Impact of Tillage and Crop Rotation Systems on Soil Carbon Sequestration

by Mahdi Al-Kaisi

What is carbon (C) sequestration?

Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere. The idea is to (1) prevent carbon emissions produced by human activities from reaching the atmosphere by capturing and diverting them to secure storage, or (2) remove carbon from the atmosphere by various means and store it.

What is the importance of carbon sequestration?

The scientific consensus is that the levels of greenhouse gases in the atmosphere are increasing. These changes in greenhouse gas emissions generally are linked to human activities. The concern is that the mean global level of greenhouse gases in the atmosphere is increasing to a level that can trigger serious climate changes in air temperature and violent weather cycles.

Carbon sequestration by agricultural land has generated international interest because of its potential impact on and benefits for agriculture and climate change. Where proper soil and residue management techniques are implemented, agriculture can be one of many potential solutions to the problem of greenhouse gas emissions. Additionally, agriculture conservation practices such as the use of different cropping and plant residue management, as well as organic management farming, can enhance soil carbon storage. Farmers, as well as the soil and environment, receive benefits from carbon sequestration.

Agricultural ecosystems represent an estimated 11% of the earth's land surface and include some of the most productive and carbon-rich soils. As a result, they play a significant role in the storage and release of C within the terrestrial carbon cycle (Lal et al., 1995). The major considerations of the soil C balance and the emission of greenhouse gases from the soil are: (1) the potential increase of CO_2 emissions from soil contributing to the increase of the greenhouse effect, (2) the potential increase in other gas emissions (e.g., N_2O and CH_4) from soil as a consequence of land management practices and fertilizer use, and (3) the potential for increasing C (as CO_2) storage into soils, which equals $1.3 – 2.4 \times 10^9$ metric tons of carbon per year (Tans et al., 1990), and to help reduce future increases of CO_2 in the atmosphere.

Carbon benefit to the soil

Soil carbon, or organic matter in general, is important because it affects all soil quality functions (Fenton et al., 1999):

- Sustaining biological activity, diversity, and productivity
- Regulating and partitioning water and solute transport
- Filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal byproducts and atmospheric deposition
- Storing and cycling nutrients and other elements within the earth's biosphere

The impact of soil organic matter on the soil qualities listed above and soil functions can be summarized as follows:

- **Physical effects:** soil aggregation, erosion, drainage, aeration, water-holding capacity, bulk density, evaporation, and permeability.
- **Chemical effects:** cation exchange capacity; metal complexing; buffering capacity; supply and availability of N, P, S, and micronutrients; and adsorption of pesticides and other added chemicals.

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■ **Biological effects:** activities of bacteria, fungi, actinomycetes, earthworms, roots, and other microorganisms.Different sources of organic matter supply soils with carbon to replenish their C and nutrient pools. However, organic materials added to soils contain a wide range of C compounds that vary in their rate of decomposition. The biological breakdown of the added organic material depends on the rate of degradation of each of the carbon-containing materials. Changes in environmental factors can cause changes in the rate of decomposition of organic materials in soils, such as soil moisture status, soil aeration, soil temperature, pH, and availability of minerals.

Carbon pools and sinks

Soils store a significant amount of carbon. It has been estimated that global soils contain approximately 1.5×10^{12} metric tons of carbon (Post et al., 1998). As a component of the carbon cycle (Figure 1), soils can be either net sources or net sinks of the atmospheric carbon dioxide. Changes in land use and agricultural activities during the past 200 years have made soils act as net sources of atmospheric CO_2. Evidence from long-term experiments suggests that carbon losses due to oxidation and erosion can be reversed with soil management practices that minimize soil disturbance and optimize plant yield through fertilization. It is possible that improved land management can result in a significant increase in the rate of carbon into the soil. Because of the relatively long turnover time of some soil carbon fractions, this could result in storage of a sizable amount of carbon in the soil for several decades.

Processes affecting carbon sequestration in soils

Several processes can affect the storage of carbon in soils. The amount of carbon stored in the soil system depends on the rate and magnitude of the process. These processes can be influenced by agriculture management systems and practices.

