Great Lakes Commission des Grands Lacs

ISSUE BRIEF

Agricultural Carbon Sequestration in the Great Lakes Region

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Preface

This issue brief synthesizes existing literature on the ability of agricultural land to capture and sequester carbon and methods of measuring and documenting the extent of carbon sequestration over time. It was developed in accordance with the Great Lakes Commission's policy resolution, "Understanding Impacts to Great Lakes Agriculture and Water Use Under Changing Climate Conditions"[1] adopted in March 2024 and 2023 GLC Strategic Plan goal to strive toward a resilient Great Lakes basin. A growing body of research indicates that implementing conservation practices that reduce phosphorus inputs and improve water quality may also enhance the carbon storage capacity of agricultural soils, leading to improved soil health and providing resilience to flooding events and drought conditions that impact the ecosystems, communities, and economy of the Great Lakes region.

Soils as Dynamic Carbon Reservoirs

On Earth, all carbon is distributed across multiple reservoirs—including the atmosphere, oceans, soils, biosphere, and Earth's underlying geology—and is recycled between them through physical, chemical, and biological processes collectively known as the carbon cycle. The movement of carbon between these reservoirs is described as a flux, and the balance of these fluxes determines whether a given reservoir functions as a source or a sink. A reservoir is considered a carbon source when its net emissions exceed its inputs, and a carbon sink when its net uptake exceeds its outputs. Globally, soil constitutes the second-largest active carbon reservoir after the oceans. Under certain environmental conditions, agricultural lands can be managed to act as a sink. Enhancing soil carbon sequestration has the potential to contribute meaningfully to climate mitigation strategies while increasing crop yields, improving soil structure, and enhancing water and nutrient retention.[2] These benefits enable greater resilience by buffering the effects of extreme environmental change like shifts in temperature and precipitation patterns that can disrupt food supplies and threaten the economic viability of farmers.

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[1] Great Lakes Commission. March 6, 2024. Understanding Impacts to Great Lakes Agriculture and Water Use Under Changing Climate Conditions.

[2] Oldfield, E. E. et al. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. SOIL, 5, 15–32.

Carbon enters the soil primarily through plant biomass and root-derived inputs. During photosynthesis, atmospheric carbon dioxide (CO_2) is fixed into organic matter, which subsequently enter the soil system via root exudates, senesced biomass, and microbial turnover becoming soil organic matter (SOM). The proportion of SOM that is composed of carbon is called soil organic carbon (SOC). The stabilization of this organic carbon is governed by a suite of physical, chemical, and biological processes. Physical protection occurs when organic matter is occluded within soil aggregates, reducing microbial access and decomposition rates.[3] Chemical stabilization involves the sorption of organic compounds onto mineral surfaces, particularly clay and metal ions, forming organo-mineral complexes resistant to microbial decomposition.[4] Biochemical recalcitrance contributes through the decomposition of organic matter and the subsequent formation of complex leftover molecules such as humus that persist in soil for decades or longer (Figure 1).[5]

