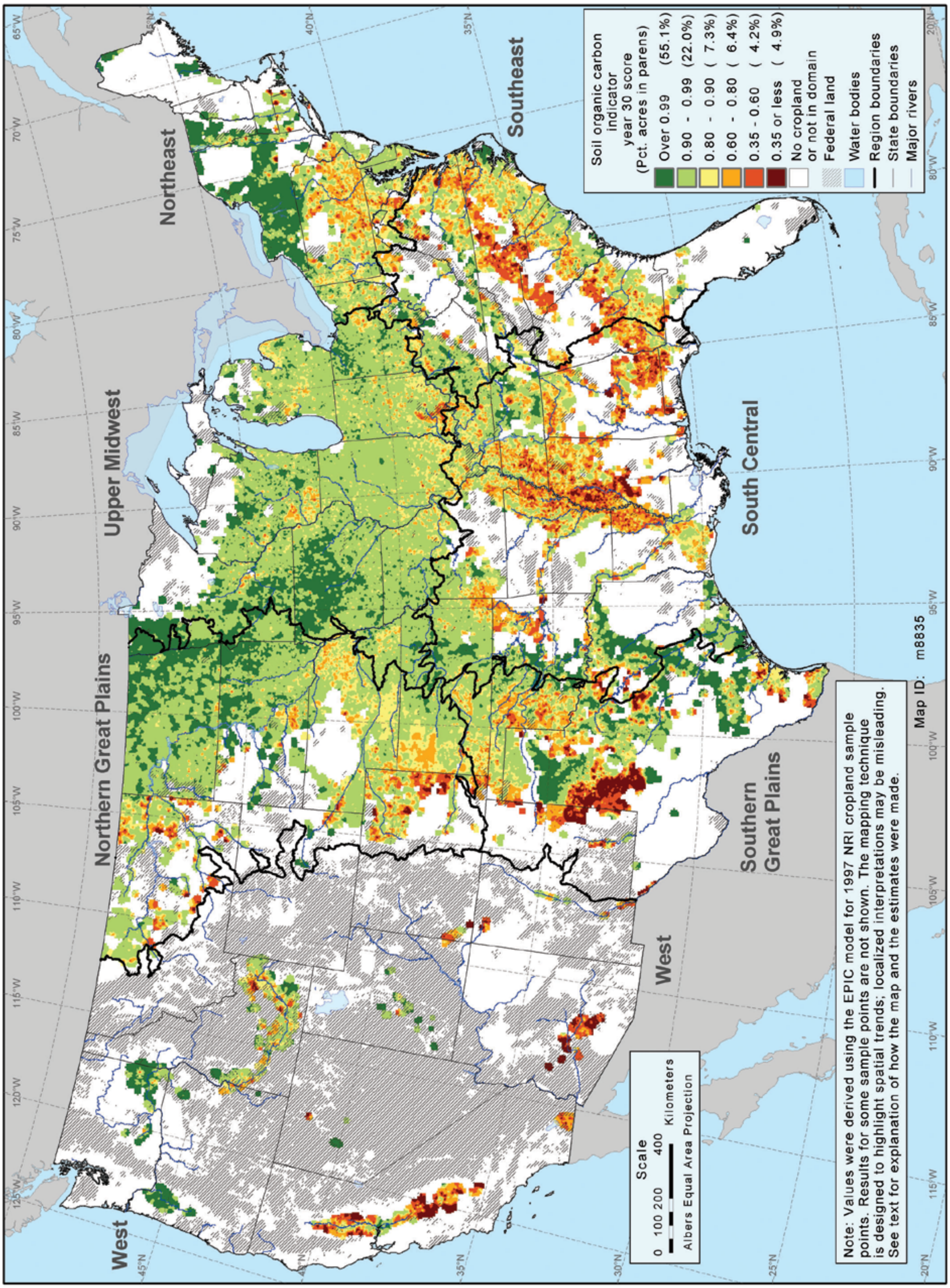
Whereas the soil organic carbon indicator is a better representation of soil function than the level of soil organic carbon, the score for any given year does not indicate whether the soil function capability is improving or worsening, which is important in identifying cropland areas where soil quality is degrading.

