ECONOMICS AND POLICY OF CARBON SEQUESTRATION IN AGRICULTURAL SOILS: A REVIEW OF RECENT LITERATURE

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EXECUTIVE SUMMARY

Early in the debate on global warming and greenhouse gas emissions, agricultural soils were identified as a potential depository of atmospheric carbon dioxide (CO_2), and terrestrial carbon (C) sequestration was identified as a means of mitigating greenhouse gas emissions. The progression of research pertaining to terrestrial C sequestration has moved from the estimation of the technical potential of soils to store CO_2 to an examination of the economic and policy aspects of soil C sequestration.

The core economic concepts are the level of financial incentives needed for private landowners and producers to adopt C sequestration activities and the cost-competitiveness of terrestrial C sequestration with other abatement measures. The general premises are that producers will adopt C sequestration activities if net revenues from those activities are greater than existing practices and that terrestrial C sequestration can be a low-cost strategy to mitigate greenhouse gas emissions.

Several economic and policy-related issues with regard to terrestrial C sequestration have been identified and discussed in the economic literature. These issues include *permanence* (the length of time C remains sequestered), *C-stock equilibrium* (a future point in time when the rate of C stored approaches zero for any given land tract under consistent management), *leakage* (unintended actions, resulting from changes in market conditions, that undermine the amount of C sequestered or produce an increase in greenhouse gas emissions), *moral hazard* (a situation where a producer switches from C-friendly practices to undesirable activities in order to qualify for financial compensation), *gross sequestration* (tracking only the amount of CO_2 sequestered), and *net sequestration* (a net measurement of both the amount of C sequestered and the level of emissions incurred during the activity). In addition, both *government-based* and *market-based* payment mechanisms have been modeled. With government-based policies, two approaches have been used to define the eligibility of participants, *good actor* (all producers are eligible for payment) and *new adopter* (only those who need financial incentives to switch practices receive payments).

Economic assessments of terrestrial C sequestration have employed numerous modeling approaches and exhibited considerable differences in geographic and analytical scope. Yet, despite these differences, several specific findings have

been generally consistent within the economic literature. At low C prices ($10–$50/metric ton [MT]), the primary C sequestration activities would be changes in tillage practices. At higher C prices (>$125/MT), afforestation becomes the dominant source of additional C sequestration. Temporal and regional differences must be accounted for when assessing the economics of C sequestration. Incentive levels sufficient to elicit desired responses from producers in one region do not guarantee similar actions in other regions. Switching agricultural land from crop production to permanent grass has not been economically viable, primarily because of the treatment of coproducts.

Economic assessment of terrestrial C sequestration is ongoing, as evidenced by a proliferation of literature in recent years. Although insights into many economic and policy aspects of terrestrial C sequestration have been recently gained, a number of issues remain unanswered. Topics where further economic research is needed include addressing producer/landowner acceptance rates and behavioral impediments to adopting C sequestration activities, quantification of transaction costs for buyers and sellers of C contracts, specifics on how to handle issues of moral hazard and leakage, holistic assessments of producer-level economics of C sequestration on grazing lands and wetlands, and expansion of economic study to include other greenhouse gases (e.g., methane and nitrous oxide).

The current consensus within the economic literature is that agricultural soils can provide low-cost C sequestration when compared to current abatement costs for nonagricultural industries, and the economic potential of agricultural soils to store C is considerably less than the technical potential. Nationally, the economic potential of agricultural soils to sequester C appears to range from 22% to 78% of technical capacity (often used to indicate the amount of C sequestration possible under "best case" situations for both land management and land use, without consideration of economic, social, or institutional constraints).

