Enhancement of Carbon Sequestration in US Soils

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Improved practices in agriculture, forestry, and land management could be used to increase soil carbon and thereby significantly reduce the concentration of atmospheric carbon dioxide. Understanding biological and edaphic processes that increase and retain soil carbon can lead to specific manipulations that enhance soil carbon sequestration. These manipulations, however, will be suitable for adoption only if they are technically feasible over large areas, economically competitive with alternative measures to offset greenhouse gas emissions, and environmentally beneficial. Here we present the elements of an integrated evaluation of soil carbon sequestration methods.

Keywords: soil carbon sequestration, full carbon accounting, terrestrial ecosystems, land-use change, integrated assessment

Rising atmospheric carbon dioxide (CO_2) concentration is a concern because of its potential for altering climate. Since the beginning of the Industrial Revolution in the 18th century, atmospheric CO_2 has increased by more than 30%. The increase in fossil fuel burning and associated CO_2 emissions is expected to continue for the foreseeable future, and a doubling or even tripling of the preindustrial concentration of atmospheric CO_2 is possible by the end of the 21st century (IPCC 2001a). Management of vegetation and soils for terrestrial carbon sequestration can remove significant amounts of CO_2 from the atmosphere and store it as carbon in the organic matter of ecosystems. However, such management changes will not happen unless there are economic incentives or penalties associated with CO_2 management. For terrestrial carbon sequestration to be useful, it must not only result in carbon accumulation in vegetation and soil but also induce lower net release of CO_2 or other greenhouse gases.

Many factors intervene between demonstrating that a particular management practice can enhance carbon sequestration in the soil and determining that widespread application of the method is useful, acceptable, and cost-effective. A general methodological approach is currently lacking for evaluating all aspects of a carbon sequestration practice. Here we outline a complete and integrated methodology for evaluating alternative approaches to increase terrestrial carbon sequestration. The methodology has six components:

- Identifying promising technologies for soil carbon sequestration
- Understanding the effects of technologies on carbon at the site scale
- Evaluating other environmental impacts
- Including a full carbon and greenhouse gas accounting
- Performing a sensitivity analysis over the range of applicable conditions (model, laboratory, or field experiments)
- Performing an economic analysis of the practice's cost competitiveness, market implications, and other factors

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There is considerable uncertainty in each of these steps. In this article, we review recent information on carbon sequestration and clearly identify significant areas of uncertainty in each step of the evaluation process. We concentrate on soil carbon sequestration, but most aspects of the methodology should be applicable to other carbon sequestration methods.

Global carbon cycle context of soil carbon sequestration

The concentration of CO_2 in the atmosphere has risen—at first gradually and then at an exponentially increasing rate—from approximately 280 parts per million by volume (ppmv) in the mid-1800s to 371 ppmv in 2001. This increase is expected to continue, since current emission rates are far in excess of rates that may lead to stabilization of CO_2 concentration. The observed increase in atmospheric CO_2 concentration reflects the trend in CO_2 emissions caused by fossil fuel combustion and land use. Emissions of CO_2 from land use occur when land is converted from one vegetative cover to a less dense vegetative cover, especially from native vegetation to agriculture. About half of all emitted carbon remains in the atmosphere, which translates in an average increase of 3.2 petagrams (Pg) carbon per year. The world's oceans and terrestrial ecosystems take up the remainder (table 1).

Oceans take up and release CO_2 at their interface with the atmosphere. The net flux is negative (i.e., into the oceans), because the rising atmospheric CO_2 creates a partial pressure gradient that results in additional CO_2 dissolving in surface seawater. The net land-atmosphere sink consists of two different components. The first net exchange represents carbon released to the atmosphere as a result of land-use changes (now mostly from tropical deforestation). This flux is estimated to contribute 0.6 to 1.0 Pg carbon to the atmosphere per year (Houghton 2003). The second component is the difference between the inferred net land-atmosphere sink of –2.1 to –0.7 Pg carbon per year and the flux caused by land-use change. This difference has been estimated to range between 1.3 and 3.1 Pg carbon per year and has been termed the *residual carbon sink.* Several lines of evidence indicate that the residual carbon sink occurs in terrestrial ecosystems and represents sequestration of carbon in soils and plants. Leading hypotheses suggest that the processes involved in this residual sink include recent climate change, atmospheric nitrogen deposition, and the stimulation of photosynthesis resulting from higher CO_2 concentrations (Pacala et al. 2001). Other indirect effects of land-use change that may contribute to the residual carbon sink include fire suppression and regrowth of perennial vegetation, both of which increase total biomass; erosion that results in carbon burial in wetlands, lakes, and reservoirs; the diversion of forest products to long-lived wood products or landfills; and changes in land management that lead to increases in soil carbon. Estimates of the magnitude of each of these possible carbon sinks appear in table 2.

Table 1. Average global carbon dioxide budget.

Carbon source or sink	Carbon flux to atmosphere (Pg per year)
Emissions (fossil fuel, cement manufacture)	6.3 ± 0.4
Net ocean–atmosphere flux	–1.7 ± 0.5
Net land–atmosphere flux	–1.4 ± 0.7
Total atmospheric increase	3.2 ± 0.1

Pg, petagram (1×10^{15} g).

Note: Positive values represent carbon fluxes to the atmosphere; negative values represent carbon removal from the atmosphere. Error estimates denote uncertainties (± 2 standard deviations) and not interannual variability, which is much larger (Prentice et al. 2001).

Land management plays a small but significant role in overall global carbon cycle fluxes (table 2). It may account for about 4% to 14% of the residual carbon sink. Regrowth of perennial vegetation accounts for only a small potential soil carbon sink, because of the small amount of land area that is expected to be involved. Furthermore, most of the fairly substantial carbon sink caused by forest regrowth (70% to 90%) is in biomass rather than soil. Although land management is not a dominant factor in the residual carbon sink, it involves intentional soil and vegetation manipulation over large land areas. The carbon sink associated with land management (except for the amount associated with improved forestry, which is largely biomass) results from soil carbon sequestration and may amount to more than 0.4 Pg carbon per year. With focused effort, the amount of carbon sequestered in soil by land management could be significantly increased. Various studies estimate that soil carbon sequestration may be increased to a rate of 0.44 to 0.88 Pg carbon per year and sustained over a 50-year time frame (Cole et al. 1997). While these rates will offset only a fraction of the emissions from fossil fuels, results from integrated assessment analyses (Edmonds et al. 1999, Rosenberg and Izaurralde 2001) indicate that soil carbon sequestration may have an important strategic role—due to its low cost and potential for early deployment—within a portfolio of technologies to mitigate climate change. The important aspect of land management for soil carbon sequestration is that, unlike many other technologies to offset fossil fuel emissions (e.g., geologic carbon sequestration, carbon capture), it can be implemented immediately, provided there are economic and other incentives to do so. Because of the cumulative effect of CO_2 on climate, an immediate increase in carbon sequestration to offset CO_2 emissions provides a significant delay in the rise of atmospheric CO_2 concentration. In addition, by the time the carbon sequestration resulting from land management begins to saturate the soil's capacity to store additional carbon, other methods of reducing emissions or sequestering carbon may be available or already in use.

