Science Societies

Environmental outcomes from on-farm agricultural production in the United States

Part 3: Soil carbon

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August 3, 2022



This article is brought to you by the SPARC Initiative created in partnership between the American Society for Agronomy, the Agricultural Retailers Association, Environmental Defense Fund, and Field to Market: The Alliance

for Sustainable Agriculture to empower trusted advisers to deliver services that drive continuous improvement in the productivity, profitability, and environmental outcomes of farmers' operations. Learn more about the SPARC Initiative and access additional resources, including the six-module series on sustainability at **www.fieldtomarket.org/SPARC**. This article is an excerpt from Field to Market's Fourth *National Indicators Report*, released in December 2021. Access the entire report at **www.fieldtomarket.org/report**. Sections covering biodiversity, land use, soil erosion, irrigation water use, energy use, and greenhouse gas emissions were covered in previous issues of *Crops & Soils* magazine. The final installment in this series covering water quality will be included in the November–December issue. All articles from the SPARC series can be found online at **https://bit.ly/3yVScpl**.

Soils are the largest organic carbon pool on the land surface, and agricultural soils that have been disturbed by tillage and other practices for many years have lost carbon to the atmosphere. This historical loss, however, means that there is substantial opportunity to increase soil organic carbon (SOC) in agricultural soils by adopting practices that reduce soil disturbance and increase carbon from organic matter. These practices include conservation tillage, diverse crop rotations, residue retention, and cover crops (Paustian et al., **2016**). In recent years, many private-sector efforts have begun to explore potential SOC sequestration as a strategy for meeting company and industry targets for climate change mitigation.

Carbon accumulation in the soil is difficult to measure because it occurs slowly over long time periods and does not follow a linear trend. While initial increase in carbon following a farm management change may be rapid, that rate will slow over time as the soil system begins to approach a new ecosystem equilibrium, or steady state (Paustian et al., **2016**). For example, after conversion from conventional tillage to a continuous, no-till system, a field may approach a new equilibrium after 15 to 20 years with the largest sequestration rates occurring between 5 and 10 years. Measuring soil carbon sequestration is complex; there are important dynamics occurring underground and out of range of direct observation. For example, studies have shown that SOC increases in the upper layers of soil following adoption of no-tillage correspond with reductions of SOC in the lower layers. In effect, reduction in tillage reallocates carbon in the soil profile (Blanco-Canqui & Lal, **2008**). This dynamic is attributed to how the shift to no-tillage reduces the incorporation of crop residues and root material into soils (Baker et al., **2007**). Regardless of the climate mitigation benefit, SOC is an important sustainability indicator as a measure of soil health that supports many of the functions and ecosystem services vital to agricultural production (Lal, **2016**).

Field to Market: The Alliance for Sustainable Agriculture recognizes the critical functions of soil carbon both to mitigate climate change and to improve soil health and the resilience of agricultural lands to extreme climate events. The Fieldprint Platform (**https://calculator.fieldtomarket.org**) is a free, online tools that measures the environmental impacts of commodity crop production and identifies opportunities for continuous improvement. The Fieldprint Platform addresses soil carbon along with soil conservation, energy use, greenhouse gas emissions, land use, irrigation water use, water quality, and biodiversity. The soil carbon metric assesses the potential to increase SOC in farm fields by adopting conservation practices.

Soil Carbon Metric

The primary Soil Carbon metric in the Fieldprint Platform is the Soil Conditioning Index (SCI), a conservation-planning tool developed by USDA-NRCS to provide guidance to users on probable directional change in soil carbon as a result of practice adoption and change. There are three main components of the SCI: soil organic matter (SOM), field operations, and erosion. Soil organic matter contains approximately 58% carbon, and therefore the SCI provides an indication of whether a soil is gaining or losing carbon. The Soil Conditioning Index is calculated from the Revised Universal Soil Loss Equation 2 (RUSLE2) and is a unitless, relative, and crop-specific measure with an output range of –1 to +1. Very small values (–0.05 to +0.05) represent index levels where there is little or no confidence that SOM is changing in either direction. As the SCI value moves further away from zero, it indicates greater confidence that the soil carbon is changing; therefore, higher values approaching +1.0 indicate greater confidence that SOC is increasing and lower values approaching –1.0 indicate greater confidence that soil carbon is decreasing (Figure 1). The advantages of the SCI are that it is relatively simple to use and can be applied with just one year of information about a farm operation. Note that this method only captures the dynamics of soil carbon in the surface layer of the soil.