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BACKGROUND/INTRODUCTION

As one of seven Regional Carbon Sequestration Partnerships (RCSPs), the Plains CO_2 Reduction (PCOR) Partnership is working to identify cost-effective carbon dioxide (CO_2) sequestration systems for the PCOR Partnership region and, in future efforts, to facilitate and manage the demonstration and deployment of these technologies. In this phase of the project, the PCOR Partnership is characterizing the technical issues, enhancing the public's understanding of CO_2 sequestration, identifying the most promising opportunities for sequestration in the region, and detailing an action plan for the demonstration of regional CO_2 sequestration opportunities. This report focuses on the current understanding, as documented in the literature, of the economics and policy of carbon (C) sequestration in agricultural soils.

Global debate on greenhouse gas emissions (GHGE) led to the establishment of the Intergovernmental Panel on Climate Change in 1988. Since then, numerous international conferences and agreements have addressed global warming and greenhouse gas emissions. The end result of scientific evidence linking human activities to global warming is the recognition of the need to curtail or reduce GHGE to mitigate global climate change.

Early in the debate on global warming and GHGE, agricultural soils were identified as a potential depository of atmospheric CO_2 (Moulton and Richards, 1990; Parks and Hardie, 1995). The interest in agricultural soils, within the framework of global warming, is important since soils can either be a source of GHGE or store atmospheric CO_2 through a variety of natural processes.

Agricultural lands in many regions of the world have lost soil C because of intense cultivation, deforestation, and erosion (Smith, 2003). Given the depleted level of soil C in most soils and the ability of soils to store atmospheric CO_2 in the form of organic matter, agricultural lands have been viewed as a means to mitigate greenhouse gas emissions. Agricultural lands can be used as a terrestrial sink for atmospheric CO_2 by changing the management and/or use of those lands, which has prompted soil scientists to place technical thresholds on the C sequestration capacity of soils. Generally, after agricultural soils were shown to be technically capable of providing substantial offsets to existing GHGE, economic studies were conducted to determine the cost and feasibility of using agricultural lands to sequester C.

CARBON SEQUESTRATION CAPACITY OF AGRICULTURAL SOILS

Numerous soil science studies have attempted to place a range on the technical potential or capacity for C sequestration that could occur through changes in land management and/or land use. Technical capacity is a term often used to indicate the amount of C sequestration possible under "best case" situations for both land management and land use, without consideration of economic, social, or institutional constraints.

Recent estimates indicate that agricultural soils in the United States are currently acting as a C sink. Comis et al. (2001), recapping a study presented to the U.S. Department of State, indicated U.S. cropland and rangeland were already sequestering 20 million metric tons (MMT) of soil C annually. Another estimate indicates that U.S. cropland currently has a net sequestration rate of 4 MMT of C annually (U.S. Environmental Protection Agency [EPA], 2004). Eve et al. (2002) estimated that changes in agricultural land use and management during the period 1982 through 1997 have resulted in a net gain of 21.2 MMT of C per year in U.S. agricultural soils during this period. Cropped lands account for 15.1 MMT of C per year, while grazing land soils account for 6.1 MMT. The land management changes that have contributed the most to increasing soil C are 1) adoption of conservation tillage on cropland, 2) enrollment of cropland in the Conservation Reserve Program (CRP), and 3) cropping intensification that has resulted in reduced use of summer fallow. However, several studies have indicated the technical capacity of U.S. agricultural lands to sequester C to be substantially higher than current storage rates.

The first studies to estimate the technical capacity of U.S. cropland to store C were based largely on aggregated data and did not specifically account for regional differences in climate, soil, and land management (Sperow et al., 2003). Yet these studies have been widely used to illustrate the upper bounds of soil C storage capacities of U.S. agricultural soils. Cole et al. (1996) estimated that globally, over the next century, agricultural soils could sequester 40 to 80 billion metric tons of C. Lal et al. (1998, 1999) estimated that U.S. cropland could sequester 75 to 208 MMT of C annually over a 15-year period. Bruce et al. (1999) estimated that U.S. cropland had the potential to sequester 75 MMT of C annually over a 20-year period. Comis et al. (2001) reported that government and academic scientists indicated that U.S. cropland and rangeland had the technical potential to store 180 MMT of C annually above current rates of C storage. Follett et al. (2001) provided similar estimates of the soil C sequestration potential of U.S. grazing lands. U.S. grazing lands were estimated to have a technical potential to store 29 to 110 MMT of C annually. Schuman and Derner (2004) estimated that rangelands (i.e., not all grazing lands) in the United States have a technical capacity to store 19 MMT of C per year. Sperow et al. (2003) estimated the technical potential of U.S. cropland to store C at 60 to 70 MMT annually. The above estimates assume widespread adoption of soil C sequestration management practices, but do not account for afforestation. Not accounting for changes in land use, current estimates of the technical potential of U.S. agricultural lands to sequester C range from 89 to 318 MMT per year (Lewandrowski et al., 2004).

