Enhancement of Carbon Sequestration in U.S. Soils

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Improved agricultural, forestry, and land management practices could be used to increase soil carbon and thereby significantly reduce atmospheric CO_2 concentration. Understanding biological and edaphic processes that increase and retain soil carbon can lead to specific manipulations for enhancement of soil C sequestration. These manipulations, however, will only be suitable for adoption if they are technically feasible over large areas, economically competitive with alternative greenhouse gas offsets, and environmentally beneficial. Elements for an integrated evaluation of soil carbon sequestration methods are presented.

Keywords: soil carbon, greenhouse gases, climate change, full carbon accounting, terrestrial ecosystems, land use change, integrated assessment

Rising atmospheric CO_2 concentration is a concern because of its potential for altering climate. Since the beginning of the industrial revolution atmospheric CO_2 has increased by more than 30%. The rate of fossil fuel burning and associated CO_2 emissions will increase for the foreseeable future and a doubling or even tripling of the pre-industrial concentration of atmospheric CO_2 is possible by the end of the century (IPCC 2001b). 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 organic matter of ecosystems. However, such management changes will not happen unless there are economic incentives or penalties associated with CO_2 management. In order for terrestrial carbon sequestration to be useful it must not only result in carbon accumulations in vegetation and soil but also induce lower net releases of CO_2 or other greenhouse gases.

There are many factors that intervene between demonstrating that a particular management practice can result in enhancing carbon sequestration in soil and determining that widespread application of the method is useful, acceptable, and cost effective. A general methodological approach to evaluating all aspects of a carbon sequestration practice is currently lacking. Here, we outline and show examples of a methodology for a complete and integrated approach to evaluating terrestrial carbon sequestration alternatives. The methodology has six components:

- Identification of promising technologies
- Understanding carbon implications of technologies at the site scale
- Inclusion of full C and greenhouse gas accounting

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- Evaluation of other environmental impacts
- Performance of sensitivity analysis over the range of applicable conditions (model, laboratory, or field experiments)
- Economic analysis of the practice's cost competitiveness, market implications, and other factors

There is considerable uncertainty in each of these steps. In this paper we review recent information 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.

Background

The concentration of CO_2 in the atmosphere has risen from close to 280 ppmv in the mid-1800's – at first gradually and then at an exponentially increasing rate – to 371 ppmv in 2001. This increase will 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 fossil fuel combustion and land-use caused CO_2 emissions. Land-use emissions occur when land is converted from one vegetative cover to a less dense vegetative cover, especially when converted from native vegetation to agriculture. About half of all emitted carbon remains in the atmosphere, which translates into an average increase of 3.2 Pg C y^{-1}. 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 CO_2 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 resulting from land-use changes (mostly now from tropical deforestation). This flux is estimated to contribute 0.6-1.0 Pg C y^{-1} to the atmosphere (Houghton 2003). The second component is the difference between the inferred net land-atmosphere sink of -1.4 ± 0.7 Pg C y^{-1} and the land-use change flux. This difference has been estimated to range between 1.3 to 3.1 Pg C y^{-1} and has been termed the *residual carbon sink*. Several lines of evidence indicate that this *residual carbon sink* occurs in terrestrial ecosystems and represents sequestration of carbon into soils and plants. Leading hypotheses about the processes involved in this residual sink include the stimulation of photosynthesis from higher CO_2 concentrations, recent climate change, and atmospheric nitrogen deposition (Pacala et al. 2001). There are other possibilities that result from indirect effects of land-use change. These include increased biomass due to fire suppression and successional changes in vegetation; erosion that results in carbon burial in wetlands, lakes, and reservoirs; forest products diverted to long-lived wood products or land-fills; and increases in soil carbon resulting from changes in agricultural management. Estimates of the magnitudes of each of these possible sinks appear in Table 2.

One can see from Table 2 that land management plays a small but significant role in overall global carbon cycle fluxes. It may account for about 4-14% of the residual carbon sink. Regrowth of perennial vegetation accounts for a small potential soil carbon sink due to the small amount of land area that is expected to be involved. Furthermore, most of the fairly substantial forest regrowth sink (70% to 90%) is in biomass, rather than soil. Although land management is not a dominant sink, it involves intentional soil and vegetation manipulation over large land areas. The carbon sink associated with land management, except the amount associated with improved forestry which is largely biomass, is soil carbon sequestration and amounts to over 0.4 Pg C y^{-1}. With focused effort, the amount of carbon sequestered in soil by land management could be significantly increased. Various studies estimate that the soil C sequestration rate may be increased to 0.44-0.88 Pg C y^{-1} and sustained over a 50-year time frame (Cole et al. 1997). While these rates will offset only a fraction of 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 potential for early deployment and low costs – within a technology portfolio to mitigate climate change. The important aspect of land management for soil C 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. Due to the cumulative effect of CO_2 on climate, an immediate offset of CO_2 emissions provides a significant delay in the rise of atmospheric CO_2 concentration. In addition, by the time that land management C sequestration begins to saturate the soil's capacity to store additional C, other methods of reducing emissions or sequestering carbon may be available or already in use.