The soil quality degradation indicator was determined on the basis of the 30-year change in the soil organic carbon indicator and the indicator score for the last year of the simulation. The 30-year change in the soil organic carbon indicator was calculated as the difference between the SOC indicator score for the first year and the SOC indicator score for the last year in the 30-year simulation. Results showed that 73.6 percent of the acres had a negative change in SOC score between year 1 and year 30, indicating that soil condition was decreasing over the 30-year simulation period. For sample points with a positive change, the soil quality degradation indicator was set equal to the SOC score for year 30. For sample points with a negative change, the soil quality degradation indicator was set equal to one minus the SOC score for year 30 and converted to a negative number. Subtracting the SOC score from one is necessary to preserve the ranking of the original score.

Thus, the soil quality degradation indicator is a modification of the SOC indicator score for year 30, adjusted to reflect whether or not the score is increasing or decreasing at a point and adjusted to preserve the ranking that the SOC indicator score provides. The soil quality degradation indicator for sample points with increasing SOC indicator scores ranged from 0 to 1. The soil quality degradation score for sample points that were decreasing ranged from -1 to 0, with 0 corresponding to the SOC indicator score of 1. The resulting distribution for the soil quality degradation indicator scores is:

Soil quality degradation indicator score	Percent acres
>0.90	19.3
0.60 to 0.90	4.1
0.25 to 0.60	1.8
>0.0 to 0.25	1.2
0 to -0.01	41.4
-0.12 to -0.01	17.8
-0.35 to -0.12	7.7
<-0.35	6.8
Total	100.0

Map 39 Soil organic carbon indicator (year 30 score)



Cropland acres with increasing SOC indicator scores comprised 26.4 percent of the acres. The bulk of these acres scored above 0.90, representing nearly fully functioning or fully functioning soils that were improving over time. About 41.4 percent of the acres had a score of zero or nearly zero. These acres all had negative values for the change in the SOC indicator, but still had SOC indicator scores close to one in year 30 of the simulation. Even though the SOC score was declining for these acres, it was declining so slowly that soil quality degradation would probably not be a concern.

Acres that are at most risk of soil quality degradation—and thus loss of soil function—comprise the remaining third of the acres. These acres would benefit the most from conservation practices designed to enhance soil quality. The spatial distribution of the soil quality degradation indicator scores is shown in map 40. The most vulnerable acres from a soil quality standpoint are the areas colored orange, red, and brown. The brown areas, which indicate areas where the average soil quality degradation indicator score is below -0.35, are the most sensitive cropland acres. About 7 percent of the acres included in the study have scores in this range. These sensitive acres are most concentrated in the southern half of the United States. The orange and red areas, representing average soil quality degradation indicator scores ranging from just below zero to -0.35, are often adjacent to the most sensitive acres, but can also be found scattered throughout most cropland areas.

Note that the mapping process calculates the average score for sample points within each grid cell and assigns a color to the grid cell based on that average score. The map thus depicts the general spatial trends showing where the most vulnerable soils tend to be concentrated. The visual representation of acres in the classes shown in map 40, however, will not always correspond to the distribution statistics obtained from the NNLSC database and reported in the table above.

Reflecting the spatial trends shown in map 40, the distribution of soil quality degradation indicator scores varies markedly from region to region, as shown in table 69. The average soil quality degradation indicator score was negative for only one region—the Southern Great Plains region (-0.119). In this region, 75 percent of the acres had a soil quality degradation indicator score less than zero. The Southeast and South Central regions had the next lowest average soil quality indicator scores, where more than 50 percent of the acres had negative scores. The highest average scores were for the Northeast region (0.332) and the Upper Midwest region (0.278). All regions, however, had significant acreage with negative soil quality degradation indicator scores.