Identifying promising technologies for soil carbon sequestration

Land managers can enhance soil sequestration by (a) increasing the rates of organic matter input, (b) partitioning carbon to longer-lived pools, and (c) increasing the longevity of all or selected carbon pools. Different methods of agricultural management use one or more of these pathways to enhance carbon sequestration (see table 3 for a description of the most widely employed management practices). Depending on the process involved, variations are expected in the length of time the enhancement method is effective (time to saturation) and in the average residence time and susceptibility to disturbances that would release this sequestered carbon back to the atmosphere (permanence).

The amount of soil carbon in various forms is determined by the balance between inputs of organic detritus and losses of carbon through decomposition, leaching to groundwater, and erosion. At a basic level, the mechanisms controlling these processes and their balance can be tied to soil-forming factors (table 4) and thus are generally well known to soil scientists. Disturbance or management practices also exert considerable influence on the amount of soil carbon, both through direct effects on inputs and losses and through indirect effects on the factors controlling these fluxes. However, the complex interactions and feedbacks among controlling mechanisms and processes lead to uncertainties in predicting changes in soil carbon. It is critically important to identify, develop, and quantitatively evaluate appropriate technologies and their effects on processes that determine soil carbon dynamics.

Understanding the effects of technologies on carbon at the site scale

Table 3 lists several widely used land-management practices that, when applied to plow-tilled cropland, have demonstrated significant carbon sequestration potential. Most of the increases in soil carbon associated with these practices result from reversing processes by which traditional management has depleted the soil carbon stocks that accumulated under native perennial vegetation (Cole et al. 1997). There is sufficient information from intensive studies of these soil management practices to gain insight into the processes that are involved in increasing soil carbon content.

Cropping intensification. Elimination of fallow periods (dry fallow in seasonally dry environments, winter fallow in cold environments), use of high-yielding crop varieties, and the wide-scale application of inexpensive fertilizer and other soil amendments greatly increase the amount of organic matter produced, thereby increasing organic matter input into the soil (Parton et al. 1995, Buyanovsky and Wagner 1998, Lal et al. 1998). Precision agriculture, an intensive approach to optimize crop yields relative to fertilizer and other inputs, results in increased soil carbon inputs. A large component of the increased crop residue input resulting from cropping intensification is readily decomposed and does not add to long-term soil carbon increases. A portion remains to be converted into humus, contributing to increasing long-term soil organic carbon pools. The increases in soil carbon due to cropping intensification alone are often limited in amount and result in saturation within a few decades. Much greater increases in soil carbon are frequently obtained if manures (biologically altered inputs) are applied (Jenkinson 1990). Such amendments not only increase the amount of organic carbon input but appear to contain a larger fraction of organic carbon materials that are more resistant to decomposition than unaltered plant material.

Table 2. Estimates of the current magnitude of possible terrestrial carbon sinks.

Terrestrial carbon sink	Carbon sequestration (petagrams per year)	References
Carbon dioxide fertilization	0.9 to 3.1	McGuire et al. 2001
Climate change	–0.8 to +0.2	McGuire et al. 2001
Nitrogen deposition	0.1 to 2.5	Peterson and Melillo 1985 Holland et al. 1997
Regrowth of perennial vegetation[a]		
Forest	0.39	IPCC 2000
Grassland	0.04	IPCC 2000
Wetland	0.004	IPCC 2000
Fire suppression (United States only)	0.2	Hurtt et al. 2002
Erosion and deposition	0.6 to 1.5	Stallard 1998
Long-lived wood products[a]	0.3	IPCC 2000
Land management		
Land and soil restoration	0.003	IPCC 2000
Improved cropland management[a, b]	0.16	IPCC 2000
Improved grassland management[a]	0.24	IPCC 2000
Improved forestry management[a, c]	0.17	IPCC 2000

a. Estimated potential for the year 2010; current sink may be less than this amount.

b. Includes reduced tillage, fertility management, erosion control, irrigation management, and improved rotations and cover crops.

c. Includes forest land operations (regeneration, fertilization, species selection and improvement, reduced degradation) and urban land operations (tree planting, waste management, wood product management).

Conservation tillage. Part of the decrease in soil organic carbon that occurs when native vegetation is plowed for row crops results from mechanical disruption of soil aggregates. Soil structure plays a dominant role in the physical protection of soil organic matter (SOM) by controlling microbial access to substrates, microbial turnover processes, and decomposer food web interactions. Relatively labile material may become physically protected from decomposition if it is incorporated into soil aggregates or deposited in micropores that are inaccessible even to bacteria (figure 1). Macroaggregates (at least 0.25 millimeters [mm] in diameter) are sensitive to soil disturbance, but microaggregates (less than 0.25 mm in diameter) are generally more stable, appear to turn over more slowly, and are more resistant to disturbance (Tisdall and Oades 1982). Increases in SOM can be tied to the linkages and feedbacks between macroaggregate turnover, microaggregate formation, and carbon stabilization within microaggre-

Table 3. Management practices that significantly alter the amount, partitioning, and longevity of organic matter inputs into the soil.

Management category	Management practices	Potential for carbon sequestration
Cropping intensification	Soil fertility enhancement, erosion control, irrigation, summer fallow elimination, integrated pest management, precision agriculture	Cropping intensification increases the input of organic matter to the soil, resulting in the return of soil organic carbon lost because of previous cropping management (Parton et al. 1995). Using USDA data on cropland area and crop residue increases, adoption of best management practices can result in an average increase of 6 Tg carbon in crop residues per year. Assuming that 10% is converted to soil carbon, the average increase in carbon sequestration is estimated at 0.6 Tg per year (Lal et al. 1998).
Organic amendments	Animal manure, green manure, mulches, compost	Organic matter supplementation increases organic matter inputs. Animal manures (biologically altered inputs) are particularly effective at increasing the amount of soil organic carbon (Jenkinson 1990).
Conservation tillage	Ridge tillage, mulch tillage, no tillage	Compilation of long-term experimental data (West and Post 2002) shows that the greatest increases occur with no tillage, resulting in an average carbon sequestration rate of 50 g per m^2 per year. In the United States, the area under no tillage has tripled over the last decade, from 6.8 Mha (6.0% of planted area) in 1990 to 21.1 Mha (17.5% of planted area) in 2000. Using a value of 50 g per m^2 per year, this could result in an increase in carbon sequestration of at least 10.5 Tg per year.
Perennial vegetation	Pasture or forest establishment, CRP	Surveys (Gebhart et al. 1994, Paustian et al. 1995, Post and Kwon 2000) indicate that for afforestation and grassland establishment, the average rate of soil carbon accumulation ranges from 10 to 40 g per m^2 per year, with the highest rates in more humid regions. The USDA has been authorized to increase the CRP area from 14.3 to 15.4 Mha. Using a value of 30 g per m^2 per year, this could result in an estimated increase in carbon sequestration of 4.3 to 4.6 Tg per year.
Biomass crops	Switchgrass, short-rotation woody crops	Lal and colleagues (1998) estimate that 10 Mha of idle cropland could sequester 50 Tg carbon per year, offsetting 35 Tg carbon per year from fossil fuel. Accounting for all biofuel carbon emissions (production, transport, efficiency of use, and waste disposal), this offset may be considerably smaller. Soil carbon accumulation of 30 g per m^2 per year would result in 3 Tg carbon per year being sequestered in the soil. The biofuel offset, no matter how small, could ultimately go on forever.