Organic production

Carbon production can be increased through photosynthesis, in which the permanent vegetation cover can store a significant amount of carbon dioxide as organic carbon. The volume of vegetation acts as a sink for capturing CO_2 and secures storage of it as carbon. Farming practices and and land use can greatly affect the carbon status in the soil system. During plant growth, CO_2

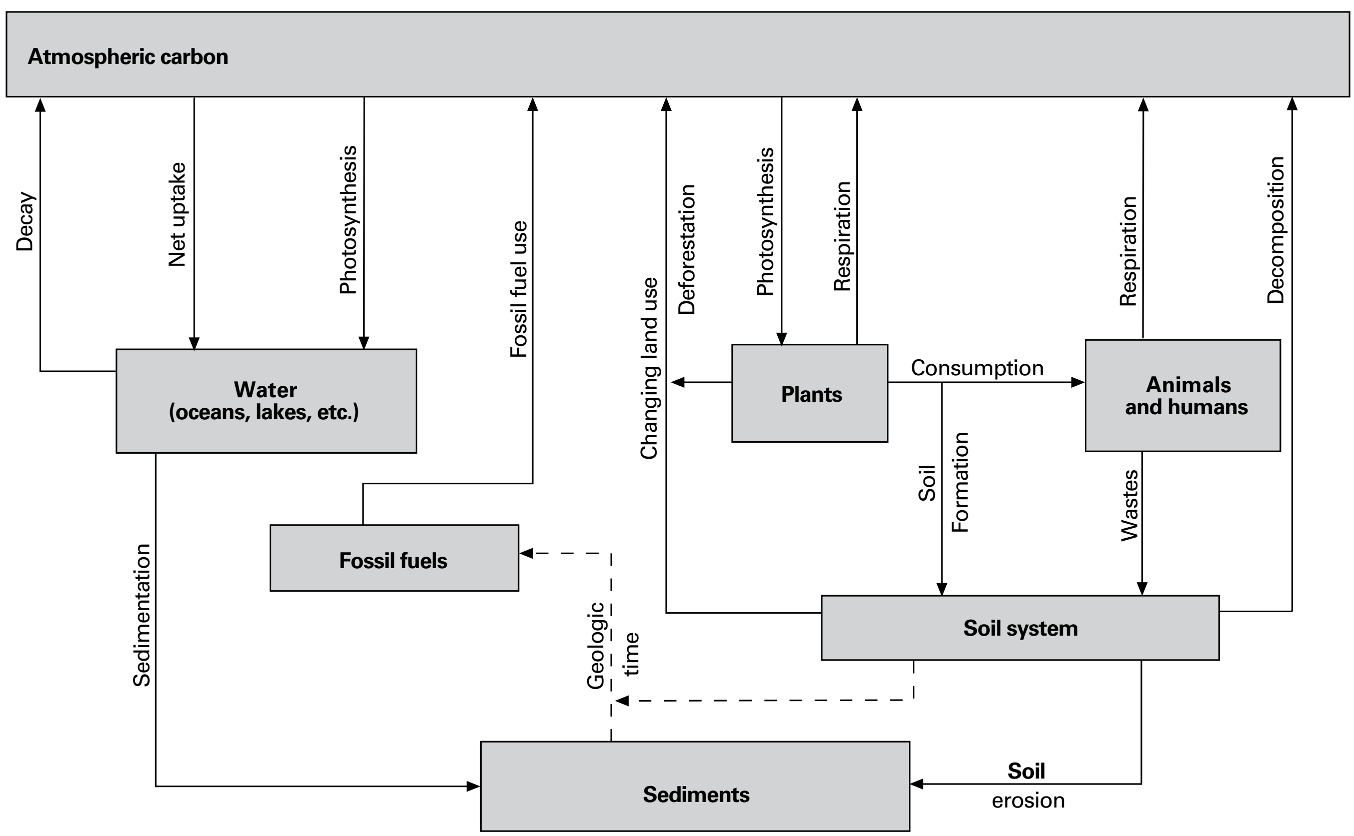


Figure 1. Carbon cycle aspects (modified from Paul and Clark, 1996)

from the atmosphere will be fixed in the plant as carbon compounds. Therefore, the primary source of carbon is the plant, in which the carbon has been manufactured initially through the photosynthesis process.