Identification of Promising Soil Carbon Sequestration Technologies

We can enhance soil sequestration by (1) increasing the rates of organic matter inputs, (2) partitioning carbon to longer-lived pools, and/or (3) increasing the longevity of all or selected C pools. Different methods of agricultural management use one or more of these pathways to enhance carbon sequestration (see Box 1 for a description of the most widely employed management methods). Depending on the process involved, variations are expected in the length of time that the enhancement method is effective (time to saturation) and the average residence time and susceptibility to disturbances that would release this sequestered carbon back to the atmosphere (permanence).

The amount of soil C in various forms is determined by the balance between inputs of detritus material and losses through decomposition, leaching to groundwater, or erosion. At a basic level, the mechanisms controlling these processes and their balance can be tied to soil-forming factors (Table 3) and, thus, are generally well known to soil scientists. Disturbance or management practices also exert considerable influence on soil C amounts via direct effects on inputs and losses as well as through indirect effects on the factors controlling these fluxes. Uncertainties in predicting changes in soil C, however, are caused by complex interactions and feedbacks among controlling mechanisms and processes. Identification, development, and quantitative evaluation of appropriate technologies and their effects on processes that determine soil C dynamics is critical.

Understanding Carbon Implications of Technologies at the Site Scale

Box 1 lists several widely used land-management practices that, when applied to plow-tilled cropland, have demonstrated significant C sequestration potential. Much of the soil C increases associated with these practices result from reversing processes by which traditional management depleted the soil C stocks that had 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 the soil C content.

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

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 food web interactions. Relatively labile material may become physically protected from decomposition by incorporation into soil aggregates or by deposition in micropores inaccessible even to bacteria (Figure 1). Macroaggregates (>0.25 mm diameter) are sensitive to soil disturbance, but microaggregates (<0.25 mm 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 C stabilization within microaggregates (Jastrow and Miller 1998, Six et al. 2000). Recent research (Jastrow and Six 2003), using soil fractionation procedures that isolate microaggregates from the macroaggregate structure of soil and also takes advantage of shifts in the natural abundance of stable C isotopes following a change in grassland type, is finding 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% new chemically resistant C was incorporated into the mineral fractions of microaggregates 62 years after the change in grassland composition, whereas less than 30% new C was present in equivalent fractions of non-microaggregated soil. Reductions in tillage intensity allow aggregation processes to be reestablished thereby rebuilding this physical protection. Long-term experimental data shows that greatest increases occur with no tillage (West and Post 2002) indicating that physical protection in aggregates, which increases the longevity of soil C, is a significant component of soil C increases with conservation tillage.

Recent research suggests that management practices that decrease 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 (Bailey et al. 2002, Bardgett and McAlister 1999, Stahl et al. 1999). In addition, decreases in disturbance and changes in plant communities can increase the amounts of mycorrhizal fungal biomass, which is also biochemically recalcitrant but is derived directly from plant photosynthates rather than the rendering of detrital residues.

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

Perennial vegetation. Perennial vegetation establishment on previously plow-tilled land results in substantial increases in soil C (Gebhart et al. 1994, Post and Kwon 2000). Even without additional management, rates of soil C increase are similar to or greater than found with no-till. Processes involved are largely the same as 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 reductions in erosion.

Biomass accumulations with establishment of perennial vegetation also contribute to carbon sequestration and for forest ecosystems the biomass C accumulation rate usually greatly exceeds the soil accumulation rate. Biomass accumulations can be lost with catastrophic fire or insect outbreaks and so should be discounted appropriately 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 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 through maintenance of soil pH at neutral or higher levels. Chemical stability, both biochemical recalcitrance and physiochemical protection, results in SOC increases through increases in the rate of humic compound formation or decreases in the rate of mineralization. Formation of humic compounds is maximized under partly oxidizing conditions – too much oxygen and full mineralization occurs, too little oxygen and 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 C. Similarly, practices that optimize the amounts of Fe and Mn oxide minerals 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). Presence of polyvalent cations such as Ca, Mg, and Fe facilitate sorption of organic polymers to soil minerals thereby protecting them further from microbial and chemical attack. The judicious addition of divalent liming agents and Fe and Mn fertilizers coupled with management of drainage conditions can do much to enhance the net rate of C 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 it into the pore water (Jardine et al. 1989, Jardine et al. 1990, Kooner et al. 1995). In soils with deep profiles and limited lateral flow, this process could serve to actually enhance organic C sequestration since the DOC would have ample opportunity to readsorb on mineral particles deeper in the soil. Since subsurface mineral-stabilized C pools are significantly less dynamic than C in upper soil horizons, manipulating the geochemical environment in order to move C from upper to lower soil layers through desorption and adsorption of DOC is a potential means of enhancing C sequestration in the subsurface. Managing fertilizer sources to drive organic C deeper into a soil profile or manipulating the mineral components of a particular soil to favor C sorption are potential land management strategies for enhancing subsurface organic C 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 if microbial communities can be manipulated to enhance carbon stabilization. New methods using nucleic acid-based techniques to assess microbial community dynamics and activities in natural environments are valuable tools for microbial analyses. For example, 16S and 18S rDNA probes were used with terminal restriction fragment length polymorphism (T-RFLP) 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 reversion to prairie even though fungal biomass and activity was 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., carbon dioxide fixation, plant polymer degradation, methanogenesis and methane 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 we more clearly understand how specific microbial processes are involved in carbon sequestration, we may be able to directly (e.g. inoculation or use of biocides) or indirectly (e.g. manipulation of vegetation, soil pH, substrate additions) manipulate microbial populations or modify specific genes to increase (or decrease) particular functions associated with production and decomposition of biochemically resistant compounds.

