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# STORING CARBON IN AGRICULTURAL SOILS TO HELP MITIGATE GLOBAL WARMING

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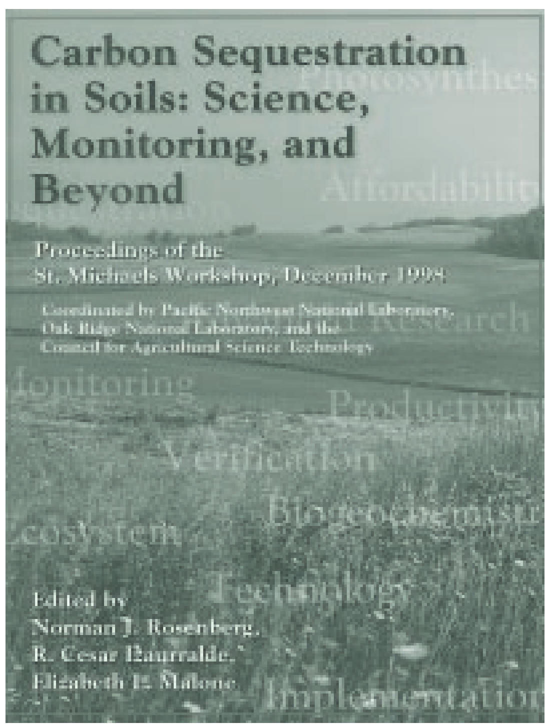


**Norman J. Rosenberg, R. Cesar Izaurralde, Elizabeth L. Malone (Eds.). 1999.** ***Carbon Sequestration in Soils: Science, Monitoring, and Beyond. Proceedings of the St. Michaels Workshop, December 1998.*** **Available with CAST discount from Battelle Press, Columbus, Ohio at (800) 451-3543 or www.battelle.org/bookstore.**

## Summary

As an important constituent of soils, organic matter contributes greatly to plant productivity and ecosystem stability. Soil organic matter is also an important repository of carbon (C) and plays a central role in the global C-cycle. Soils may act either as a source, releasing C to the atmosphere, or as a sink into which C from the atmosphere is deposited, depending on season, time of day, vegetative cover, weather conditions, and land management. But land management is the critical determinant of whether the net change in soil C is a gain or a loss. Since the beginning of the industrial revolution, land use changes, such as conversion of temperate forests and prairies to agricultural fields, have contributed significantly to the recorded increase in concentration of atmospheric $CO_2$. And current deforestation in the tropics continues to add $CO_2$ to the atmosphere. Because of justified concern that emissions of $CO_2$ and other greenhouse gases in the atmosphere are causing global warming, national policies and programs are emerging to slow, offset, or eliminate emissions. Agricultural practices that conserve soil and increase productivity while improving soil quality also increase the C content in soils, thereby removing $CO_2$ from the atmosphere. Integrated assessments of energy and economic options needed to stabilize atmospheric $CO_2$ during this century indicate that soil C-sequestration can provide an important opportunity for limiting the increase of atmospheric $CO_2$, especially if action is taken worldwide during the next three decades.

But a stronger knowledge base that now exists is required before this can be accomplished. In December of 1998, a workshop was convened at St. Michaels, Maryland by the Department of Energy's Pacific Northwest and Oak Ridge National Laboratories, in conjunction

with CAST, to address the questions of (1) how best to improve the scientific understanding of the biophysical processes that regulate C-sequestration in currently farmed lands and lands requiring protection and/or reclamation from desertification; (2) how best to monitor natural and management-driven change in soil C-content; and (3) how best to implement soil C-sequestration programs. The 100 scientists, practitioners, and policy makers who attended the workshop emphasized the need for research leading to an in-depth understanding of the mechanisms responsible for C stabilization and turnover in soil aggregates, of landscape effects on C sequestration, and of ways to use C sequestration to combat desertification. High priority was assigned to research on the environmental impacts of soil C-sequestration and on the applications of genetic engineering to enhance plant productivity and to increase C sequestration. The workshop also recognized the urgent need for a rapid, economical, reliable method to verify and to monitor soil C-sequestration. A more comprehensive understanding of the social, economic, and environmental implications of incentives potentially leading to widespread adoption of soil C- sequestration programs was also deemed essential.