Minimize organic carbon breakdown

The oxidation and breakdown of plant residue will accelerate the loss of carbon as CO_2. Several factors can accelerate organic carbon breakdown and production of greenhouse gases. They include soil moisture, soil pH, the oxidation-reduction process, soil temperature, chemical and physical soil properties, nutrient status, and plant residue quantity and quality. The breakdown of residue through conventional tillage and soil disturbance must be minimal to fully store carbon in the soil system. Carbon stored in the soil can help improve soil physical properties such as infiltration rate, water-holding capacity, aggregate stability, soil structure, soil aeration, and a host of other physical properties. In addition, carbon storage can contribute significantly to improving soil nutrient pools and other chemical properties. Plant residues play a significant role in providing a positive environment for improving soil microbial populations, which in turn play a significant role during the decomposition process of organic materials. Keeping plant residues intact is a critical component of soil management, not only for nutrient value, but also for soil protection from wind and water erosion.

Soil erosion

Improper soil and residue management results in increased erosion by water and wind. Soil erosion is a leading cause of soil degradation due to the loss of organic matter, which is the “glue” or binding factor in soil. In Iowa, water erosion contributes significantly to the degradation of soil quality. The most effective way to minimize soil erosion is through the use of conservation tillage practices. The impact of no-tillage practices in improving soil quality in terms of carbon content at the upper part of the soil profile is evident where permanent vegetation has been established in grassy areas. Tillage can cause the loss of significant amounts of carbon (lost as CO_2 bursts) immediately after tillage. The exposure of soil organic carbon to aeration during soil erosion increases CO_2 emissions. In addition, soil erosion can cause carbon to accumulate with soil sediments and be removed from the soil carbon pool. The removal of carbon from the soil will lead to a decline in soil fertility and aggregate stability.

Benefits of Organic Matter

- Source of nutrients for crops
- Provides the major natural source of inorganic nutrients and microbial energy
- Promotes soil aggregation and root development
- Favors the development of antagonistic organisms that serve to combat certain plant diseases
- Improves water infiltration and water use efficiency
- Improves soil water-holding capacity
- Increases soil aggregate stability to resist erosion

Impact of conservation practices and fertilizer use on carbon storage in soils

Conservation tillage practices can minimize the rapid breakdown of plant residues, reduce CO_2 emission, and reduce the production of inorganic dissolved nitrogen (i.e., nitrate and ammonium) in soil. When conventional tillage is converted to conservation tillage, both CO_2 emission from soil and N-uptake by crops are reduced. Reduction in CO_2 emission from soils enhances soil organic carbon (SOC) content, but reduction in N-uptake decreases residue production and hence, organic C storage in soils. Also, it was found that reducing tillage significantly decreases SOC loss from soils with high organic matter content.

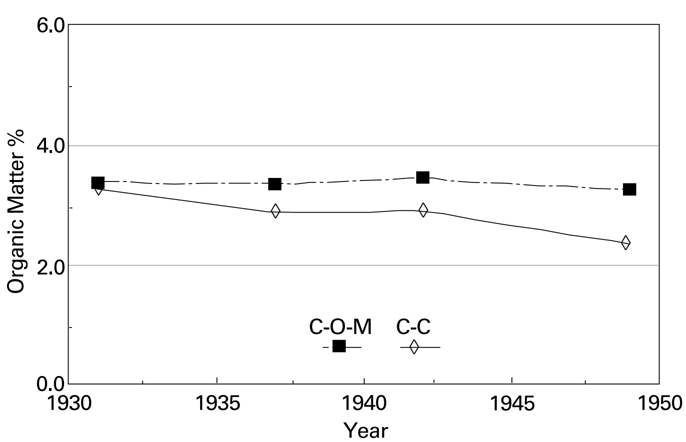
The Morrow plots at the University of Illinois were established in 1876 to study the effects of crop rotations and fertilization on yield (Table 1). Crop sequences, in a single replication, were continuous corn, corn-oats rotation, and corn-oats-clover rotation, with and without lime, manure, and rock phosphate (Stauffer et al., 1940). The results show that continuous corn plots with no fertilizer decreased soil organic matter (SOM) content by 45.6% in 55 years as compared with the adjacent sod (Table 1). Neither the cropping system nor the soil treatment had much effect on soil organic carbon below 9 inches.