Given what is known about soil carbon processes, 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 manipulation of processes associated with biochemical recalcitrance, chemical protection, and physical protection.

Evaluation of 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 soil organic matter 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). Management impact on erosion is probably the most significant co-benefit. Conventional plow tillage, especially with winter or dry period fallow, exposes soil to erosive forces of wind and water. Reduced tillage, especially no-till, reduces 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 (Dearmont et al. 1998, Pimentel et al. 1995) show this potentially has considerable economic value.

The loss of soil organic matter 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. Soil organic matter losses have affected not only agricultural productivity but also have been translated into a significant release of CO_2 into the atmosphere – 55 Pg C worldwide (Cole et al. 1997). However, soil organic matter lost from fields through erosion may be retained at depositional sites or deposited in water bodies downstream. The ultimate fate of the C 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 C eroded from fields becomes buried in depositional areas and is thus sequestered and unavailable for decomposition. With time, the C eroded from agricultural lands is replaced by new C fixed by plants growing on both eroding and depositional sites. Stallard (1998) estimated that up to 1.5 Pg C y^{-1} could be sequestered globally by these processes. Lal (1995), however, argued that because soil aggregates break down in the process of erosion, physically protected C 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 C y^{-1} from the soil to the atmosphere as the result of water erosion.

Erosion-deposition processes, however, appear to have non-linear interactions with the C cycle. At a small watershed in Maryland, McCarthy and Ritchie (2002) used ^{137}Cs to test whether upland agricultural activities could increase C 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 C storage in the wetland buffer. Harden et al. (1999) used a sampling and modeling approach to study the link between erosion-deposition processes and soil carbon cycling at three sites in Mississippi developed on loess parent material. Their results revealed that erosion processes could generate a significant sink for C in sediments where it is protected from decomposition. Clearly, we need to advance our understanding between erosion-deposition processes and the C cycle in order to improve the accuracy of C budgets constructed at local, regional, and global scales.

Other environmental impacts, in addition to soil stabilization and erosion controls, need evaluation when a sequestration practice is to be implemented. Impact on species diversity (Huston and Marland 2003), biocide impact on non-target species including decomposers, nutrient retention impacts on water and air quality, local and regional climate (through changes in albedo and surface energy balance) are important and need consideration. Additionally, if an energy related emission of CO_2 is continued because C sequestration is mitigating it's 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 (Elbakidze and McCarl 2004). Objective methods for evaluating all of the direct and indirect co-benefits and potential negative impacts of soil carbon sequestration projects are needed.

Inclusion of Full C 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 consumption of fossil fuels during agricultural operations, net emissions of other greenhouse gases, and the effects on land productivity and crop yield. CO_2 emissions occur not only from plant and soil respiration, but also from (a) the use of fossil fuels in the production and use of agricultural machinery such as tractors, harvesters, and irrigation equipment; and (b) the use of fossil fuels in the production, transportation, and application of agricultural inputs such as fertilizer and pesticides.

Additionally, changes in agricultural practice and land use may alter the net flux of N_2O and CH_4 to the atmosphere. Since agriculture is a major contributor of both gases to the atmosphere (IPCC 2001a), 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 (GHGs). When multiple GHGs are to be considered, IPCC recommends the use of 100-year Global Warming Potentials (GWP) to express the integrated effect of C sequestration practices on the climate system in terms of carbon or CO_2 equivalents (C_{eq}). The 100-year GWPs for methane (CH_4) is 23 and for nitrous oxide (N_2O) is 296 indicating how much more effective these GHGs are at trapping heat relative to CO_2.

Microbial denitrification is the major pathway for gaseous loss of soil N as N_2O and N_2. Cultivated soils normally emit more N_2O than uncultivated soils, primarily because of the synthetic N fertilizer and animal manures applied. Of course, there are many edaphic factors (soil texture, water status, and temperature) and management controls (amounts and type of crop residues added to soil and fertilizer N management) that interact to determine how much N_2O will evolve from 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 N mineralization. In general, gaseous N losses are greater in no-till than on conventionally tilled soils (Aulakh et al. 1992). The enhanced loss under no-till has been attributed partly to increased (a) soil bulk density, (b) anaerobiosis in soil aggregates and (c) water filled porosity. Other studies, however, have reported emissions of N_2O under no till 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 fertilizer N application may also affect the magnitude of N_2O emissions from soil. Matson et al. (1998), studying N_2O emissions under alternative and conventional wheat production in Mexico found that losses of N_2O were smaller when fertilizer N was applied at rates and times that matched crop demand than when applied in a single dose. The large GWP for N_2O and the sensitivity of N_2O emissions to tillage make consideration of this GHG 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 soils. Thus, soils behave either as sources or sinks of CH_4 depending on their oxidation status. Cultivated soils have generally less capacity to oxidize CH_4 than do native soils. Robertson et al. (2000) reported that soils under annual cropping systems have 4 to 6 times less capacity to oxidize CH_4 than do mid- to late-successional forests.