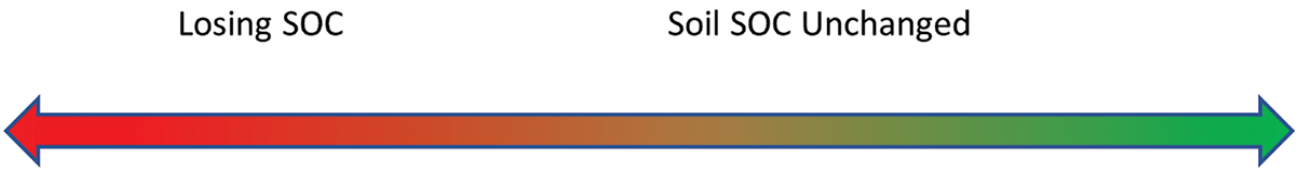


Figure 1, *Soil Conditioning Index results range from –1.0 to +1.0.*

Field to Market has also integrated a second tool—COMET-Planner—as an optional scenario planner to assess how recent or planned changes in practices might impact soil carbon (Swan et al., 2020). This feature allows producers and their advisers to quickly and simply estimate the quantity of carbon various conservation practices

might sequester in their fields. Together, these tools provide both a high-level assessment of soil health and a starting point for understanding the potential benefits to a producer and farm from engaging with private-sector carbon markets before committing to the extensive testing and modeling requirements of market entry.

National Trends in Soil Carbon from 1990–2015

Given the complexity of soil organic carbon measurements, understanding how the SOC content of agricultural soils in the United States has changed over time requires application of sophisticated simulation models. As a party to the United Nations Framework Convention on Climate Change, the United States produces annual inventories of all greenhouse gas emission sources and sinks (USEPA, **2021a**), including those from agriculture. To support this reporting, the USDA publishes a quadrennial greenhouse gas inventory, focused on agriculture, forestry, and land use change, which contains detailed national- and state-scale modeling of all greenhouse gas sources and sinks for agricultural lands. The most recent USDA Agriculture and Forestry Greenhouse Gas Inventory assesses these changes from 1990–2015 (USDA, **2021**) and provides the most comprehensive estimate of SOC change on U.S. croplands available. Here we examine the results for major cropping systems grown on mineral soils, which are low in organic matter. It is important to note that organic soils, while small in area in the U.S., are very vulnerable to soil carbon loss when cultivated.

The USDA uses a simulation model called DayCent to estimate soil carbon using detailed data on land management, weather conditions, soil characteristics, and land use history. The modeling is conducted for 400,000 National Resources Inventory survey points that represent a statistical sampling of land use and management practices on all non-federal lands in the United States. DayCent models plant–soil nutrient cycling by simulating key processes occurring in the soil, including plant

growth, senescence, decomposition of dead plant matter and other organic matter, and nitrogen mineralization (DelGrosso et al., **2001**). Because the simulations run for multiple years, they are accounting for whole-crop rotations, so results are available for entire cropping systems rather than just individual crops. The analysis defined 10 major cropping systems based on five-year rotations as determined by the National Resources Inventory survey data. Six of the cropping systems contain results for the commodity crops considered in this article.

1. **Row crops**: At least three of five years in corn, soybean, and/or sorghum.
2. **Small grains**: At least three of five years in barley, wheat, and/or oats.
3. **Low-residue crops**: At least three of five years in cotton, potatoes, sugar beets, dry beans, onions, and/or tomatoes.
4. **Hay (legume)**: Five continuous years in legume hay.
5. **Flooded rice**: At least three of five years in flooded rice production.
6. **Other**: agricultural lands that did not have three out of five years in any of the other definitions. Contains a mix of crops and diverse rotations.