CRP, Conservation Reserve Program; g, grams; m, meters; Mha, megahectares; Tg, teragrams; USDA, US Department of Agriculture.

gates (Jastrow and Miller 1998, Six et al. 2000). Recent research making use of soil fractionation procedures to isolate microaggregates from the macroaggregate structure of soil, and also taking advantage of the shifts in the natural abundance of stable carbon isotopes following a change in grassland type, has found that microaggregates facilitate the creation of chemically resistant organomineral associations with relatively long residence times. As a result of the protection afforded by microaggregates, up to 40% of the chemically resistant carbon in the mineral fractions of microaggregates was derived from plant inputs produced during the 62 years following the change in grassland composition. New carbon made up less than 30% of equivalent fractions of non-microaggregated soil. Reductions in tillage intensity allow aggregation processes to be reestablished, thereby rebuilding this physical protection (Six et al. 2000).

Recent research suggests that management practices resulting in decreased disturbance (e.g., no-till cultivation or establishment of perennial vegetation) generally increase fungal-dominated pathways in organic matter cycling, which may increase the residence time of microbial residues and lead to their buildup in SOM (Bardgett and McAlister 1999, Stahl et al. 1999, Bailey et al. 2002). In addition, decreases in disturbance and the accompanying changes in plant communities can increase the amount of mycorrhizal fungal biomass, which is also biochemically recalcitrant but is derived directly from plant photosynthates rather than from the rendering of detrital residues.

An additional benefit of conservation tillage is the reduction of wind and water erosion. Even if soil mineral particles are not removed, erosion processes cause disruption of soil aggregates and loss of particulate organic matter. These losses reduce soil water-holding capacity and nutrient regeneration and can result in reduced crop productivity. The direct and indirect effects of erosion result in soil carbon losses that must be counteracted by increased irrigation or fertilizer application if soil carbon is to be maintained or increased (Lal 1995).

Perennial vegetation. Perennial vegetation establishment on previously plow-tilled cropland results in substantial increases in soil carbon (Gebhart et al. 1994, Post and Kwon 2000). Even without additional management, the rates at which soil carbon increases after the establishment of perennial

Table 4. Influence of the soil-forming state factors identified by Jenny (1980) on the balance between inputs to and losses from soil carbon stocks.

State factor	Influence on soil carbon stocks
Climate	Temperature and precipitation constrain plant production, decomposer activity, and weathering of soil minerals.
Organisms	Vegetation controls input rates, depths, timing, and form (surface litter versus belowground input), affects decomposition through the inputs' decomposability (e.g., size, density, ratios of carbon to nitrogen and of lignin to nitrogen), and competes with decomposers for water and nutrients. Soil biota (types, populations, community structure, and activities) controls decomposition and the cycling and availability of nutrients (which constrain plant productivity).
Parent material	Soil type, degree of weathering, mineralogy, texture, and structure influence pH, water and nutrient supply, aeration, organo-mineral complexation, and the habitat for soil biota, affecting both plant production and decomposition.
Topography	Topography affects erosion, deposition, infiltration, moisture, and temperature, influencing soil and vegetation type at the landscape scale; it affects temperature, moisture availability, and soil texture at finer spatial scales.
Time	Time affects the balance of carbon input and loss, and temporal scale influences the relative importance of other state factor effects on production and decomposition.

vegetation are similar to or greater than those associated with converting to no-till cropland. The processes involved are largely the same as those for conservation tillage (i.e., increased aggregate formation; increased fungal-dominated pathways in decomposition; greater inputs of organic matter, especially belowground through plant roots and mycorrhizal fungi; and reduced erosion).

Biomass accumulation associated with the establishment of perennial vegetation also contributes to carbon sequestration, and in forest ecosystems the rate of carbon accumulation in biomass usually greatly exceeds the rate of accumulation in soil. Biomass accumulation can be lost with catastrophic fire or insect outbreaks, and so estimates of its effects should be reduced depending on the frequency of such events. Perennial vegetation grown as a biomass crop has the additional advantage that a portion of the biomass production may be used to offset fossil fuel use. Estimates of potential carbon emissions savings are larger than the sequestration potential for the same land area (Cole et al. 1997, Lal et al. 1998). Although soil carbon accumulation would eventually saturate, the biofuel offset could accumulate forever.

Liming, irrigation, and fertilizer management. Transformations involving the formation of melanin-like humic compounds increase biochemical resistance to decomposition (Kuo and Alexander 1967) and are promoted by phenoloxidase enzymes and abiotic oxidants. Current research suggests that the stability and activity of these enzymes and oxidants can be significantly enhanced by maintaining soil pH at neutral or higher levels. Chemical stability—in the form of biochemical recalcitrance, physicochemical protection, or both—increases the rate of humic compound formation and decreases the rate of mineralization, resulting in increased soil organic carbon. The formation of humic compounds is maximized under partly oxidizing conditions: If there is too much oxygen, full mineralization occurs; if there is too little, oxidative polymerization is stifled. Frequent wetting and drying cycles avoid the stagnation that occurs under either oxidizing or reducing conditions and promote the oxidative polymerization reaction that stabilizes carbon. Similarly, practices that optimize the amounts of minerals containing iron and manganese oxide have the potential to stimulate formation of humic materials (Nelson et al. 1979, Shindo and Huang 1984). A decrease in the rate of mineralization can also be promoted by the development of chemical or physicochemical associations between decomposable compounds and soil mineral components (e.g., organics sorbed to clay surfaces by polyvalent cation bridges). The presence of polyvalent cations such as calcium, magnesium, and iron facilitates the sorption of organic polymers to soil minerals, thereby protecting these organic compounds further from microbial and chemical attack. The judicious addition of divalent liming agents and of iron and manganese fertilizers, coupled with management of drainage conditions, can do much to enhance the net rate of carbon sequestration in soils (Jardine et al. 1989).

Soil anions such as sulfate and, in particular, phosphate can effectively compete for dissolved organic carbon (DOC) sorption sites, releasing DOC into the pore water (Jardine et al. 1989, 1990, Kooner et al. 1995). In soils with deep profiles and limited lateral flow, this process could actually serve to enhance organic carbon sequestration, since the DOC would have ample opportunity to readsorb on mineral particles deeper in the soil. Because subsurface mineral-stabilized carbon pools are significantly less dynamic than carbon in upper soil horizons, manipulating the geochemical environment to move carbon from upper to lower soil layers through desorption and adsorption of DOC is a potential means of enhancing carbon sequestration in the subsurface. Managing fertilizer sources to drive organic carbon deeper into a soil profile and manipulating the mineral components of a particular soil to favor carbon sorption are potential land-management strategies for enhancing subsurface organic carbon sequestration.