Marland et al. (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 depicts the interrelationships in the model along with estimates of average 20-year alterations in greenhouse gas fluxes following conversion from conventional tillage to no-till for an average continuous corn crop. This example shows a net greenhouse gas emission reduction over the 20-year period. Savings in fuel consumption by farm machinery is partially offset by the slight increase in N fertilizer use associated with moving from conventional tillage to no-till (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 after approximately 20 years the soil carbon pool will reach a new steady state in the no-till system. 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 required or 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 effect of changes in land use and management on CO_2 and non-CO_2 greenhouse gases, and considers the impact of crop productivity on soil carbon sequestration.

Performance of Sensitivity Analysis Over the Range of Applicable Conditions

Multiplying land areas that could be converted to an alternate land use or land-management practice by the average sequestration rates for those changes can be used to make estimates of regional sequestration potentials. However, with each land use or management practice, rates of C sequestration, the magnitude of C stocks at steady state, and the time required to reach a new steady state can vary spatially as influenced by differences in climate, and edaphic conditions. Thus, better and more realistic assessments of sequestration potentials 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 C storage. Follett et al. (2001) estimate that land enrolled in the Conservation Reserve Program (CRP) across a 13-state region in the U.S. Midwest could sequester an average of 570, 740, and 910 kg C $ha^{-1}yr^{-1}$ to soil depths of 5, 10, and 20 cm deep respectively. Most estimates to date are similarly derived from measurements obtained during the first decade of CRP, when rates of soil C gain are likely to be the greatest. For aggrading systems, the differential between the rates of organic inputs and decomposition losses narrow with time and C accumulation slows until a new steady state – dependent on vegetation type, soil conditions, and environmental factors – is achieved. Although the rapid initial rates of C gain under CRP cannot be sustained indefinitely, soil C sequestration can continue at substantial rates over several decades. Jastrow (1996) used a native prairie remnant to constrain the estimated rate of soil organic C accrual for a chronosequence of restored grasslands (Figure 3) according to a simple model that annually balances new input to soil C with fractional loss to decomposition (Jenny 1980). The model shows soil C increases during the first 15 years of restoration that are comparable to the 740 kg C ha^{-1} yr^{-1} estimated by Follett et al. (Follett 2001) for the surface 10 cm in CRP land, and then demonstrates a decline in accrual rates over time. However, even the slower accrual rates computed for the 30-45 year interval represent significant soil C storage.

Each combination of land-use history, climate, edaphic factors, and vegetation type leads to different responses of soil carbon to changes in management. Understanding this variation provides insight about the relationships among environmental factors and carbon sequestration. A quantitative understanding of the relationships among environmental factors and soil organic matter dynamics is most often formulated in soil organic matter models such as Century (Parton et al. 1988), RothC (Jenkinson 1990), and EPIC (Izaurralde et al. 2001). Models may be correlative models derived from empirical relationships, complex feedback models derived from process understanding, or something in between. Deploying models spatially by driving them with information about the spatial distribution of biotic/abiotic information that these models use as inputs allows for regional analyses of soil C sequestration (Paustian et al. 1997, Pennock and Frick 2001).

Economic Analyses

For technologies to be effective they must be cost competitive and this is largely an economic question. Changing management practices for C sequestration can be expensive to implement, either because of increased costs or increased risk (new equipment, more complex operations) or because of a reduction in income (loss of yield or production capacity). If agricultural soil based sequestration is to play a role in the endeavor to reduce GHG emissions we must both determine that soil sequestration practices are competitive low cost producers of GHG offsets and design programs or incentives that make these practices attractive for use by land managers. In the U.S. a general soil related GHG program or incentive framework would likely include 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 governmental based implementation where at least some parts of the costs are borne by government such as in the set aside, EQUIP, Conservation Reserve, and other current/past USDA programs supporting soil conservation practices.

Carbon sequestration and other agriculturally based options for reducing net GHG emissions should be evaluated to see how competitive they are in comparison with a variety of other options such as forest carbon sequestration; emissions capture and carbon removal from the atmosphere by flue gas capture operations; or carbon avoidance by electricity generation with biofuels, natural gas, or nuclear power instead of with coal or petroleum. A useful approach is to consider how much it costs to deliver to a buyer, on average, a ton of sequestered C and then to determine whether that delivered cost is less than or equal to available costs from other sources. Conceptually, the cost of delivering a ton of greenhouse gas offsets via a given practice is composed of the total change in all costs involved with the practice, adoption, and sale to buyers divided by the incremental quantity of greenhouse gas offset produced:

$$\text{Delivered Cost per ton to a Buyer} = \frac{\text{Total Net Cost of Practice}}{\text{Claimable Amount of GHG Offset}} \qquad (1)$$

The net cost of the practice for a market based commodity consists of several major terms that include (see Box 2) the cost the producer bears in adopting the practice, the other incentives necessary to cause the producer to adopt, plus any market transaction costs involved in selling offsets to the buyers. 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 project is paid for by the government then the net cost of the practice would be the amount of money paid to the producer to obtain practice adoption possibly reduced by the value of the co-benefits obtained.