Assessment of critical acres for soil quality degradation

Acres with the lowest negative soil quality degradation indicator scores are identified here as critical acres. Following the same approach used to identify critical acres for soil and nutrient loss, five categories of critical acres, representing different degrees of severity, are defined on the basis of national level results:

- acres where the soil quality degradation indicator is below the 5th percentile (-0.488) for all acres included in the study
- acres where the soil quality degradation indicator is below the 10th percentile (-0.220) for all acres included in the study
- acres where the soil quality degradation indicator is below the 15th percentile (-0.113) for all acres included in the study
- acres where the soil quality degradation indicator is below the 20th percentile (-.0.060) for all acres included in the study
- acres where the soil quality degradation indicator is below the 25th percentile (-0.025) for all acres included in the study

Critical acres for soil quality degradation are less concentrated in one or two regions than was the case for sediment loss, wind erosion, or nutrient loss. About 65 percent of the critical acres in the bottom 5 percent category were in the South Central region (33.4% of critical acres) and the Southern Great Plains region (31.6%) (table 70). All regions had critical acres in this category. As the criterion for critical acres expanded from the bottom 5 percent category to the bottom 25 percent category, the representation of critical acres in other regions expanded to a more balanced distribution of critical acres among four of the regions, with significant representation in all but the West region.