## Introduction

Addition of organic matter to soil increases water-holding capacity, imparts fertility, increases soil aggregation, and improves tilth. Depending on the type — humus, manure, stubble, or litter — organic matter is between 40 and 60% carbon (C). In the form of carbon dioxide ($CO_2$), C is accumulating in the atmosphere as the result of fossil fuel combustion, land use change, and tropical deforestation (Table 1). The atmospheric concentration of $CO_2$ has increased by about 32% from about 280 parts per million by volume (ppmv) at the beginning of the industrial revolution (ca. 1850) to about 370 ppmv today.

There is strong consensus among atmospheric scientists that continued increase in the concentration of atmospheric $CO_2$ and other greenhouse gases such as methane ($CH_4$) and nitrous oxide ($N_2O$) will enhance the earth's natural greenhouse effect and lead to global warming (Intergovernmental Panel on Climate Change, 1996). Some scientists argue from the fact that 1997 was the warmest and 1998 the second warmest years on record that the global climate change "footprint" already is detectable.

Carbon dioxide, the greenhouse gas of primary concern with regard to climate change, is also essential to photosynthesis. Elevated $CO_2$ concentration stimulates photosynthesis and growth in plants with C-3 metabolism (legumes, small grains, most trees) and decreases transpiration, or water use, in plants with C-3 and C-4 (tropical grasses such as maize, sorghum, and sugar cane) metabolism. Together, these phenomena are termed the *$CO_2$-fertilization effect.*

**Table 1. Global carbon (C) flux budget**

| Carbon Flows | Pg[a] C |
|---|---|
| Annual atmospheric increase of carbon dioxide ($CO_2$) | 3.4 |
| Sources | |
| Fossil fuels | 6.4 |
| Land use change | 1.1 |
| Tropical deforestation | 1.6 |
| Sinks | |
| Terrestrial in temperate regions | 2.0 |
| Oceans | 2.0 |
| "Missing" | 1.7 |
| Potential sinks in croplands alone (50 to 100y[b]) 40 to 80 Pg C | |

[a]1 Pg = 1 billion tonnes or $10^{15}$ grams.
[b]Intergovernmental Panel on Climate Change, 1996.

Table 1 provides current estimates of global C *sources* and *sinks*. Fossil fuel combustion, land use change, and tropical deforestation are global C *sources* adding about 9.1 Pg C/year (yr) (1 Pg is equal to 1 billion metric tonnes, or $10^{15}$ grams [g]) to the atmosphere. Of this, only about 3.4 Pg C/yr accumulates in the atmosphere. The remainder is absorbed by global C sinks such as the oceans (about 2.0 Pg C/yr) and by the regrowth of forests in temperate regions (also about 2.0 Pg C/yr). About 1.7 Pg C/yr is not accounted for. Most of this "missing C" is probably going into the terrestrial biosphere in the Northern Hemisphere. Likely, the $CO_2$-fertilization effect is contributing to the increased capture of C in terrestrial ecosystems.

The Intergovernmental Panel on Climate Change (1996) estimated in its Second Assessment Report that it may be possible during the next 50 to 100 years to sequester 40 to 80 Pg of C in cropland soils (Cole et al., 1996; Paustian et al., 1998; Rosenberg et al., 1998). Table 1 shows that, if these estimates are accurate, agricultural soils alone could capture enough C to offset further increases in the atmospheric inventory for 12 to 24 years. These calculations are crude, but they do suggest a potential to offset significant amounts of $CO_2$ emissions by sequestering C in the soils of lands now in agricultural production. Of course, there is additional C sequestration potential in the soils of managed forests and grassland, a potential not addressed here. And, as will be discussed below, there is a great potential for C storage in the soils of degraded and desertified lands. But unless alternatives to fossil fuels are found, the energy demands created by growing populations and rising standards of living could greatly increase $CO_2$ emissions over this century and the capacity of agricultural soils to sequester C could be exhausted, to little long-term effect.

The decade of the 1990s marked the beginnings of a political recognition of the threats that greenhouse gas emissions — at increasing or even at steady rates — may pose to stability of the global climate. In response to this threat, the United Nations adopted the Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro in 1992 (United Nations, 1992). The convention aims at the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." In December 1997, the parties to the UNFCCC met in Kyoto, Japan and drafted a protocol to place binding limits on and to begin the process of stabilizing atmospheric concentrations of greenhouse gas emissions (United Nations, 1997). The protocol recognizes that its objectives can be met by either *decreasing the rate at which greenhouse gases are emitted to the atmosphere or increasing the rate at which they are removed from it.* It was well recognized in the Kyoto negotiations that photosynthesis, by fixing C in standing and below-ground portions of trees and other plants, provides a powerful means of removing $CO_2$ from the atmosphere and sequestering it in the terrestrial biosphere. The Kyoto Protocol establishes the concept of credits for C sinks (Article 3.3) but allows credits for a limited list of activities including afforestation and reforestation (Article 3.4). The protocol allows no credits for soil-C sequestration except, perhaps, (and this is not yet clear) for C accumulating in the soils of afforested or reforested lands. The Kyoto Protocol does not currently permit sequestration in agricultural soils to produce C sequestration credits, although the capacity for allowing such credits clearly exists. Ostensibly because of the difficulty and costliness of verifying that C is actually being sequestered and maintained in soils, this mitigation option was set aside in the Kyoto negotiations; it is, however, mentioned specifically in Article 3.4 for possible inclusion at a later time.