The quantity of offset that can be claimed for a project is the incremental quantity of GHG emission avoided plus the carbon sequestered and adjusted for any discounts imposed in determining the claimable credits as required by the GHG accounting system or the buyer. There are several components to the incremental GHG offset which include:

- Project induced carbon sequestration in the soil or in standing plants or trees over time,
- Project induced net reductions in methane and nitrous oxide emissions,
- Project induced net savings in fossil fuel emissions due to changes in system inputs, and
- Project induced net savings in carbon releases from input manufacturing due to changes in input use.

All of these would be adjusted to a carbon or carbon dioxide equivalent basis using the GWP as discussed above.

Not all credits may be claimable due to accounting system rules or offset characteristics. Internationally, the concerns of additionality (ADD), uncertainty (UNCER), leakage (LEAK), and permanence (PERM) have been raised relative to the claimable portion of offsets produced.

These terms are defined in the lower part of Box 2. Thus in general the claimable quantity is the project created quantity adjusted by a discount factor that is the multiplication of all of the relevant discount factors DISC = (1-ADD)*(1-LEAK)*(1-PERM)*(1-UNCER). Such discounts may vary across greenhouse gas accounts and projects with different discounts applying to reduced emissions and sequestration. The denominator of equation (1) becomes

Claimable Amount of GHG offset produced = ProjectOffsets * DISC (2)

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

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

Finally one should consider the issue of co-benefits from an economic standpoint. In general these involve many non-market 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 (Elbakidze and McCarl 2004). However, one must also consider the costs that might arise if sequestration offsets allow increased emissions elsewhere and those emissions are associated with increased pollution. For example, increased emissions by power plants may increase ozone and other pollutants. Evaluation of co-benefits is difficult but should at least be inventoried if not used in forming cost estimates.

Conclusions

The notion 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 is at hand, many co-benefits seem likely, the potential magnitude appears promising, and initial cost estimates appear to be low. As a result there is a rising demand to know precisely how much and how fast carbon may be sequestered in soil and what other environmental and economic impacts will occur from this sequestration. There are, however, many considerations beyond just the technological capability that will determine the rate and cumulative magnitude of soil carbon sequestration. Our 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 extrapolation of information across many conditions and provide a basis for predictions of future soil carbon sequestration. The net greenhouse gas emissions of a particular soil C sequestration method, the costs of delivering offsets to buyers, and the ancillary environmental issues must also be evaluated.

Finally, the societal and land-manager acceptance of sequestration methods will be a significant factor in determining the rate of soil carbon sequestration. The willingness of society and buyers to utilize soil C sequestration methods to achieve net greenhouse gas reduction in the atmosphere will depend on the costs and economic benefits that include unpriced environmental benefits. The outline of integrated elements for evaluating sequestration methods presented here can be modified for assessment of other C sequestration activities, such as geological injection or deep ocean disposal of CO_2.

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Box 1. Management methods that significantly alter amount, partitioning, and longevity of organic matter inputs into the soil.

Management Category	**Included Practices**	**Potential for Carbon Sequestration**
Cropping intensification	Soil fertility enhancement, erosion control, irrigation, summer fallow elimination, integrated pest management, and precision agriculture	Increasing organic matter inputs resulting in returning of SOC lost due to previous cropping management (Parton et al. 1995). Using USDA data on cropland area and crop residue increases with adoption of best management practices an average of 6 Tg C y^{-1} increase in crop residues can be produced. Assuming 10% is converted to soil C average increase in carbon sequestration is estimated as 0.6 Tg C y^{-1} (Lal et al. 1998).
Organic amendments	Animal and green manure, mulches, compost	Organic matter supplementation increases organic matter inputs. Animal manures (biologically altered inputs) are particularly effective at increasing soil organic carbon amounts (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 that results in an average carbon sequestration rate of 50 g m^{-2} y^{-1}. In the U.S., 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 m^{-2} y^{-1} this could result in an increase in carbon sequestration of at least 10.5 Tg C y^{-1}.
Perennial vegetation	Pasture or forest establishment, Conservation Reserve Program (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 m^{-2} y^{-1}, with the highest rates in more humid regions. USDA has been authorized to increase CRP from 14.3 to 15.4 Mha (http://www.fsa.usda.gov/pas/farmbill/). Using a value of 30 g $m^{-2}y^{-1}$, this could result in an increase in estimated carbon sequestration from 4.3 to 4.6 Tg C y^{-1}.
Biomass crops	Switchgrass, short-rotation woody crops	Lal et al. (1998) estimate 10 Mha of idle cropland could grow 50 Tg C y^{-1} offsetting 35 Tg C y^{-1} of fossil fuel. Accounting for all biofuel carbon emissions (production, transport, utilization efficiency, and waste disposal) this may be considerably smaller. Soil carbon accumulation of 30 g C $m^{-2}y^{-1}$ would result in 3 Tg C y^{-1} sequestered in soil. The biofuel offset, no matter how small, could ultimately go on forever.

Box 2. Economic components for determining sequestration cost per ton, value of co-benefits and discounts.