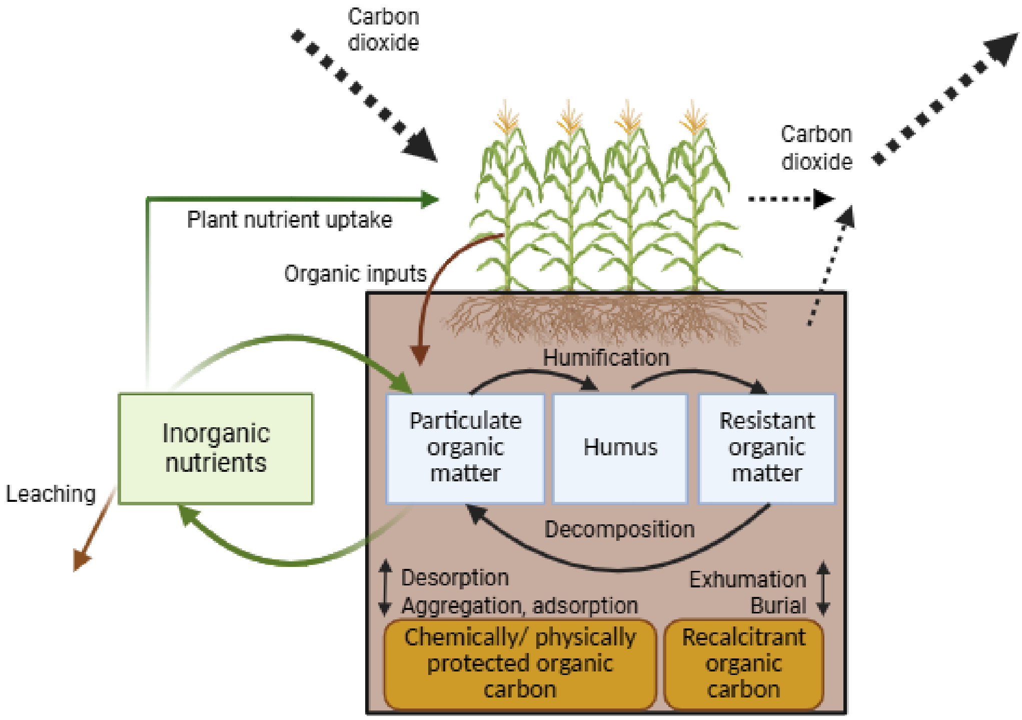

Figure 1. Organic carbon cycling in soil. Adapted from Hoyle, F C, and Murphy, D. (2018), Soil Quality: 3 Soil Organic Matter.

The average residence time of soil organic carbon (SOC) spans a wide range, from days to centuries, depending on climatic conditions, soil texture and mineralogy, microbial activity, and land management practices. Often, SOC is categorized into pools that differ in their stability and how long they remain in the soil, ranging from labile (fast turnover) to stable (intermediate), refractory, and inert (very slow turnover) forms.

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[3] Six, J. et al. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research, 79(1), 7–31.
[4] Sollins, P. et al (1996). Stabilization and destabilization of soil organic matter: Mechanisms and controls. Geoderma, 74(1), 65–105.
[5] Hoyle, F. (2013). Managing soil organic matter: A practical guide. Department of Agriculture and Food Western Australia.

Conservation Management Strategies

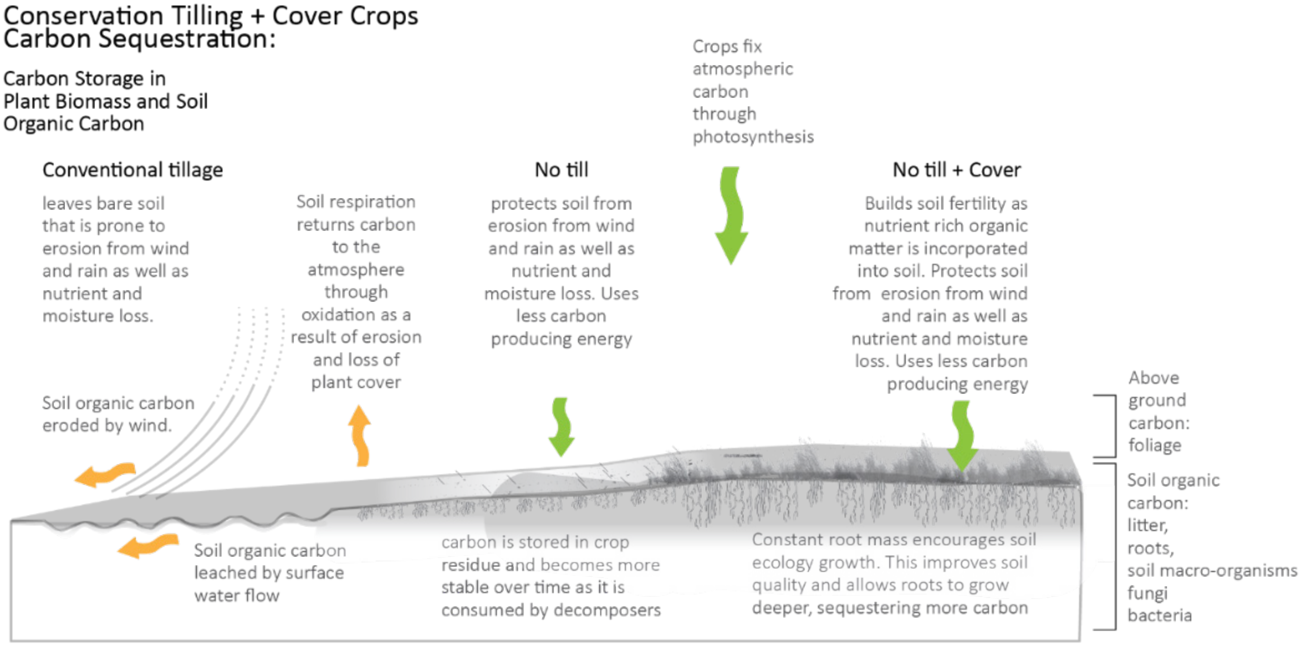

Figure 2. Effects of management strategies like conservation tillage and cover crops on soil carbon sequestration. Reproduced from Minnesota Board of Water & Soil Resources.