Microbial manipulation. Microbial communities play an important part in regulating the cycling and stabilization of organic residues in the soil. Information is needed to determine whether microbial communities can be manipulated to enhance carbon stabilization. New methods using nucleic acid–based techniques to assess microbial community

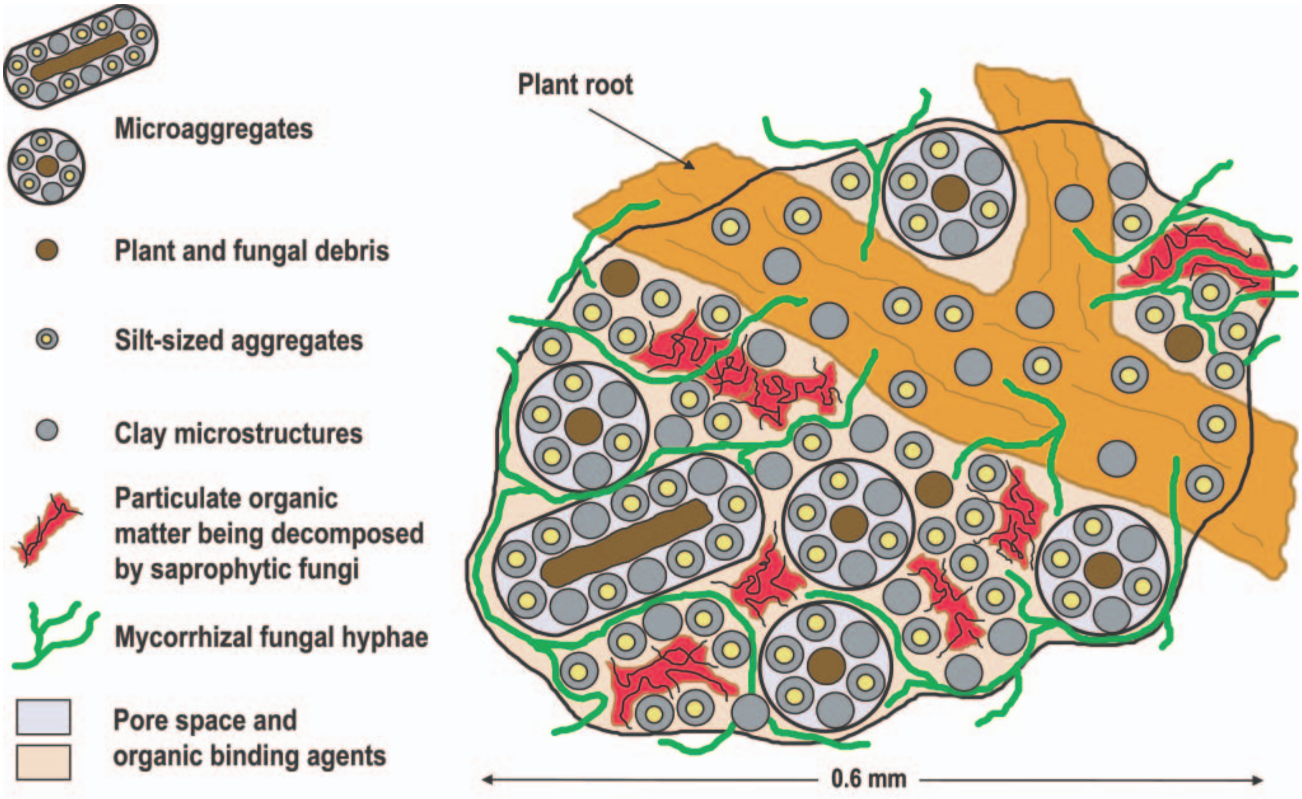

Figure 1. Conceptual diagram depicting the hierarchical organization of microaggregates within a macroaggregate. Reprinted with minor modifications from Jastrow and Miller (1998), with permission.

dynamics and activities in natural environments are valuable tools. For example, 16S and 18S ribosomal DNA probes were used with T-RFLP (terminal restriction fragment length polymorphism) to create a profile of the structure of the soil microbial community across a prairie restoration chronosequence (farmland, restored prairies planted in 1993 and 1979, and native prairie). The recovery of bacterial communities was faster than the recovery of fungal communities during the reversion to prairie, even though fungal biomass and activity were greater (Bailey et al. 2003).

Microarray technology represents an approach that can greatly enhance the deployment of nucleic acid–based techniques. A microarray is an orderly arrangement on glass slides of thousands of spot DNA samples less than 200 microns in diameter. It provides a medium for matching known and unknown DNA from samples using base-pairing rules. This technology is potentially well suited for identifying populations of microorganisms in natural environments. Although DNA microarray technology has been used successfully to analyze global gene expression in pure cultures, it has not been rigorously tested and evaluated within the context of complex environmental samples (Wu et al. 2001). Several types of microarrays have been developed and evaluated within the context of soil samples (Zhou and Thompson 2002). Under development and evaluation are 50-mer oligonucleotide microarrays containing all known genes involved in nitrogen cycling (e.g., nitrogen fixation, nitrification, denitrification, bacterial assimilatory nitrate reduction), carbon cycling (e.g., CO_2 fixation, plant polymer degradation, methanogenesis, methane [CH_4] oxidation), sulfate reduction, phosphorus utilization, organic contaminant degradation, and metal resistance. Preliminary results show that oligonucleotide microarrays can be used as specific, sensitive, and quantitative tools for analyzing the composition, structure, function, and dynamics of microbial communities under different environmental conditions. Once researchers and managers understand more clearly how specific microbial processes are involved in carbon sequestration, it may be possible to directly (e.g., through inoculation or use of biocides) or indirectly (e.g., through manipulation of vegetation, soil pH, or substrate additions) manipulate microbial populations or modify specific genes to increase or decrease particular functions associated with the production and decomposition of biochemically resistant compounds.

Given what is known about soil carbon processes, the development of appropriate technologies that build on this large body of science can lead to land-management technologies that enhance carbon sequestration. Current and new technologies will be able to enhance soil carbon sequestration through the manipulation of processes associated with biochemical recalcitrance, chemical protection, and physical protection.

Evaluating other environmental impacts

Agricultural activities affect the environment in many and complex ways. For example, they can increase or reduce erosion, improve or worsen soil tilth, elevate or lower SOM levels, intensify or weaken the leakage of nutrients and pesticide residues to the environment, or alter biogeochemical cycles. The environmental consequences of a new management regime, other than on-site carbon sequestration, are called *co-benefits* (although detrimental environmental consequences are also possible). The impact of management on erosion is probably the most significant co-benefit. Conventional plow tillage, especially with winter or dry-period fallows, exposes soil to erosive forces of wind and water. Reduced tillage, and especially no-till methods of land management, reduce erosion and, consequently, the loss of soil carbon. The benefit of erosion reduction resulting from carbon sequestration activities generally has been difficult to evaluate. However, several studies (Pimentel et al. 1995, Dearmont et al. 1998) show that the reduction in erosion potentially has considerable economic value.