Economic Component, Explanation, and Major Elements
Producer level development cost: When producers choose to undertake a sequestering activity they will need to change land management practices and/or land use. 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 include: Differences in crop yields under existing and alternative land management, changes in input costs, costs of needed new equipment and the salvage value of discontinued equipment.
Producer adoption inducement costs: Alternative uses or management may be economically and agronomically attractive but not adopted because of learning time, investment costs, increased risk and other factors. For example, many cases exist where reduced tillage adoption has been limited despite calculations that average income is increased. This cost would represent any inducements needed to overcome barriers to adoption of the project practices that are above and beyond development costs.
Market transactions costs: The producer development and adoption inducement costs are only part of total commodity costs. In particular, offsets still need to be conveyed to the buyer. In this conveyance there are several additional costs to consider such as: broker commission costs, measurement and monitoring, enforcement, and insurance fees protecting against adverse outcomes.
Government role: Government may offset some proportion of the costs through practice or land use subsidies.
Co-benefits: Sequestration practices can have environmental quality and income distributional implications. 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 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 GHG offsets that a project will be paid for may be subject to discounts due to system rules and compliance requirements. Key concerns in that regard involve additionality, uncertainty, leakage and permanence as discussed in the Kyoto Protocol context. The concept of *additionality* indicates that projects should only receive credit for sequestration that would not have otherwise occurred and projects may have their quantity of offsets reduced by the estimated proportion of non-additional activity. The concept of *Leakage* indicates that 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. The *uncertainty* concept indicates that society and buyers recognize that there will be climate and other factor induced variability in sequestration volumes and a safety margin discount may be desired that falls below average offsets expected to be created to protect against potentially penalized shortfalls. *Permanence* concerns arise for a couple of reasons. First sequestered carbon is stored in a volatile form where future changes to alternative practices can cause reemission of some or all of the sequestered carbon to the atmosphere and maintenance costs may be needed beyond the time when a practice ceases carbon uptake to maintain the practice. 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.

Table 1. 1990's decadal average global CO_2 budget (in Pg C y^{-1}). Positive values are fluxes to the atmosphere and negative values are removal from the atmosphere. Error estimates denote uncertainties (± 2 standard deviations) and not interannual variability, which is much larger (Prentice et al. 2001).

Net Source or Sink	*Source (Pg C y^{-1})*	*Sink (Pg C y^{-1})*
Emissions (fossil fuel, cement)	6.3 ± 0.4	
Atmospheric increase		3.2 ± 0.1
Net ocean-atmosphere flux		-1.7 ± 0.5
Net land-atmosphere flux		-1.4 ± 0.7

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

Terrestrial Carbon Sink	*Rate (Pg C y^{-1})*	*References*
CO_2 fertilization	0.9 – 3.1	McGuire et al. 2001
Climate change	-0.8 – +0.2	McGuire et al. 2001
N deposition	0.1 – 2.5	Holland et al. 1997, Peterson and Melillo 1985
Regrowth of Perennial Vegetation		
Forest[a]	0.39	IPCC 2000
Grassland[a]	0.04	IPCC 2000
Wetland[a]	0.004	IPCC 2000
Fire suppression	0.2	Hurtt et al. 2002 (U.S. Only)
Erosion/deposition	0.6 – 1.5	Stallard 1998
Long-lived wood products[a]	0.3	IPCC 2000
Land management		
Land/soil restoration	0.003	IPCC 2000
Improved Cropland Mgmt.[a,b]	0.16	IPCC 2000
Improved Grassland Mgmt.[a]	0.24	IPCC 2000
Improved Forestry Mgmt.[a,c]	0.17	IPCC 2000

[a] An estimated potential for 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).

Table 3. Influence of soil forming state factors identified by Jenny (Jenny 1980) on the balance between inputs to and losses from soil C stocks.

State factor	Influence on soil C 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 vs. belowground inputs) and affects decomposition through input form and quality/decomposability (e.g., C:N and lignin:N ratios) and uptake/competition for water and nutrients Soil biota (types, populations, community structure, and activities) control decomposition and nutrient cycling and availability (which constrains plant productivity)
Parent material	Soil type, degree of weathering, mineralogy, texture, and structure influence pH, water and nutrient supply, aeration, organomineral 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 and finer scale effects on temperature, moisture availability, and soil texture
Time	Time affects input/loss balance and temporal scale influences relative importance of other state factor effects on production and decomposition

List of Figures:

Figure 1. Conceptual diagram depicting the hierarchical organization of microaggregates within a macroaggregate. Modified from Jastrow and Miller (1998).

Figure 2. Diagram of the agricultural component of the net greenhouse gas emission model GORCAM (Schlamadinger and Marland 1996) illustrating a change from conventional moldboard plow tillage to no-till for a continuous corn monoculture. Values in arrows represent changes in annual flows of greenhouse gases expressed in carbon equivalents (C_{eq}). 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 N_2O emissions from fertilizer application and changes in CO_2 emissions from production, transport and application of the fertilizer. Units are kg $C_{eq}ha^{-1}y^{-1}$ and represent the average over the first 20 years following conversion. This diagram is updated from that used by Marland et al. (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).