Another way of looking at the potential role of soil C-sequestration appears in Figure 1, which

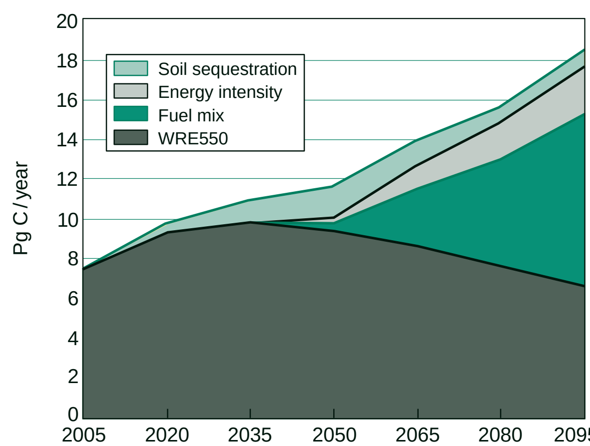


**Figure 1. Global carbon emissions trajectories (Pg = $10^{15}$ g) of carbon (C) during this century according to the MiniCAM's business as usual scenario (top line) and the Wigley-Richels-Edmonds scenario (bottom line) required to limit atmospheric carbon dioxide concentration to 550 parts per million per volume (Wigley et al., 1996). The figure shows a hypothetical path to C emission reductions under a scenario in which credit for soil C sequestration is allowed. Soil C sequestration alone achieves the necessary net C emission reduction in the early part of the century. From the middle of the century on, further emission reductions must come from energy system changes (such as fuel switching and decreased total energy consumption).**

was produced with the integrated assessment model MiniCAM 98.3 (Edmonds et al., 1996a, b; Rosenberg et al., 1999). The top line in the figure represents the anticipated increase in C emissions to the atmosphere in the twenty-first century, using a so-called "business-as-usual" scenario produced by the Intergovernmental Panel on Climate Change (1990). The figure also shows the Wigley-Richels-Edmonds $CO_2$ stabilization trajectory whereby C emissions are allowed to increase to a maximum by 2035 but reduced steadily to about 6–7 Pg C/yr by 2100. Bringing the upper emissions line down to the desired level will require substantive changes in current energy systems. The caption of Figure 1 identifies technologies that will promote the needed change in the next century. Increased efficiency in the uses of fossil fuels; development of non-C-emitting fuels; improvements in power generation; a greater role for biomass fuels (which recycle C but do not increase its concentration in the atmosphere), solar, wind, and nuclear energy; and other technological advances ultimately will be needed to mitigate climate change. Figure 1 shows that soil C-sequestration can play a strategic role but, in and of itself, cannot offset all of the excess C emissions. Soil C-sequestration, however, could alone make up the difference between the expected and desired emissions trajectories in the first three to four decades of the twenty-first century, thus buying time for development of the technological advances just identified. The calculations shown in Figure 1 are based on the assumption that in the twenty-first century, agricultural soils will sequester C at global annual rates ranging from 0.4 to 0.8 Pg/yr, with rates twice as great in the initial years and half as great in the later years. It is further assumed that the potential of soil C-sequestration is realized without additional net cost to the economy — not unreasonable in view of the known benefits of organic matter in soils. Additionally, by allowing time for new technologies to be developed and for existing facilities to live out their design lifetimes, the costs of an avoided tonne of C emissions during the next century can be cut approximately in half.