The loss of SOM during cultivation and the higher erosion rates of cultivated lands relative to those under native vegetation are two of the most important impacts of agriculture on the environment. Losses of SOM not only have affected agricultural productivity but also have been translated into a significant release of CO_2 into the atmosphere (55 Pg carbon worldwide; Cole et al. 1997). However, SOM lost from fields through erosion may be retained at depositional sites or deposited in water bodies downstream. The ultimate fate of the carbon associated with erosion processes is not well known (Lal 1995, Stallard 1998) and is currently the subject of research (Harden et al. 1999, McCarty and Ritchie 2002).

Stallard (1998) hypothesized that a significant amount of carbon eroded from fields becomes buried in depositional areas and is thus sequestered and unavailable for decomposition. Over time, the carbon eroded from agricultural lands is replaced by new carbon fixed by plants that grow on both eroding and depositional sites. Stallard (1998) estimated that up to 1.5 Pg carbon per year could be sequestered globally by these processes. However, Lal (1995) argued that because soil aggregates break down in the process of erosion, physically protected carbon would become available for decomposition, and a substantial amount could be lost as CO_2. Lal (1995) calculated a global CO_2 flux of 1.14 Pg carbon per year from the soil to the atmosphere as a result of water erosion.

Erosion and deposition processes, however, appear to have nonlinear interactions with the carbon cycle. At a small watershed in Maryland, McCarty and Ritchie (2002) used cesium-137 to test whether upland agricultural activities could increase carbon storage within a narrow streamside forest (riparian or wetland buffer) by increasing sediment deposition and enhancing net primary productivity. Their data revealed that deposition of agricultural sediments enhanced carbon storage in the wetland buffer. Harden and colleagues (1999) used a sampling and modeling approach to study the link between soil carbon cycling and the processes of erosion and deposition at three sites in Mississippi developed on loess parent material. Their results revealed that erosion processes could generate a significant sink for carbon in sediments where the carbon is protected from decomposition. Clearly, researchers need to understand more fully the links between the carbon cycle and the processes of erosion and deposition in order to improve the accuracy of carbon budgets constructed at local, regional, and global scales.

Other environmental impacts, in addition to soil stabilization and erosion controls, need to be evaluated before widespread recommendation of a sequestration practice. The impacts of carbon sequestration practices on species diversity (Huston and Marland 2003); the impacts of biocide on nontarget species, including decomposers; the impacts of nutrient applications on water and air quality; and changes in local and regional climate through changes in albedo and surface energy balance are all important considerations. If an energy-related emission of CO_2 is continued because carbon sequestration is mitigating its greenhouse gas emissions, but other environmental pollution is associated with this energy emission, then the impact of this additional pollution should also be included in the evaluation. Objective methods are needed for evaluating all of the direct and indirect co-benefits and potential negative impacts of soil carbon sequestration projects.

Including a full carbon and greenhouse gas accounting

Changes in agricultural management or land use can enhance carbon sequestration in soils. However, the net effect on the atmosphere also involves associated changes in CO_2 emissions resulting from the consumption of fossil fuels during agricultural operations, from net emissions of other greenhouse gases, and from the effects of these changes on land productivity and crop yield. Emissions of CO_2 occur not only from plant and soil respiration but also from the use of fossil fuels in (a) the production and use of agricultural machinery, such as tractors, harvesters, and irrigation equipment, and (b) the production, transportation, and application of agricultural inputs such as fertilizer and pesticides.

Changes in agricultural practice and land use may alter the net flux of nitrous oxide (N_2O) and CH_4 to the atmosphere. Since agriculture is a major contributor of both gases to the atmosphere (IPCC 2001b), recommendations to promote soil carbon sequestration should be made with a comprehensive understanding of how these practices might influence the net flux of other greenhouse gases. When multiple greenhouse gases are to be considered, the Intergovernmental Panel on Climate Change recommends the use of 100-year global warming potential (GWP) to express the integrated effect of carbon sequestration practices on the climate system in terms of carbon or CO_2 equivalents (C_{eq}). The 100-year GWP is 23 for CH_4 and 296 for N_2O, indicating how much more effective these greenhouse gases are at trapping heat relative to CO_2.

Microbial denitrification is the major pathway for gaseous loss of soil nitrogen as N_2O and N_2. Cultivated soils normally emit more N_2O than uncultivated soils, primarily because of the synthetic nitrogen fertilizer and animal manures applied. Of course, many edaphic factors (soil texture, water status, temperature) and management controls (amount and type of crop residues added to soil, management of nitrogen fertilizer) interact to determine how much N_2O will evolve from the soil under a given management regime. Tillage (or the lack of it) causes changes in the thermal and hydrological regime of the soil, thereby affecting many microbially mediated processes, such as nitrogen mineralization. In general, gaseous nitrogen losses are greater in untilled than in conventionally tilled soils (Aulakh et al. 1992). The enhanced nitrogen loss under no-till farming practices has been attributed partly to increased soil bulk density, anaerobiosis in soil aggregates, and water-filled porosity. Other studies, however, have reported emissions of N_2O under no-till cultivation to be equal to or even lower than those observed under conventional tillage (Lemke et al. 1999, Robertson et al. 2000). The time, amount, and chemical form of nitrogen fertilizer application may also affect the magnitude of N_2O emissions from soil. Matson and colleagues (1998), studying N_2O emissions under alternative and conventional wheat production in Mexico, found that losses of N_2O were smaller when nitrogen fertilizer was applied at rates and times that matched crop demand than when it was applied in a single dose. The large GWP for N_2O and the sensitivity of N_2O emissions to tillage make consideration of this greenhouse gas critical.