Figure 3. Accumulation of whole-soil organic C (surface 10 cm) in a chronosequence consisting of conventionally tilled rowcrop soil, four prairie restorations (aged 1 to 10 y), 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 and assume a soil bulk density of 1.15 g cm^{-3}. 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 ha^{-1} y^{-1}); whereas, a 10% higher equilibrium would result in greater accumulation rates during all three time periods (840, 710, and 610 kg ha^{-1} y^{-1}). Modified from Jastrow (1996).

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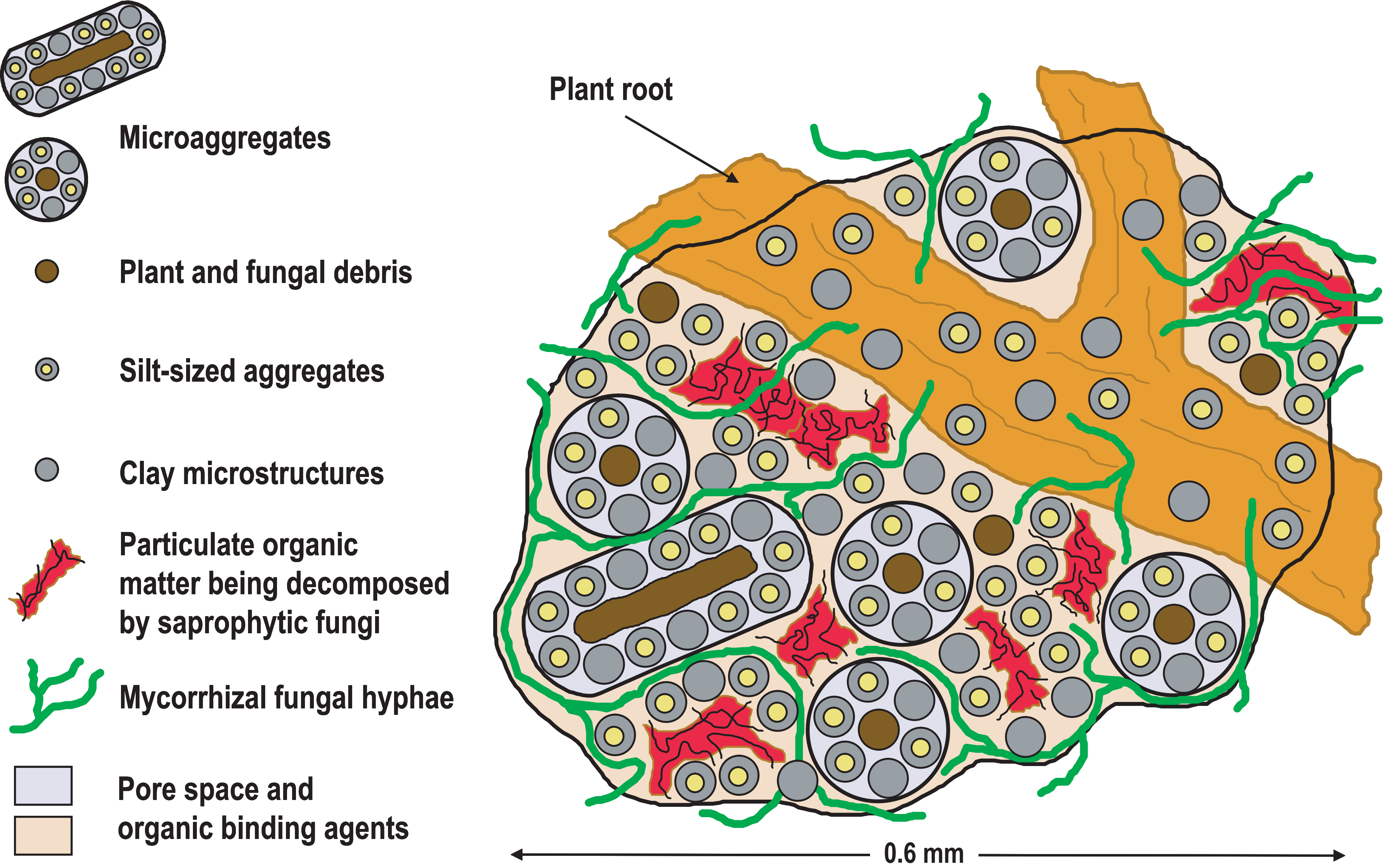
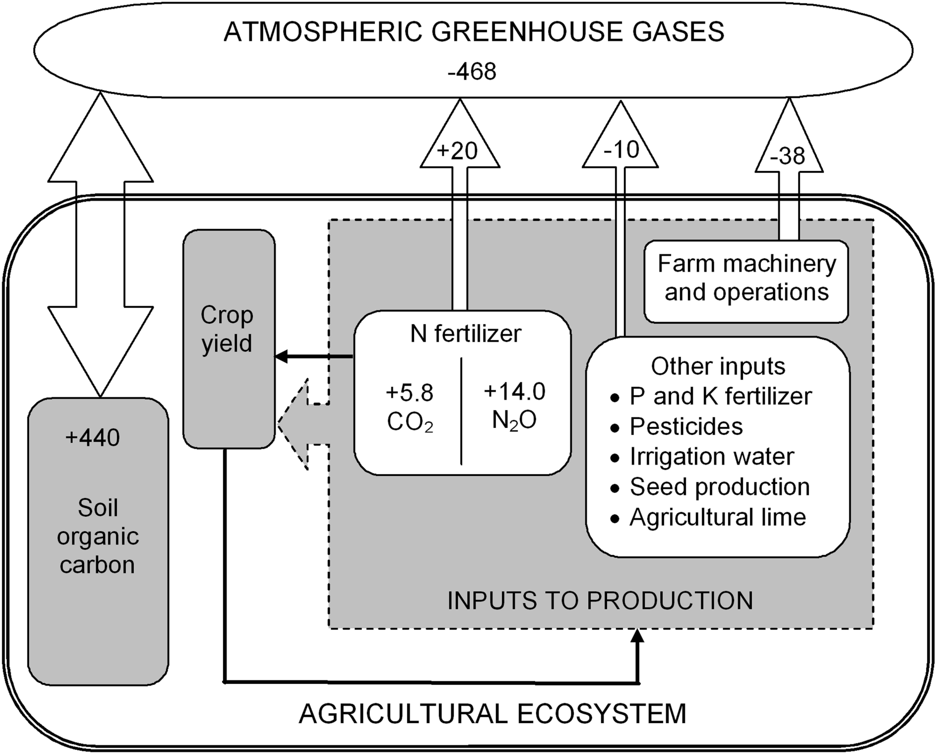
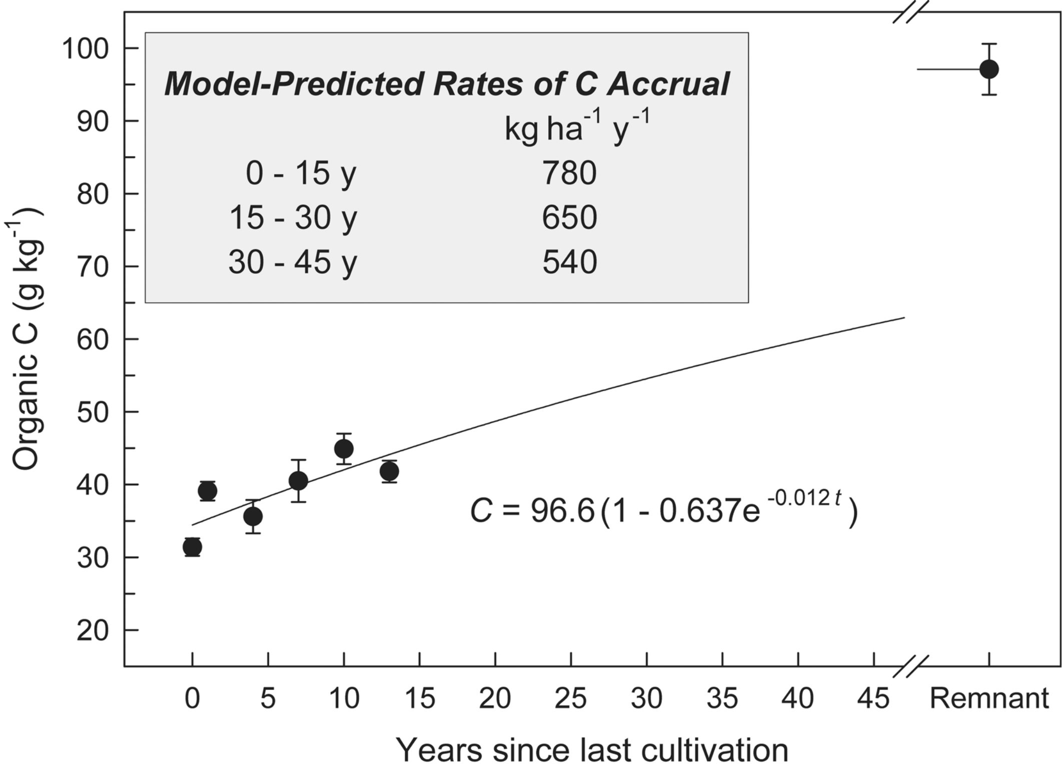

Microaggregates
Plant and fungal debris
Silt-sized aggregates
Clay microstructures
Particulate organic matter being decomposed by saprophytic fungi
Mycorrhizal fungal hyphae
Pore space and
organic binding agents
Plant root
0.6 mm


ATMOSPHERIC GREENHOUSE GASES
-468
+20
-10
-38
Farm machinery and operations
Crop yield
N fertilizer
+5.8 CO_2
+14.0 N_2O
Other inputs
• P and K fertilizer
• Pesticides
• Irrigation water
• Seed production
• Agricultural lime
+440
Soil organic carbon
INPUTS TO PRODUCTION
AGRICULTURAL ECOSYSTEM



Model-Predicted Rates of C Accrual
kg ha-1 y-1
0 - 15 y 780
15 - 30 y 650
30 - 45 y 540
Organic C (g kg-1)
100
90
80
70
60
50
40
30
20
C = 96.6 (1 - 0.637e -0.012 t)
0
5
10
15
20
25
30
35
40
45
Remnant
Years since last cultivation