SOIL CARBON SEQUESTRATION IN AGRICULTURE: RESEARCH EFFORTS IN THE CENTRAL U.S.

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Since the late 1800's fossil fuel use, expansion of cultivated agriculture, and forest clearing have led to an increase in atmospheric CO_2 from 260 ppm to current levels >370 ppm (IPPC, 1995). Most of the recent increase in CO_2 has been attributed to combustion of fossil fuels for energy and transportation. This increase in atmospheric CO_2 potentially impacts climate, as it is a greenhouse gas. It has been estimated that 20-40% of targeted emission reductions in the U.S. can be met by carbon sequestration into soils.

Recent models of land use suggest terrestrial systems can mitigate the increase of atmospheric CO_2 by sequestering C into vegetation and soils. The estimated amount of C stored in world soils is about 1100 to 1600 Pg. more than twice the C in living vegetation (560 Pg) or in the atmosphere (750 Pg) (Sundquist, 1993). Hence, even relatively small changes in soil C storage per unit area could have a significant impact on the global C balance. Approximately 50% of the soil organic carbon (soil organic matter) has been lost from the soil over a period of 50 to 100 years of cultivation. However, this loss of soil carbon also represents the potential for storage of C in soils. Carbon sequestration by soils occurs primarily through plants. Plants convert CO_2 into tissue through photosynthesis. Upon their death, plant tissues decompose, primarily by soil microorganisms, and the carbon in the plant material is eventually released back into the atmosphere as CO_2. However some of the C in plant material forms soil organic matter sometimes referred to as "humus." Some of this carbon in the soil can persist in soils for hundreds and even thousands of years.

The amount of carbon soils can sequester is dependent on several factors. Inherent factors include climate variables (temperature and rainfall) and clay content. Vegetation type and productivity also affect the amount of soil C. While much of the discussion of carbon sequestration has been directed to forests, soils have the potential to store additional C in many ecosystems. Grasslands have similar levels of C as many forest systems.

Global estimates for C sequestration for different ecosystems indicate the agricultural lands are 45 to 90 % of forests (Metting et al., 1999) (Table 2). If grasslands and rangelands are considered, then managed lands contributions to carbon sequestration are greater than forests. Thus all ecosystems must be considered in any plan to increase C sequestration.

Economic analysis suggest that soil carbon sequestration is among the most beneficial and cost effective options available for reducing greenhouse gases, particularly over the next 30 years until alternative energy sources are developed and become economic feasible. Recent estimates of the potential for U.S. agriculture, using existing technologies, are on the order of 75-200 MMT C per year (Lal et al., 1998; Bruce et al., 1998). Soils have the potential to achieve reduction in net carbon emissions until 2050 (Rosenberg et al., 1999). After 2050 reductions in carbon emissions must come from changes in energy technologies.

As a result of the need to develop a integrated study on carbon sequestration in agricultural soils the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS) was formed. CASMGS is a coalition of scientists from 10 institutions in the U.S. to provide a highly coordinated, comprehensive, and efficient study of how agricultural soils can be managed to increase soil carbon (C) sequestration and reduce greenhouse gas (GHG) emissions. CASMGS scientists are also examining how policies designed to encourage C sequestration and reduce GHG emissions can be assessed, and how results can be quantified and verified. To accomplish this, the Executive Committee of CASMGS has established five tasks areas.

1) Develop a better understanding of the basic processes of soil C sequestration and GHG emissions;
2) Evaluate BMPs to increase C sequestration and reduce net GHG emissions from soils;
3) Utilize computer models and databases to predict and assess C sequestration and GHG emissions;
4) Develop tools for measuring and monitoring soil C sequestration rates and GHG emissions; and
5) Communicate C sequestration and GHG reduction information to policymakers, and the agricultural and energy industry.

Some of the research results are illustrated below.

Basic understanding of biophysical and biochemical processes that control soil C dynamics.

Soil carbon sequestration is governed by microorganisms that consume and decompose plant residues. The fate of these decomposition products, how long and in what form they are retained in soils is dependent on the composition and activity of the microbial community and the physical and chemical environment of the soil. We are following the change and sequestration of carbon in different fractions of organic matter and in different components of the microbial community. A better understanding of these basic processes, at the micro-level in soils, may help in the design of more effective ways to sequester carbon.

Plant varieties may vary in chemical composition which could lead to differences in carbon sequestration. High and low lodging grain sorghum varieties were selected for laboratory incubation experiments to determine if the increased lignin of lodging-resistant varieties can increase the stable soil C pool as compared to the non-lodging-resistant varieties. Initial research indicates chemical composition of the plant can impact carbon retention in soil.

In agricultural systems, maintenance of soil organic matter (SOM) has long been recognized as a strategy to reduce soil degradation. No-tillage and manure amendments are management practices that can increase SOM content and improve soil aggregation. We investigated the effects of 10-yr of different tillage systems and N sources on soil aggregate size distribution and aggregate-associated C and N. No-tillage and manure treatments significantly increased total C and N and the formation of macroaggregates. Conventional tillage in comparison with NT significantly reduced macroaggregates with a significant redistribution of aggregates into microaggregates. Aggregate protected labile C and N were significantly greater for macroaggregates. (> 2000 and 250-2000 µm) than microaggregates (53-250 and 20-53 µm) and greater for M than F indicating physical protection of labile C within macroaggregates.