Map 40 Soil quality degradation indicator for cropland

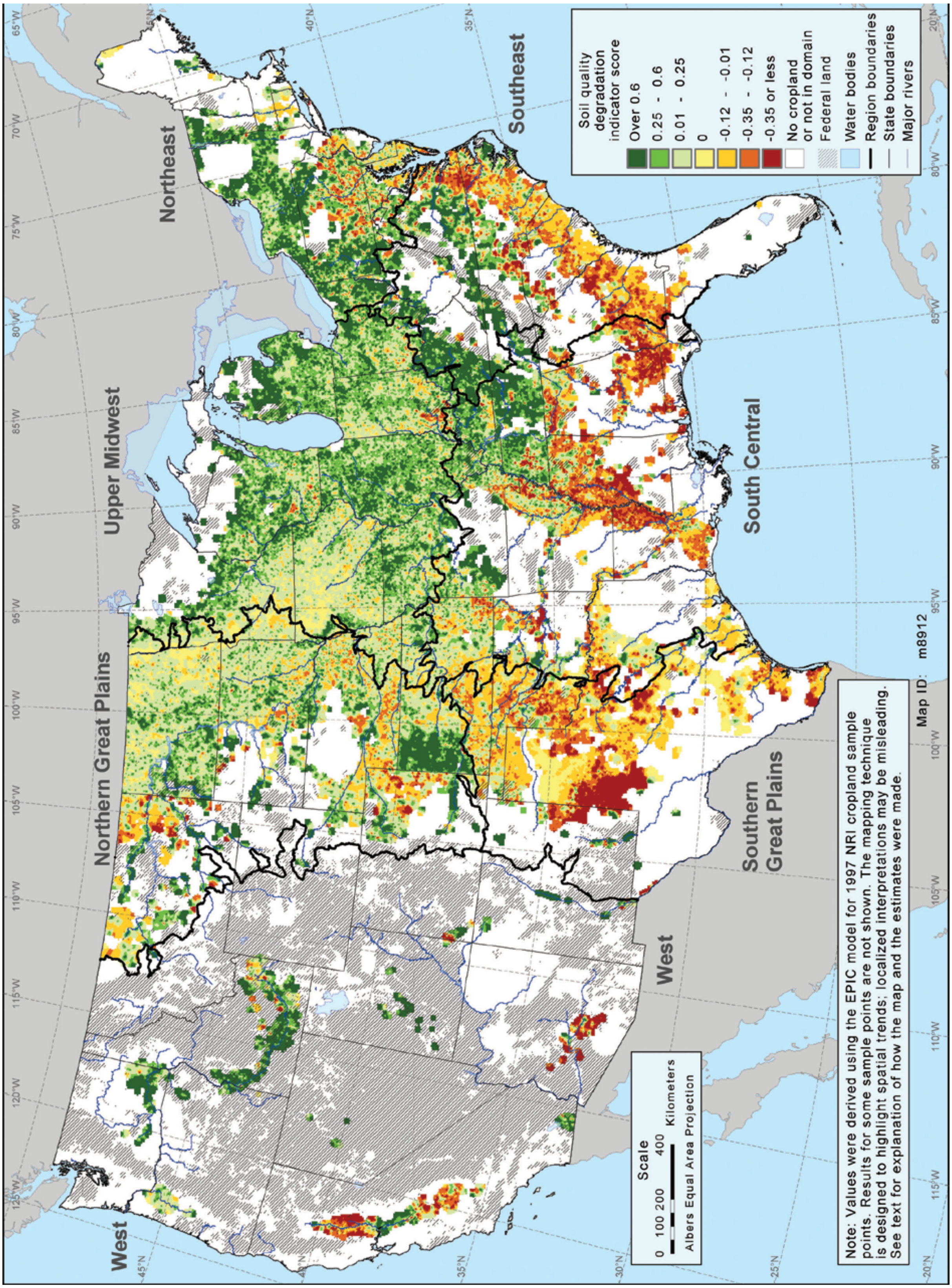


Table 69 Percentiles for the soil quality degradation indicator

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	0.332	-0.449	-0.290	-0.079	0.000	1.000	1.000	1.000
Northern Great Plains	72,396,500	36,035	0.154	-0.219	-0.099	-0.010	0.000	0.000	0.994	1.000
South Central	45,349,900	27,465	0.047	-0.710	-0.532	-0.159	-0.009	0.000	0.961	1.000
Southeast	13,394,400	8,955	0.100	-0.719	-0.490	-0.160	-0.006	0.412	1.000	1.000
Southern Great Plains	32,096,000	14,495	-0.119	-0.880	-0.710	-0.170	-0.010	0.000	0.000	0.301
Upper Midwest	112,580,900	74,691	0.278	-0.128	-0.060	-0.003	0.000	0.948	1.000	1.000
West	9,018,400	5,644	0.241	-0.818	-0.665	-0.074	0.036	0.972	1.000	1.000
All regions	298,478,000	178,567	0.164	-0.488	-0.220	-0.025	0.000	0.300	0.999	1.000

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower soil quality degradation indicator scores.

Table 70 Critical acres for the soil quality degradation indicator

		Soil quality indicator score in bottom 5% nationally		Soil quality indicator score in bottom 10% nationally		Soil quality indicator score in bottom 15% nationally		Soil quality indicator score in bottom 20% nationally		Soil quality indicator score in bottom 25% nationally	
Region	Acres	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
Northeast	13,641,900	594,200	4.0	1,829,100	6.2	2,866,100	6.4	3,775,100	6.3	4,524,800	6.1
Northern Great Plains	72,396,500	1,559,500	10.5	3,576,700	12.0	6,952,200	15.5	9,911,100	16.5	12,830,900	17.2
South Central	45,349,900	4,982,800	33.4	9,104,400	30.7	12,745,000	28.5	15,705,700	26.1	19,213,500	25.8
Southeast	13,394,400	1,355,600	9.1	2,946,100	9.9	4,279,000	9.6	5,191,100	8.6	5,810,600	7.8
Southern Great Plains	32,096,000	4,717,100	31.6	7,661,200	25.8	8,930,900	20.0	11,494,700	19.1	14,325,500	19.2
Upper Midwest	112,580,900	498,000	3.3	2,807,300	9.5	6,955,100	15.5	11,738,200	19.5	15,392,900	20.6
West	9,018,400	1,215,300	8.1	1,763,400	5.9	2,034,200	4.5	2,292,400	3.8	2,508,500	3.4
All regions	298,478,000	14,922,500	100.0	29,688,200	100.0	44,762,500	100.0	60,108,300	100.0	74,606,700	100.0

Note: The bottom 5 percent corresponds to the 5th percentile in table 69. Other columns correspond to table 69 in a similar manner.