How realistic are the potential soil C-sequestration estimates on which the IPCC economic modeling is based? The panel's estimates for cropland assume the restoration of up to two-thirds of soil C released by the conversion of grasslands, wetlands, and forests to agriculture since the mid-nineteenth century. The experimental record confirms that C *can* be returned to soils in such quantities. For example, C has been accumulating at rates exceeding 1 Mg/ha/yr (1 Mg = $10^6$ g = 1 metric tonne) in former U.S. croplands planted to perennial grasses through the Conservation Reserve Program (CRP) (Gebhart et al., 1994). Soil C increases ranging from 1.3 to 2.5 Mg/ha/yr have been estimated in experiments on formerly cultivated land planted to switchgrass (*Panicum virgatum*), a biomass crop (preliminary data, Oak Ridge National Laboratory). Further, there have been a substantial number of experiments in the last two or three decades with low-till and no-till management of farm fields that demonstrate these practices lead to increases in soil C content (Janzen et al., 1998; Lal et al., 1998; Nyborg et al., 1995).

Despite the indications that needed quantities of C can be sequestered in agricultural soils, there remain four important questions regarding such a possibility.

1. Can methods be developed to increase the quantities of C accumulating in soils and, perhaps more important, can the length of time during which C resides in soils be extended?
2. Can opportunities for C sequestration be extended beyond the currently farmed lands to the vast areas of degraded and desertified lands worldwide?
3. Can we develop quick, inexpensive, reliable methods to monitor and to verify that C is actually being sequestered and maintained in soils?
4. What are the political and economic problems associated with implementation of soil C- sequestration programs worldwide?

In December 1998, a workshop exploring these questions was organized by the Pacific Northwest National Laboratory, the Oak Ridge National Laboratory, and the Council for Agricultural Science and Technology and held in St. Michaels, Maryland. The workshop was attended by nearly 100 Canadian and U.S. scientists, practitioners, and policy makers representing agricultural commodity groups and industries, Congress, governmental agencies, national laboratories, universities, and the World Bank. Support for the workshop was provided by the U.S. Environmental Protection Agency, the U.S. Department of Agriculture, the U.S. Department of Energy, the Monsanto Company, and the National Aeronautics and Space Administration. Position papers addressing the four key questions were prepared for presentation and discussion. The papers, revised to take account of workshop critiques, discussions, and recommendations, are reported in Rosenberg et al. (1999).

## Key Findings of the St. Michaels Workshop

### New Science

The potential for C sequestration in all managed soils is great, and progress can be made using proven crop, range, and forest management practices. The potential might be even greater if ways could be found to restore more than the two-thirds of the C lost from conversion to agriculture and perhaps even to exceed original C contents in some soils and regions. Carbon restoration would involve a search for ways to effect greater, more rapid, and longer-lasting sequestration. Promising lines of research are evolving that could lead to an improved understanding of soil C dynamics and the subsequent development of superior C sequestration methods. The studies have the following goals:

- to improve the understanding of the mechanisms of C stabilization and turnover in soil aggregates;
- to improve the description of the various C pools and the transfer among them to allow more realistic modeling of the dynamics of soil organic matter;
- to improve understanding of landscape effects on C sequestration and how it might be controlled through precision farming;
- to apply genetic engineering to enhance plant productivity and to favor C sequestration; and
- to improve understanding of the environmental effects of soil C-sequestration on erosion, nutrient leaching, and emissions of other greenhouse gases.

### Soil Carbon Sequestration/Desertification Linkage

There are estimated to be some 2 billion hectares of desertified and degraded lands worldwide, 75% of them in the tropics, with degradation most severe in the dry tropics. The potential for C sequestration on these lands probably is even greater than on currently farmed lands. Improvements in rangeland management, dryland farming, and irrigation can add C to soils in these regions and provide the impetus for changes in land management practices that will begin the essential process of stabilizing soil against further erosion and degradation while improving fertility and productivity. Erosion control, forest establishment in dry regions, and biomass cultivation seem to offer the greatest potential for increased C sequestration on degraded lands. Soil C-sequestration offers a special opportunity to address objectives of two United Nations Conventions simultaneously — the UNFCCC and the Convention to Combat Desertification.

### Monitoring and Verification

There is opposition to the use of soil C-sequestration to offset C emissions in the calculations of a nation's adherence to its Kyoto Protocol commitments. One reason for this opposition is the perception that it will be difficult if not impossible to verify claims that C is actually being sequestered in the soils of fields that may eventually number in the millions. It is currently possible to monitor changes in soil C content, but methods are time consuming and expensive and not sensitive enough to distinguish year-to- year change. If there are to be international agreements allowing soil sequestration to figure into a nation’s C balance, agreed-upon means of verification will be necessary. Improved methods for monitoring changes in soil organic C might involve spatial integration based on process modeling and geographical information systems (GIS), application of high-resolution remote sensing, and continuous direct measurements of $CO_2$ exchange between the atmosphere and terrestrial ecosystems. In addition, new instruments are needed that can serve as direct in-field "carbon-probes." All of these verification and monitoring methods will have to be developed or tailored to operate at different scales, e.g., field or region. Verification of changes in soil C in individual fields will rely on laboratory analyses of soil samples or, perhaps a few years from now, on C probes. Estimates of regional soil C changes will be made with the aid of simulation models. High-resolution remote sensing and GIS will be used to extrapolate C-sequestration data from field observations and modeling results, to aggregate them to still broader regions, and to track trends in C sequestration with time.