Soil Carbon Trends by Cropping System

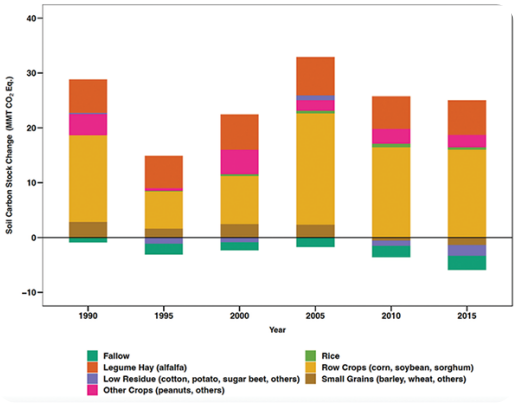


Figure 2, *Soil organic carbon stock change in major U.S. commodity crop systems from 1990–2015 (million metric tons of CO2*

equivalent per year).

The results presented here are taken from the USDA analysis (USDA, **2021**) and represent the change in SOC stock in one year from all lands in the U.S. in a particular cropping system (as defined above). The results are displayed in units of million metric tons of carbon dioxide equivalent. We display carbon sequestration (gain) in soils as a positive stock change and carbon emissions (loss) from soils as a negative stock change.

Overall, soils actively managed under the six cropping systems considered here have increased soil carbon stock throughout the last 25 years (Figure **2**). Carbon sequestration fluctuates over time with the area in production for each of the cropping systems, changes in management practices, and weather. Lands that are left fallow are also included and illustrate the importance of living plants to maintaining and increasing soil carbon. The most recent two years of analysis available (2010 and 2015) indicate relatively steady SOC sequestration, except for small grains and low-residue crops, which show net emissions.

Row Crops

Row crop rotations typically contain some high-residue crops. These lands have consistently added carbon to the soil over the past 25 years. The increase in soil carbon can be attributed both to increases in the acreage used for production of these crops as well as shifts toward reduced- and no-tillage that have occurred since 1990 (Figure **3**).

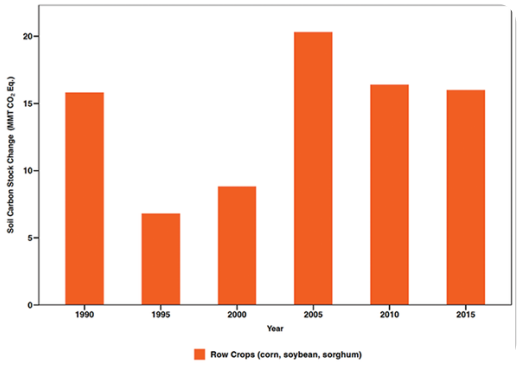


Figure 3, *Soil organic carbon stock change in row crop systems from 1990–2015 (million metric tons of CO2 equivalent per year).*

Small Grains

Land area dedicated to small-grain systems has been declining over the past 25 years. These crops produce lower amounts of crop residues and were responsible for a modest amount of soil carbon gain from 1990–2005. However, in 2010 and 2015, these lands have seen net emissions of CO_2 from the soil (Figure 4).

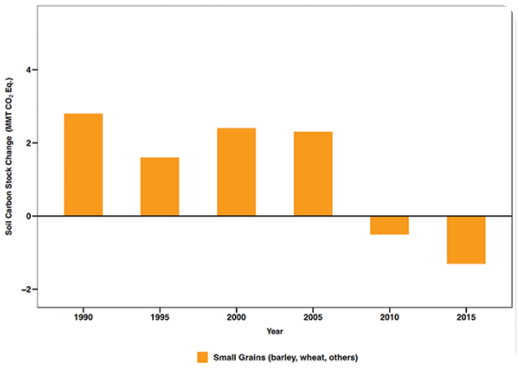


Figure 4, *Soil organic carbon stock change in small-grain systems from 1990–2015 (million metric tons of CO2 equivalent per year).*