Management practices, including conservation tillage and cover cropping, reduce soil disturbance and have been shown to improve soil quality, control erosion, retain nutrients, and lower production costs, while also sequestering more carbon than conventional tillage (Figure 2).[6] The addition of cover crops during fallow periods further enhances carbon sequestration by adding biomass above and below ground, with root-derived carbon persisting longer and promoting soil aggregation. These practices also support beneficial soil microbial communities, which contribute to long-term carbon storage and soil health. Research demonstrates that combining conservation tillage with cover crops provides greater gains in SOC than either practice alone, highlighting the synergistic benefits of integrating conservation management approach for both environmental and agricultural outcomes.[7]

Documenting Carbon Sequestration

To monitor and verify the efficacy of conservation management strategies, an accurate and reliable method of measuring carbon sequestration is necessary, including baseline measurements.[8] Long-term research from agricultural experiments in Michigan hints at the benefits from monitoring conservation management approaches, finding that over 25 years, non-traditional management (cover crops, perennial

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[6] Minnesota Board of Water & Soil Resources. (n.d.). Carbon sequestration: Conservation tilling + cover crops. Retrieved October 2025, from https://bwsr.state.mn.us/carbon-sequestration-conservation-tillage-and-cover-crops.

[7] Mbuthia, L.W. et al. (2015) Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. Soil Biology and Biochemistry 89, 24–34.

[8] Olson, K. R. (2013). Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: Issues paper for protocol development. Geoderma, 195–196, 201–206.

crops, and no-till) accumulated soil organic carbon (SOC), in contrast to conventional practices which stagnated SOC pools.[9]

Standard procedures are available for laboratory (*ex-situ*) and point (*in-situ*) scales,[10] yet, standardized methods for broader spatial and longer temporal scales are still needed.[11] This will require harmonization of measurement methods and protocols employed across management sectors to facilitate data interoperability and exchange.[12] Existing efforts to quantify soil carbon sequestration are often challenged by spatial heterogeneity of SOC across fields and soil column, by temporal variability and uncertainty surrounding carbon sequestration, and by model uncertainty when estimating whole fields or regions from point-based observations.

Estimates of carbon sequestration depend on the spatial extent assessed, from point-level soil cores to field-scale sampling to regional or basin-wide ecosystem assessments. Each scale presents tradeoffs between precision, spatial coverage, and resource requirements. The following monitoring approaches reflect both current practices and emerging technologies that are shaping the field.[13]

Laboratory Methods

Direct sampling and laboratory analysis of soil organic carbon remains the gold standard for accuracy. Soil cores analyzed for soil organic carbon content provide high-resolution data but are generally performed in laboratories and require either correction factors or expensive equipment, limiting their exclusive use for tracking carbon dynamics across broad geographic scales.[14]

Spectroscopic Methods

Spectroscopic methods offer rapid and efficient ways to measure and monitor soil organic carbon in the point, field, regional, and ecosystem contexts. Historically limited to laboratory use, these methods are now increasingly applied *in-situ* and via remote platforms such as unmanned aerial vehicles, aircraft, and satellites.[15] Spectroscopic approaches estimate SOC by analyzing soil reflectance at different wavelengths, calibrated against reference samples. While they enable efficient large-scale mapping and can reduce laboratory costs, their accuracy depends on robust calibration datasets and site-specific soil characteristics.

Eddy Covariance

Eddy covariance flux systems provide measurements of net ecosystem carbon exchange at the field to ecosystem scale. By measuring vertical fluxes of CO_2 between the land surface and the atmosphere, these tower-based systems capture real-time data on the balance between photosynthetic uptake and respiratory

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[9] Córdova, S. et al. (2025). Soil carbon change in intensive agriculture after 25 years of conservation management. Geoderma, 453, 117133.

[10] Bispo, A. et al. (2017). Accounting for carbon stocks in soils and measuring GHG emission fluxes from soils: Do we have the necessary standards? Frontiers in Environmental Science, 5, 41.

[11] Miller, B. A. et al. (2016). Towards mapping soil carbon landscapes: Issues of sampling scale and transferability. Soil and Tillage Research, 156, 194–208.
Smith, P. (2004), How long before a change in soil organic carbon can be detected?. Global Change Biology, 10: 1878-1883.

[12] Paustian, K. et al. (2016). Climate-smart soils. Nature, 532, 49–57.

[13] Nayak, A. K. et al. (2019). Current and emerging methodologies for estimating carbon sequestration in agricultural soils: A review. Science of The Total Environment, 665, 890–912.

[14] Chatterjee, A. et al. (2009). Evaluation of Different Soil Carbon Determination Methods. Critical Reviews in Plant Sciences, 28(3), 164–178.

[15] Ben-Dor, E. et al. (2009). Using Imaging Spectroscopy to study soil properties. Remote Sensing of Environment, 113, S38–S55.

release.[16] Although limited by their high installation and maintenance costs, flux towers offer an unparalleled window into ecosystem-scale carbon dynamics. Long-term flux networks can serve as calibration sites for upscaling efforts and for validating carbon models used in decision-making.