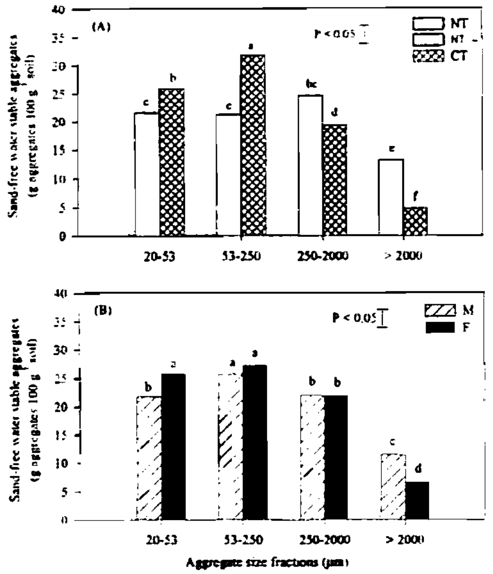

Figure 1. Distribution of soil aggregates associated with tillage and manure/fertilizer treatments after 10 years on a Kennebec silt loam (Mikha, 2003).

Physical and economic potential of best management practices (BMPs) for sequestering carbon

Estimates of the rate of soil carbon sequestration for the most important and potentially applicable BMPs. Both the physical potential and economic potential of these systems are being studied. The list of BMPs and systems that is being considered fall into the three categories discussed above and are listed in Table 1.

Table 1: List of BMPs under study.

Land Management	**Perennial Ecosystems**	**Irrigation and Water Management**
Conservation tillage	Agroforestry	Irrigation management
Cropping intensity	Riparian zones and buffers	Water management
Nutrient management and precision farming	Prairie restoration	Soil restoration, saline soil reclamation
	Wetlands restoration	
	Grazing intensity and fires on prairies	

Some of the initial results across the central U.S. indicate increased C sequestration across a variety of agricultural systems. Elimination of summer fallow, adoption of no-tillage and the use of manure and rotations that intensify crop residue inputs are the better management practices that promote sequestration. Differences in systems will vary in response to climate and soil type.

Table 2. Rate of SOC sequestration

Treatment	Scenario	Rate (Mg C/ha/y)	Duration (yrs)	State
1. Elimination of summer fallow	(i) 3-year system	0.073	12	Eastern Colorado
	(ii) 4-year system	0.117		
	(iii) Continuous cropping	0.229		
2. Integrated Nutrient Management (corn)	(i) Notill with 150 kg/ha of N as manure	0.535	10	NE Kansas
	(ii) Notill with 150 kg/ha of N as NH_4NO_3	0.473		
	(iii) Conventional tillage with 150 kg N/ha as manure	0.452		
3. Rotations	(i) Conventional tillage wheat to no-till	0.764	10	SC Kansas
	(ii) Conventional till to no-till sorghum	0.605		
	(iii) CT sorghum/NT wheat to NT sorghum/NT wheat	0.624		
4. Conservation tillage	Conservation till at different N rates in a wheat/sorghum/fallow rotation	0	37	Semi-arid Kansas
5. Farming systems	(i) No till corn	0.379	14	NE Ohio
	(ii) Notill corn in rotation with grass meadow	0.375	20	
	(iii) Notill corn in rotation with alfalfa and with manure	0.760	20	
	(iv) Corn-soybean with poultry manure	0.392	13	

Economic analysis of practices that enhance carbon (C) sequestration with and without C credit payments have been conducted by Williams et al. (2003). These practices include different fertilizer sources and applications, tillage systems, and crop rotations. The value of C credits needed to adopt practices that sequester C in the soil are derived with and without accounting for

C released from production inputs to the atmosphere. In southcentral Kansas no-tillage systems were economically feasible when compared to conventional tillage. Carbon credits are not needed to encourage sequestration of additional soil carbon with no-tillage in many cases. In a related study the use of ammonium nitrate N sources in conjunction with no-tillage has higher net returns than the use of beef manure as an N source. Although manure fertilized system sequester more soil carbon than ammonium nitrate N systems, positive carbon credits are needed to encourage the use of manure as an N source.

Measurement and Monitoring

Traditionally, changes in SOC induced by management have been measured in long-term experiments by soil sampling and laboratory determinations. These data have been instrumental in the development of models able to predict SOC changes that result from various climate-soil-management combinations. The most effective verification plan will likely use some combination of direct measurement and modeling.

Monitoring of soil C sequestration is challenging because of substantial spatial variability. Benchmarks offer an effective means of monitoring soil C sequestration dealing with soil heterogeneity. A sampling protocol was developed to monitor C sequestration at an agricultural site (Kennebec silt loam (Fine-silty, mixed, mesic Cumulic Hapludolls)). The spatial variability of soil C and bulk density was studied using composite and systematic grid sampling schemes. Composite sampling more precisely characterized the C status than the grid sampling with about 75% less variability in the final estimate of soil C. This variability was reduced only by 35% at the prairie site. The precision of soil C analysis by dry combustion ranged from 2.4 to 3.2%.

Table x. Variability of the final C status (Mg ha^{-1}) for an agricultural site

Sampling scheme	Mean	SD	CV%	n†
Grid 1	48.36	3.94	8.2	25
Grid 1	47.84	3.61	7.5	25
Grid 1	47.83	2.77	5.8	25
Average	48.01	3.44	7.2	
Composite 1	48.47	0	0	1
Composite 2	44.65	0	0	1
Composite 3	46.66	0	0	1
Average	46.59	1.91	4.1	

† number of samples

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