Low-Residue Crops

Cotton, potatoes, and sugar beets are included in the USDA modeling category of low-residue crops due to the plant characteristics and harvest practices that leave little residue on the soil after harvest. Harvesting root crops like potatoes and sugar beets requires a greater amount of soil disturbance. Together, low crop residue and necessary soil disturbance contribute to the soils in these cropping systems typically emitting, rather than gaining, carbon. Their overall acreage and contribution to the total soil carbon storage on croplands is small and has typically gained or lost less than 1 million metric tons of carbon dioxide equivalent. in the years considered. The exception is a greater loss of soil carbon occurring in the most recent analysis year of 2015 (Figure 5).

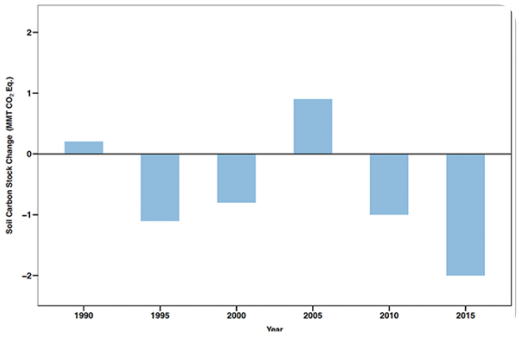


Figure 5, *Soil organic carbon stock change in low-residue crop systems from 1990–2015 (million metric tons of CO2 equivalent per year).*

Legume Hay

Perennial hay crops have greater potential to increase SOC as they require less soil disturbance in most years. Lands producing alfalfa, the most common legume hay grown in the United States, consistently gained soil carbon stock throughout the time period analyzed here (Figure 6) as a result of the combined benefits of reduced disturbance and nitrogen fixation.

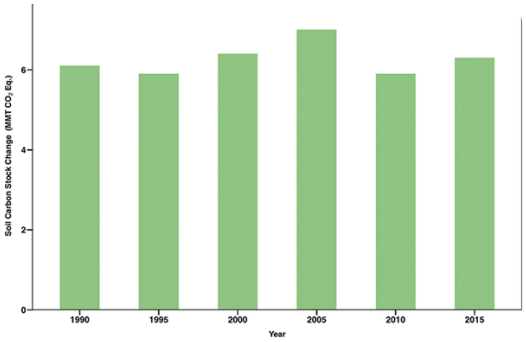


Figure 6, *Soil organic carbon stock change in legume hay systems from 1990–2015 (million metric tons of CO2 equivalent per year).*

Rice

Rice systems are considered separately in the USDA modeling analysis as the crop is typically grown on flooded fields and the biogeochemical cycles that determine the carbon and nitrogen balance in the soil operate differently in the oxygen-deficient flooded environment. In the United States, the acreage in rice production is small, so the contribution to overall soil carbon stock is small. Rice has consistently demonstrated a gain in soil carbon stock over the past 25 years (Figure 7).

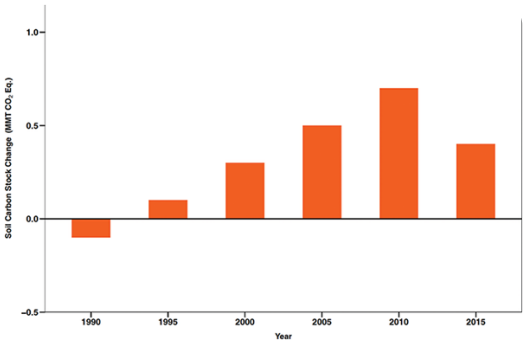


Figure 7, *Soil organic carbon stock change in rice systems from 1990–2015 (million metric tons of CO2 equivalent per year).*

Other Crops

The “other crops” category refers to cropping systems that did not fall under the more specific categories considered above and typically represent more complex rotations. These lands also demonstrate consistent increase in soil carbon stock over the study period (Figure 8).