Table 1. Effect of rotation and treatments on organic carbon content in Morrow plots, 1876–1940, University of Illinois (after Stauffer et al., 1940)

Rotation	Treatment[a]	% Organic C	% Organic Matter	% C change[b]
Corn	None	1.74	2.99	–45.6
	MLP	2.09	3.59	–34.7
Corn-Oats	None	2.14	3.68	–33.1
	MLP	2.44	4.20	–23.6
Corn-Oats-Clover	None	2.28	3.92	–28.7
	MLP	3.35	5.76	+4.0
Sod	None	3.20	5.50	0.0

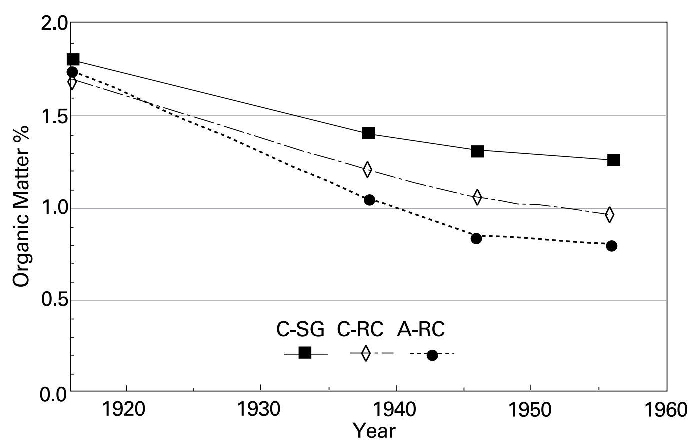
[a]MLP = Manure-Lime-Phosphorus
[b]% C changes based on sod C value

Figure 2 summarizes the long-term impact of different crop rotations on soil carbon content. The data showed a higher rate of soil carbon decline under continuous corn compared to corn-oats-meadow crop rotation. The plots were located on 9% slope gradients and some loss of soil organic carbon can be attributed to erosion. The uncultivated Marshall soil on which the plots are located should have soil organic matter of approximately 4.5–5% (Fenton et al., 1999). Figure 3 shows another long-term crop rotation system. The rate of decline was the greatest during the period of 1916–1938 and then the rate of change decreases. The average loss of soil organic carbon during 1946–1956 was 2.1%.



C-O-M = Corn-Oats-Meadow
C-C = Continuous Corn

Figure 2. Changes in organic matter in Iowa (after Van Bavel and Schaller, 1950)



C-SG = Continuous Small Grain
C-RC = Continuous Row Crop
A-RC = Alternative Row Crop and Fallow

Figure 3. Influence of cropping system on organic carbon (Hays, KS) (after Hobbs and Brown, 1965)

Summary

This publication is intended to explain carbon sequestration, present facts about the carbon cycle, present concerns related to elevated atmospheric CO_2 levels, and show the relationship between current agriculture practices and the carbon cycle. Carbon sequestration is highly related to soil and management systems. Research on the impact of tillage practices and crop rotation has demonstrated that no-till and permanent vegetation are more effective in storing carbon in the soil. The use of crop rotation and conservation tillage, in addition to effective manure and nitrogen management systems, contributed significantly to improving soil carbon status. The value of storing carbon through conservation practices can be very significant in improving soil quality and productivity as listed earlier.

Farmers can benefit from carbon sequestration through the use of conservation tillage, crop rotation, the use of buffer strips, and permanent vegetation for highly eroded soils. These benefits include improved soil productivity, an improved environment due to less erosion, and improved physical and biological properties of soil. Carbon credit is another benefit that has been explored recently by many different entities. Carbon credit is worth exploring but needs careful consideration. The issues of market value, policy, carbon monitoring procedures, and management entities are among those that need to be addressed when considering carbon sequestration and credits.

The availability of recent carbon sequestration data in Iowa is very limited although many projects currently are addressing this issue. Carbon sequestration must be viewed as a long-term process in order to see meaningful impacts of conservation tillage, residue management, manure and fertilizer use, crop rotations, etc. Farmers, crop advisors, and others who deal with carbon sequestration need to recognize that carbon sequestration is a reversible process. They must adopt a system that improves soil carbon sequestration as a long-term management tool because any short-term disturbance, such as a change from conservation tillage to conventional tillage, will not achieve significant improvement in soil carbon status. Therefore, farmers need to think long-term when thinking about carbon sequestration.

The overall benefits of soil carbon sequestration need to be viewed as an opportunity to improve soil quality as well as the environment.

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