Soil Carbon Modeling

Soil carbon models can estimate the size and change of SOC pools over time using linked mathematical equations that represent our conceptual understanding of ecological processes. These models help investigate the complex interactions among climate, crop traits, soil properties, and management practices that drive long-term and large-scale changes to SOC. Traditional process-based models (e.g., CENTURY[17], RothC[18]) rely on measured inputs and mechanistic assumptions to simulate carbon cycling, providing valuable insights into soil-climate feedbacks and management outcomes.

Artificial Intelligence in Soil Carbon Modeling

While still a nascent field of study and application, artificial intelligence (AI) is emerging as a promising tool for managers and decision-makers to improve estimates of soil organic carbon. AI-based models can capture nonlinear relationships and identify patterns among environmental drivers that are difficult to capture in process-based models. When combined with large, high-quality observational datasets, AI models can improve estimates of SOC pools and fluxes, enhance spatial prediction, and support data assimilation into existing models.[19] However, AI is not a panacea for all soil organic carbon estimation. Its effectiveness depends on the availability of high-quality, timely observational data, transparent and replicable model architecture, and careful ethical and epistemological evaluation of how outputs are generated, interpreted, and applied in decision-making contexts. Without attention to these considerations, AI models risk reinforcing existing data gaps, introducing new uncertainties, or obscuring key ecological processes behind opaque algorithmic outputs.

State/Provincial Goals

The Great Lakes Commission recognizes that deploying resiliency efforts and adaptation strategies is critical to protect and promote the shared waters, natural resources, residents, and economy of the Great Lakes region. Across the Great Lakes region, state agencies and provincial ministries aim to leverage natural and working lands to store and sequester carbon to promote soil health; prevent severe flooding; and improve water quality by increasing the water filtration capacity of agricultural soils, limiting nutrient and sediment runoff. See **Table 1** for the Great Lakes-St. Lawrence state and provincial goals related to promoting the ability of agricultural land to capture and sequester carbon.[20]

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[16] Baldocchi, D. et al. (1996). Strategies for measuring and modelling carbon dioxide and water vapour fluxes over terrestrial ecosystems. Global Change Biology, 2(3), 159–168.

[17] Parton, W. J. (1996). The CENTURY model. Evaluation of Soil Organic Matter Models (pp. 283–291). Springer.

[18] Jenkinson, D. S., & Coleman, K. (1994). Calculating the annual input of organic matter to soil from measurements of total organic carbon and radiocarbon. European Journal of Soil Science, 45(2), 167–174.

[19] Grunwald, S. (2022). Artificial intelligence and soil carbon modeling demystified: Power, potentials, and perils. Carbon Footprints, 1, 5.

[20] State and provincial goals were pulled and derived from existing resilience plans developed by each jurisdiction and/or state agency and provincial ministry websites.

Table 1. Water Quality and Soil Health Goals of each Great Lakes state and province related to promoting the ability of agricultural land to capture and sequester carbon.

	Water Quality Goal	Soil Health Goal
IL	Protect water quality by increasing natural carbon storage from restored forests, grasslands, and croplands	Expand Illinois's cover crop program to provide financial incentives for participants to implement cover crops deploy new technology
IN	N/A	Improve carbon sequestration benefits of rural areas by planting cover crops on 20% of Indiana's total farmland acreage by 2030 and 50% by 2050
MI	Utilize natural and working lands to store and sequester carbon, thereby limiting water runoff pollution	Utilize natural and working lands to store and sequester carbon, thereby improving soil health
MN	Implement climate-smart peatland, grassland, and forest conservation efforts to improve carbon sequestration, protect water quality, and prevent flooding	Increase the amount of carbon sequestered and stored annually in natural and working lands 25% by 2035
NY	Implement agroforestry and reforestation to provide flood mitigation and sequester carbon emissions	Support landowners in reducing and sequestering carbon emissions on forestland and cropland
OH	N/A	Encourage actions (e.g., undertaking sustainable agricultural practices) to sequester carbon in the agricultural sector
ON	N/A	Support on-farm practices that increase and maintain practices known to reduce greenhouse gas emissions, sequester carbon and/or increase resiliency to climate change
PA	Recommend best practices for the agricultural sector to reduce impacts of flash flooding, reduce nitrogen and sediment loading to waterways, and allow soils to hold more water	Prioritize funding, policies, and programs that support the deployment of point source capture and geological storage of carbon in agricultural and forest lands
QC	N/A	Test innovative silvicultural practices on trees and soils, identifying and implementing those with the greatest potential to effectively maintain or increase carbon stocks
WI	N/A	Provide tax incentives or subsidies for farmers to increase soil carbon storage in agricultural and working lands