Methane emissions from soils occur under highly reduced conditions (rice paddies, wetlands, flooded soils). Methane can also be converted to CO_2 by oxidizing bacteria in aerobic

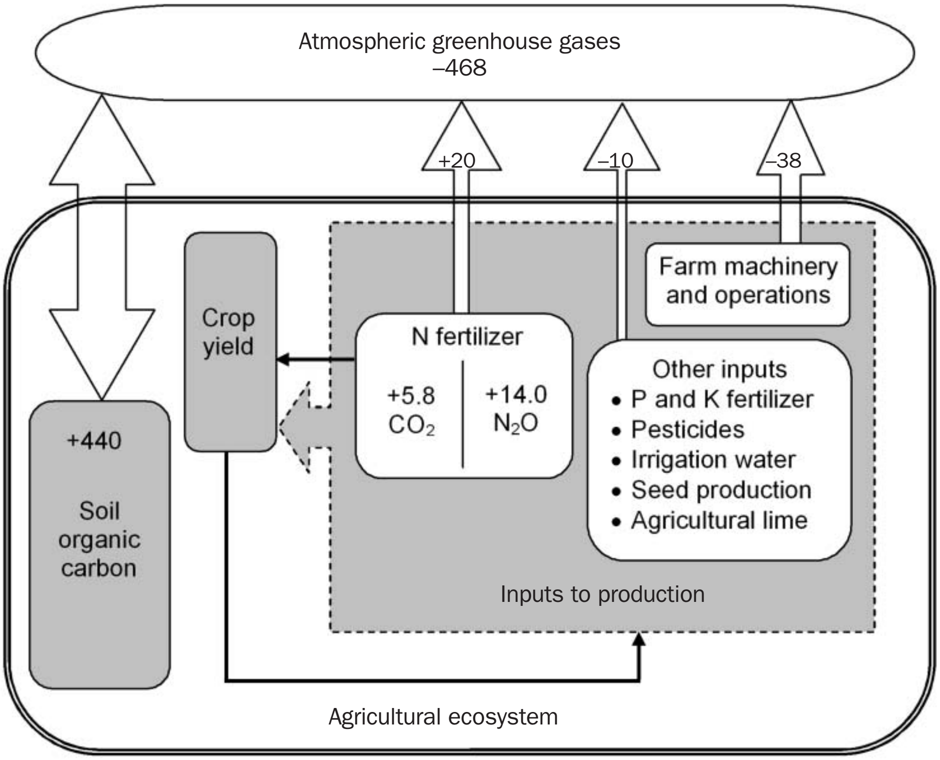

Figure 2. Diagram of the agricultural component of the net greenhouse gas emission model GORCAM (Graz–Oak Ridge Carbon Accounting Model) (Schlamadinger and Marland 1996), illustrating a change from conventional moldboard plow tillage to no-till cultivation for a continuous corn monoculture. Values in arrows represent changes in annual flows of greenhouse gases expressed in carbon equivalents (C_{eq}). The value for soil organic carbon represents the expected net change in soil carbon following a change from conventional tillage to no-till for a continuous corn crop (West and Post 2002). Emissions from nitrogen fertilizer include changes in nitrous oxide (N_2O) emissions from fertilizer application and changes in carbon dioxide (CO_2) emissions from production, transport, and application of the fertilizer. Units are kilograms C_{eq} per hectare per year, representing the average over the first 20 years following conversion. This diagram is updated from the one used by Marland and colleagues (2003) to reflect recent trends in agricultural inputs, using revised production input data (USDA 2004) and respective CO_2 emissions coefficients (West and Marland 2002). Abbreviations: K, potassium; P, phosphorus.

soils. Thus, soils behave either as sources or sinks of CH_4, depending on their oxidation status. Cultivated soils generally have less capacity to oxidize CH_4 than do native soils. Robertson and colleagues (2000) reported that soils under annual cropping systems have four to six times less capacity to oxidize CH_4 than do mid- to late-successional forests.

Marland and colleagues (2003) used a comprehensive accounting model to inclusively evaluate the factors involved in determining the net effect of management change on a total measure of greenhouse gas emissions. Figure 2 shows the interrelationships in the model, along with estimates of the average 20-year alterations in greenhouse gas fluxes following conversion from conventional tillage to no-till farming for an average continuous corn crop. The model shows a net reduction in greenhouse gas emissions over the 20-year period of no-till farming. Savings in fuel consumption by farm machinery are partially offset by the slight increase in nitrogen fertilizer use associated with moving from conventional tillage to no-till practices (USDA 2004). However, the net reductions in C_{eq} emissions associated with production inputs actually increase the net carbon savings relative to soil carbon sequestration alone. It is likely that the soil carbon pool will reach a new steady state in the no-till system after approximately 20 years. Depending on the change in cropping practice, the change in emissions will continue after soil carbon sequestration has ceased. There is also a possibility that agricultural yields will change with management changes (West and Marland 2003). If yields increase, this may result in a reduction of inputs caused by a retirement of agricultural land elsewhere, resulting in a continued net reduction of greenhouse gas emissions to the atmosphere. This modeling approach provides a useful framework for evaluating the total

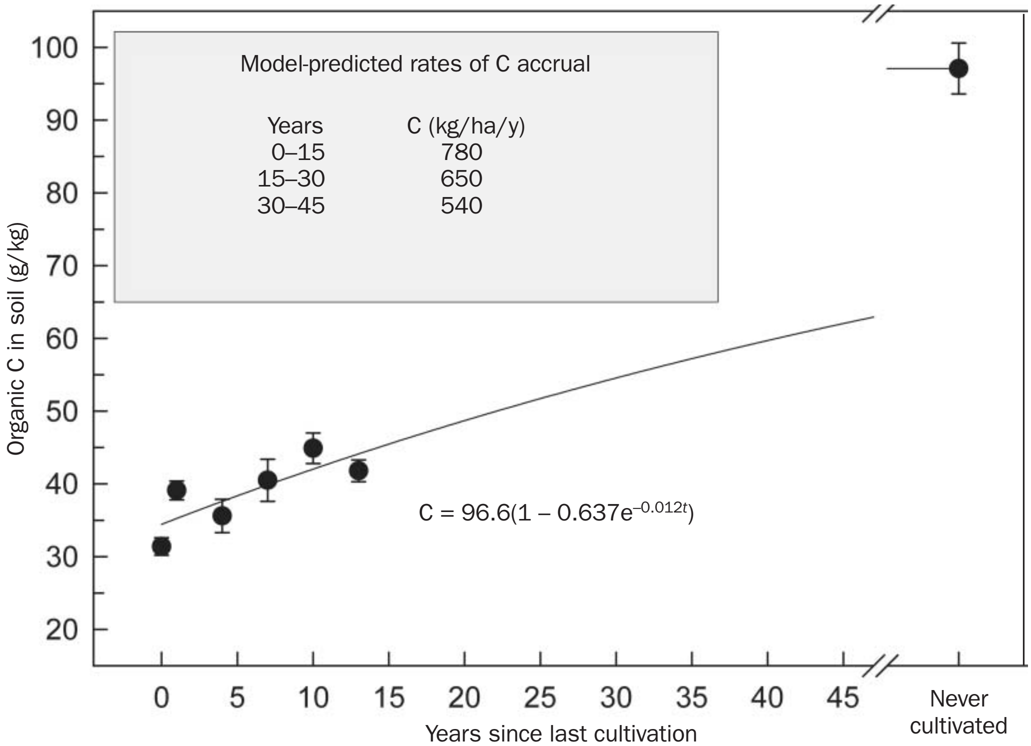

Figure 3. Accumulation of organic carbon (C) in the top 10 centimeters of soil, in grams (g) per kilogram (kg), in a chronosequence consisting of conventionally tilled rowcrop soil, four prairie restorations (aged 1 to 10 years), a 13-year-old ungrazed pasture, and a prairie remnant in northeastern Illinois. Model-predicted rates of C accrual are average annual accumulations calculated from the exponential regression model for the indicated time increments, assuming a soil bulk density of 1.15 g per cubic centimeter. The regression model is constrained by an equilibrium estimated by soil C in the never-cultivated native prairie remnant. If conditions limited restored grassland to only 20% of remnant C levels, the regression model would predict somewhat faster C accrual during the initial 15 years and considerably slower rates thereafter (860, 640, and 470 kg per hectare [ha] per year), whereas a 10% higher equilibrium would result in greater accumulation rates during all three time periods (840, 710, and 610 kg per ha per year). Modified from Jastrow (1996).

effect of changes in land use and management on CO_2 and non-CO_2 greenhouse gases, including the impact of crop productivity on soil carbon sequestration.