### Implementation Issues and Environmental Consequences

The possibility, suggested by the IPCC findings and the Kyoto Protocol, that C may become a tradable commodity has not gone unnoticed in the agriculture and forestry communities. Beneficial land-management practices might be encouraged if credit toward national emissions targets could be gained by increasing C stores on agricultural lands. But uncertainty about costs, benefits, and risks of new technologies to increase C sequestration could impede adoption. To address farmers' reluctance to adopt C sequestration practices, financial incentives could be used to encourage practices such as conservation tillage. Government payments, tax credits, and/or emissions trading within the private sector also could be employed.

Despite uncertainty on many levels, soil C sequestration projects are beginning. Some utilities and other emitters of greenhouse gases, anticipating a future in which reductions in $CO_2$ emissions may become mandatory, already are searching for cost-effective ways to offset or otherwise meet imposed limits. And transactions already are being made: In October 1999, the Trans Alta Corporation, a member of the Greenhouse Emissions Management Consortium (GEMCo, an association of energy utilities in Western Canada), announced an agreement to purchase up to 2.8 million tonnes of C emission reduction credits (CERCs) from farms in the United States. The IGF insurance company will solicit the CERCs from eligible farmers or landowners, initially from Iowa and ultimately from the entire nation. We do not yet fully understand the social, economic, and environmental implications of incentives leading to widespread adoption of soil C-sequestration programs. Most foreseeable outcomes seem benign - for example, an increased commitment to minimum-till practices. Another likely outcome is increased effort to restore degraded lands and to retire less productive agricultural lands into permanent grass or forest cover. Sustained efforts to continue and/or expand Conservation Reserve Programs will contribute to C sequestration not only through reduction of erosion in marginal land but also through restoration of lost soil C. All these actions have the potential to decrease soil erosion and its negative consequences on water quality and sedimentation and to improve soil quality. Additionally, because increases in soil organic matter content increase water-holding capacity, irrigation requirements could be decreased. Conversion of agricultural lands to grasslands or to forest could expand to provide wildlife habitat. Decreased soil disturbance and, possibly, diminished use of fertilizer could alter volume and chemical content of runoff from agricultural lands. This in turn could decrease water pollution; enhance water quality for use by nonagricultural water consumers; and improve the ecology of streams, rivers, lakes, and aquifers in these regions.

Negative social, economic, and ecological effects also are possible. Programs designed to move agricultural lands into forestry could negatively affect the traditional forest sector, leading either to deforestation of traditional parcels or to decreased levels of management and lessened C sequestration. Such actions might offset much of the benefit of sequestering C in agricultural soils as lands so employed could compete with food and fiber production. The results might be decreased production; increased consumer prices for crops, meat, and fiber; and decreased export earnings.

Decreased tillage intensity often leaves more plant material on the soil surface. Conservation tillage frequently requires additional pesticides to control weeds, diseases, and insects. Increased use of pesticides may have detrimental effects on ecological systems and water quality. Conversion of croplands to grasslands tends to decrease emissions of nitrous oxide ($N_2O$), a gas that, molecule for molecule, has a much stronger greenhouse effect than does $CO_2$. Such land use changes may also lead to a restoration of the soil's capacity to function as a site for destruction of $CH_4$ molecules.

## Conclusion

Such seemingly benign activity as soil C-sequestration is not without cost. The production, transport, and application of chemical fertilizers, manures, and pesticides and the pumping and delivery of irrigation water needed to increase plant growth and to encourage C sequestration all require expenditures of energy — in this instance, the release of $CO_2$ from fossil fuels. It is necessary to determine to what extent the energy costs (C emissions) of the practices used to increase C sequestration in soils might actually diminish its net benefits. Of course, it is unlikely that soils ever will be managed for the primary purpose of C sequestration. Rather, fertilizers, manures, chemicals, and irrigation water will continue to be used primarily for the production of food, fiber, and — increasingly in the new century — biomass as a substitute for fossil fuel. As fossil fuels are replaced with bio-products, carbon sequestration will become an important fringe benefit and an integral part of a strategy to control global warming.

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