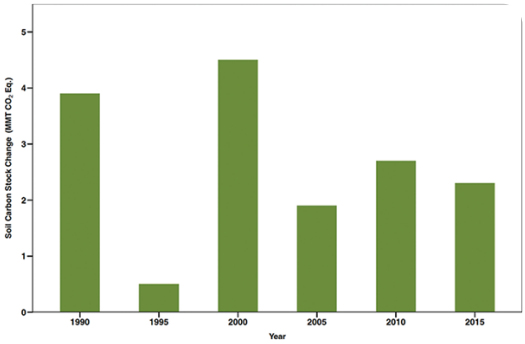


Figure 8, *Soil organic carbon stock change in other crop systems from 1990–2015 (million metric tons of CO2 equivalent per year).*

Soil Carbon Trends for Lands in the Conservation Reserve Program

Lands in the Conservation Reserve Program (CRP) are removed from active crop production for a period of time and are included here as these lands were previously, and are likely to be again, in active production of crops. Setting aside land in a perennial grassland can increase the carbon in the soil and improve the overall soil health. These lands consistently provide a sink for soil carbon throughout the study period with fluctuations in the carbon stock change determined by the extent and location of land set aside in any given period (Figure 9).

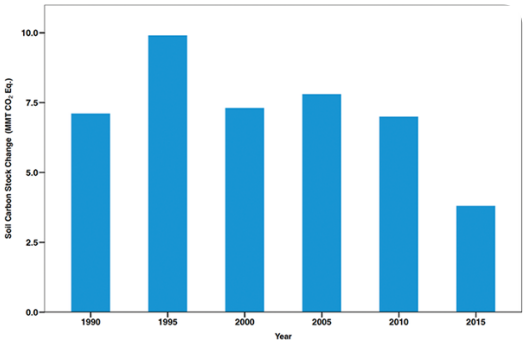


Figure 9, *Soil organic carbon stock change in Conservation Reserve Program lands from 1990–2015 (million metric tons of CO2 equivalent per year).*

Summary

Overall, soils actively managed under the cropping systems considered here have sequestered soil carbon over the past 25 years. The greatest soil carbon gain was

observed in 2005, with fluctuations in later years. These findings correlate to plateauing improvements in soil erosion at the same time as total acres under reduced- and no-tillage practices has stayed steady since 2005. The adoption of conservation tillage is the most significant factor influencing the soil carbon gains observed here, with additional contributions from manure management and including perennial hay in rotations (USDA, **2021**).

While cover crops are included in the USDA analysis, they do not correspond to a significant increase in soil carbon. This is due to a limitation in the data available for the modeling, which does not include details on cover crop termination practice and, as a result, the models assume termination using tillage (USDA, **2021**). Better information is needed from surveys on the methods of termination, such as through herbicide application or mechanical rolling, that do not involve soil disturbance. Under those conditions, cover crops are associated with increasing soil carbon (USDA, **2021**). While cover crop acreage is relatively small at this time, increased adoption of this conservation practice is likely to have greater impacts on soil carbon over time.

Other conservation practices that increase soil farmland carbon sequestration are not included in the USDA analysis. For example, conservation practices that convert small areas of sensitive and low-productivity cropland within a crop field to grasslands are also increasingly part of the toolkit available to farmers. These include grassed waterways, buffer strips at the edge of fields and prairie strips, as well as using economic and spatial analysis to identify where land can be taken out of production without negatively impacting the profitability of a farm operation. These practices have multiple environmental benefits, including soil carbon storage, erosion control, and creating habitat to support diverse ecosystems.

Over the past decade, there has been increasing awareness of the importance of soil organic carbon for agricultural productivity, soil health, and climate mitigation. Public- and private-sector efforts to improve climate outcomes hold promise to accelerate adoption of agronomic practices that improve soil health and store soil carbon. The development of incentives and market programs for these benefits hold promise to accelerate adoption of agricultural management practices through financial and technical assistance to farmers. Future soil carbon sequestration in croplands will depend on the adoption of SOC sequestering practices and changing weather conditions resulting from climate change.

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