Performing a sensitivity analysis

It is possible to estimate regional carbon sequestration potential by multiplying the areas of land that could be converted to alternate land uses or land-management practices by the average sequestration rates for those changes. However, with each land-management practice or land use, the rate of carbon sequestration, the magnitude of carbon stocks at steady state, and the time required to reach a new steady state can all vary spatially, influenced by differences in climate and edaphic conditions. Thus, more realistic assessments of sequestration potential will require spatially explicit estimates constrained by localized differences in environmental and management factors.

For example, the establishment of grass or trees on land under long-term cultivation has the potential for achieving large increases in soil carbon storage. Follett (2001) estimates that land enrolled in the Conservation Reserve Program (CRP) across a 13-state region in the US Midwest could sequester an average of 570, 740, and 910 kilograms (kg) carbon per hectare (ha) per year to soil depths of 5, 10, and 20 centimeters (cm), respectively. Most estimates to date are similarly derived from measurements obtained during the first decade of CRP, when rates of soil carbon gain were likely to be the greatest. For aggrading systems, the differential between the rates of organic input and of decomposition loss narrows with time, and carbon accumulation slows until a new steady state—dependent on vegetation type, soil conditions, and environmental factors—is achieved. Although the rapid initial rates of carbon gain under CRP cannot be sustained indefinitely, soil carbon sequestration can continue at substantial rates over several decades. Jastrow (1996) used a native prairie remnant to constrain the estimated rate of soil organic carbon accrual for a chronosequence of restored grasslands (figure 3) according to a simple exponential regression model that annually balances new input to soil carbon with fractional loss to decomposition (Jenny 1980). The model shows soil carbon increases during the first 15 years of restoration at rates that are comparable to the 740 kg carbon per ha per year estimated by Follett (2001) for the surface 10 cm in CRP land. Although the carbon accrual rates decline over time, even the slower rates of accrual 30 to 45 years after cultivation represent significant soil carbon storage.

Each combination of land-use history, climate, edaphic factors, and vegetation type leads to a different response of soil carbon to changes in management. Understanding this variation provides insight into the relationships among environmental factors and carbon sequestration. A quantitative understanding of the relationships among environmental factors and SOM dynamics is most often formulated in SOM models such as Century (Parton et al. 1988), RothC (Rothamsted carbon model; Jenkinson 1990), and EPIC (erosion productivity impact calculator; Izaurralde et al. 2001). These models may be correlative models derived from empirical relationships, complex feedback models derived from process understanding, or something in between. Researchers can deploy the models spatially by driving them with information about the spatial distribution of the biotic or abiotic factors that are used as input, allowing for regional analyses of soil carbon sequestration (Paustian et al. 1997, Pennock and Frick 2001).

Performing an economic analysis

For technologies to be effective, they must be competitive in terms of cost. New management practices for carbon sequestration can be expensive to implement, because of increased cost, increased risk (new equipment, more complex operations), or reduced income (loss of yield or production capacity). If agricultural soil sequestration is to play a role in the endeavor to reduce greenhouse gas emissions, it is important both to determine that soil sequestration practices are competitive, low-cost means of offsetting greenhouse gas emissions and to design programs or incentives that make these practices attractive for use by land managers. In the United States, a general soil-related greenhouse gas program or incentive framework would probably include these measures, separately or jointly:

- A private market implementation involving tradable emission permits such as those used in the sulfur dioxide market operating in the United States today (Stavins 1998)
- A government-based implementation in which at least some parts of the costs are borne by, for example, federal government, as in the set-aside program, EQUIP (Environmental Quality Incentives Program), CRP, and other current or past programs of the US Department of Agriculture supporting soil conservation practices

Carbon sequestration and other agriculturally based options for reducing net greenhouse gas emissions should be evaluated to see how competitive they are in comparison with a variety of other options, such as forest carbon sequestration; flue-gas capture to reduce emissions or remove CO_2 already present in the atmosphere; and the use of biofuels, natural gas, or nuclear power, instead of coal or petroleum, to reduce CO_2 emissions. A useful approach is to consider how much it costs to deliver to a buyer, on average, a metric ton of sequestered carbon and then to determine whether that delivered cost is less than or equal to costs from other available sources. Conceptually, the cost to the buyer of delivering a metric ton of greenhouse gas offsets through a given practice is equal to the total net cost of the practice (the total change in all costs involved, including adopting it and selling it to buyers) divided by the incremental quantity of claimable greenhouse gas offset produced:

$$\text{Delivered cost per ton} = \frac{\text{total net cost of practice}}{\text{claimable amount of greenhouse gas offset}} . \quad (1)$$

Box 1. Economic components for determining the cost of carbon sequestration per metric ton and the value of co-benefits and discounts.

Producer-level development costs: When producers choose to undertake a carbon-sequestering activity, they will need to change land management practices, land use, or both. The cost of such a change is the difference in net revenue and cost streams plus the difference in any long-term, fixed-cost requirements. Major elements of this cost include the differences in crop yields under existing and alternative land management, the changes in input costs, the costs of needed new equipment, and the salvage value of discontinued equipment.

Producer adoption inducement costs: Even if they are economically and agronomically attractive, alternative land uses or methods of land management may not be adopted because of learning time, investment costs, increased risk, and other factors. For example, many cases exist in which the adoption of reduced tillage has been limited, despite calculations that this practice would increase average income. Producer adoption inducement costs represent any inducements needed to overcome barriers to adoption of the project practices that are above and beyond development costs.

Market transaction costs: The producer development costs and adoption inducement costs are only part of total commodity costs. In particular, offsets still need to be conveyed to the buyer. There are several additional costs to consider in this conveyance, such as broker commission costs, measurement and monitoring, enforcement, and insurance fees protecting against adverse outcomes.

Government role: The government may offset some proportion of the costs through land-use subsidies or subsidies for sequestration practices.

Co-benefits: Carbon sequestration practices can have implications for environmental quality and income distribution. For example, adoption of reduced tillage can lead to reductions in soil erosion and consequently improve water quality, while payments to farmers may alleviate needs for income support. Such effects may justify a governmental role in subsidizing sequestration practices.

Discounts: Offsets created by projects designed to reduce net emissions need to fit in the compliance structure of the global emission accounting scheme. Consequently, the quantity of greenhouse gas offsets that a project will be paid for may be subject to discounts due to system rules and compliance requirements. Key concerns in this regard involve additionality, uncertainty, leakage, and permanence, as discussed in the Kyoto Protocol.

- *Additionality:* Projects should receive credit only for sequestration that would not otherwise have occurred, and projects may have their quantity of offsets reduced by the estimated proportion of nonadditional activity.
- *Uncertainty:* Society and buyers recognize that there will be variability in sequestration quantities as a result of climate and other factors. To create a safety margin that protects against potentially penalized shortfalls, a discount may be desired that falls below the expected average offsets created by the project.
- *Leakage:* Project credits should be reduced by the extent to which actions to enhance sequestration alter production and create market conditions (e.g., price effects) that induce emission increases elsewhere.
- *Permanence:* Sequestered carbon is stored in a volatile form. Future changes to alternative practices can cause reemission of some or all of the sequestered carbon to the atmosphere, and ongoing maintenance costs may be needed for a practice after it has ceased to influence carbon uptake. Furthermore, practices may be contracted under a lease, not a permanent arrangement. A discount may arise reflecting the potential for volatility, the existence of required maintenance costs, or the need to recontract for offsets after a lease expires.

The net cost of the practice for a market-based commodity consists of several major terms that include the cost the producer bears in adopting the practice, the other incentives necessary to cause the producer to adopt it, and any market transaction costs involved in selling offsets to the buyers (box 1). In turn, these costs will be reduced by the cost borne by the government and possibly by the value of co-benefits accruing to society. If the government pays for the project, then the net cost of the practice is the amount of money paid to the producer to adopt it, possibly reduced by the value of the co-benefits obtained.

The quantity of offset that can be claimed for a project is the sum of the incremental quantity of greenhouse gas emission avoided and of carbon sequestered, adjusted for any discounts imposed in determining the claimable credits as required by the greenhouse gas accounting system or the buyer. The components of the incremental greenhouse gas offset include the following:

- Project-induced carbon sequestration in the soil or in standing plants or trees over time
- Project-induced net reductions in CH_4 and N_2O emissions
- Project-induced net savings in fossil fuel emissions due to changes in system inputs
- Project-induced net savings in carbon releases from manufacturing agricultural inputs due to changes in use of agricultural inputs

All of these would be adjusted to a C_{eq} basis using the GWP, as discussed above.

Because of accounting system rules or offset characteristics, not all credits may be claimable. Internationally, the concerns of additionality (ADD), uncertainty (UNCER), leakage (LEAK), and permanence (PERM) have been raised relative to the claimable portion of offsets produced (box 1). Thus, in general, the claimable quantity is the project-created quantity adjusted by a discount factor (DISC) that is obtained by multiplying all of the relevant discount factors:

$$\text{DISC} = (1 - \text{ADD}) \times (1 - \text{LEAK}) \times (1 - \text{PERM}) \times (1 - \text{UNCER}). \quad (2)$$

Such discounts may vary across greenhouse gas accounts and projects, with different discounts applying to reduced emissions and sequestration. The denominator of equation 1 is obtained by multiplying the project offsets by the discount factor:

$$\text{Claimable amount of greenhouse gas offset} = \text{project offsets} \times \text{DISC}. \quad (3)$$

In turn, one can compare the cost derived using equation 1 with the market prices of other offsets to see if the project generates competitively priced offsets.

Project costing under a widespread greenhouse gas program should also consider the aggregate implications of wider adoption. Collectively, the prices of commodities will change under an active greenhouse gas program, as will energy prices. The implications of such changes are widespread throughout the economy, and the analytical approach for comparison at this scale becomes a mixture of analyses at the sectoral level (McCarl and Schneider 2001) and broader analyses (economy-wide, often global), based on a computable general equilibrium model (Weyant and Hill 1999, Sands et al. 2003).

Finally, one should consider co-benefits from an economic standpoint. In general, they involve many nonmarket items that are hard to value. Nevertheless, evidence has been amassed that such co-benefits may amount to a significant fraction of the costs of program implementation. However, one must also consider the costs that might arise if sequestration offsets allow increased emissions elsewhere, and if those emissions are associated with increased pollution. For example, increased emissions by power plants may increase ozone and other pollutants. Co-benefits are difficult to evaluate, but they should at least be inventoried, if not used in forming cost estimates.

Conclusions

The idea of using intentional sequestration of carbon in soil through land management to mitigate rising atmospheric CO_2 concentration is relatively recent. Not much is known at this point about the ease of accomplishing significant mitigation and the amount of CO_2 that might be mitigated. The technological capability for increasing carbon sequestration is at hand, many co-benefits seem likely, the potential magnitude of the results appears promising, and initial cost estimates appear to be low. As a result, there is a rising demand to know precisely how much carbon may be sequestered in soil, how quickly this sequestration can take place, and what other environmental and economic impacts will occur as a result. There are, however, many considerations beyond the technological capability and potential benefits that will determine the rate and cumulative magnitude of soil carbon sequestration. Researchers' understanding of the biological, edaphic, and physical environmental conditions that influence the potential amount and permanence of soil carbon is growing rapidly. This knowledge is being incorporated into mathematical models of soil carbon dynamics that allow the extrapolation of information across many conditions and provide a basis for predictions of future soil carbon sequestration. The net greenhouse gas emissions of different soil carbon sequestration methods, the costs of delivering offsets to buyers, and the ancillary environmental issues must also be evaluated. Finally, the acceptance of sequestration methods by land managers and the public will be a significant factor in determining the rate of soil carbon sequestration. The willingness of public and private buyers to use soil carbon sequestration methods to achieve net greenhouse gas reduction in the atmosphere will depend on the costs and economic benefits, which include unpriced environmental benefits.

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d. Free Distribution by Mail *(Samples, compliment ary, and other free)*	(1) Outside-County as Stated on Form 3541	55	1
	(2) In-County as Stated on Form 3541	0	0
	(3) Other Classes Mailed Through the USPS	1	1
e. Free Distribution Outside the Mail *(Carriers or other means)*		0	0
f. Total Free Distribution *(Sum of 15d. and 15e.)*		56	2
g. Total Distribution *(Sum of 15c. and 15f)*		6171	6050
h. Copies not Distributed		174	150
i. Total *(Sum of 15g. and h.)*		6345	6200
j. Percent Paid and/or Requested Circulation *(15c. divided by 15g. times 100)*		99.1	100.0

16. Publication of Statement of Ownership
☒ Publication required. Will be printed in the October 2002 issue of this publication. ☐ Publication not required.

17. Signature and Title of Editor, Publisher, Business Manager, or Owner: T. M. Beardsley
Date: 24 September 2004

I certify that all information furnished on this form is true and complete. I understand that anyone who furnishes false or misleading information on this form or who omits material or information requested on the form may be subject to criminal sanctions (including fines and imprisonment) and/or civil sanctions (including civil penalties).

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