Lewandrowski et al. (2004) estimated the technical potential of afforestation of U.S. cropland at 83 to 181 MMT of C annually over the first 15 years of tree growth. Also, Lewandrowski et al. (2004) estimated the technical C sequestration potential of shifting about 105 million acres of highly erodible cropland into permanent grasses at 26 to 54 MMT of C annually over a 15-year period.

Despite somewhat differing estimates of the technical potential for C sequestration on U.S. agricultural lands, the magnitude of those estimates has been consistent. Hence, agricultural lands are currently viewed as having substantial technical potential to sequester atmospheric CO_2 in the form of soil C. However, most agricultural lands in the United States are in private ownership, and changes in land management and/or land use are subject to market forces and profit-maximizing goals of individual landowners and producers. As a result, economic issues associated with terrestrial C sequestration are an important consideration when examining the role that agricultural lands will play in mitigating GHGE.

MANAGEMENT PRACTICES THAT ENHANCE CARBON SEQUESTRATION

The changes in land *management* that enhance soil C storage include reducing tillage intensity and frequency, eliminating tillage, changing crop rotations, using winter cover crops, eliminating summer fallow, improving fertilizer management, adjusting irrigation methods, implementing buffer or conservation strips, and changing grazing regimes (Lal et al., 1999; Eve et al., 2000; Follett et al., 2001; Lewandrowski et al., 2004). The most common changes in land *use* that enhance soil C storage include participation in conservation programs, retirement of land into perennial grasses, afforestation, and restoring wetlands (Lal et al., 1999; Eve et al., 2000; Follett et al., 2001; Lewandrowski et al., 2004). Economic assessments of land management and land use changes to increase C sequestration primarily have focused on switching tillage practices, changing crop rotations, eliminating summer fallow, shifting land to permanent grass, and afforestation.

ECONOMICS OF SEQUESTERING CARBON IN AGRICULTURAL SOILS

Economics is the study of allocating scarce resources among alternative uses (Solmon, 1980). While the field of economic study is broad and could be used to evaluate numerous aspects of C sequestration and greenhouse gas mitigation, to date, economic analyses of terrestrial C sequestration primarily have focused on the level of incentives needed to secure land management and/or land use changes favorable to increasing the rate of C sequestration in soils.

Since private landowners and producers generally are perceived to be profit maximizers, albeit subject to certain constraints, economic analyses have proceeded with the premise that a producer or landowner will participate in C sequestration activities if the net returns from the value of C sequestered plus returns from the alternative activity are greater than net returns from existing practices. Alternatively, producers/landowners will choose the activity(s) that provide them with the greatest level of net income. The above premise has been either explicitly stated or inherently implied in all economic analyses of C sequestration in agricultural soils.

Conceptual Issues

Key conceptual issues associated with economic analyses of C sequestration in soils include modeling concerns with respect to C sequestration and time, C payment structures, gross versus net sequestration, and payment mechanisms.

Carbon Sequestration and Time

For a unit of soil C to have the same mitigating effect as a unit reduction in atmospheric CO_2, soil C must remain sequestered for the same length of time that emitted CO_2 remains in the atmosphere (Lewandrowski et al., 2004). Typically, a 100-year time horizon is considered appropriate (EPA, 2004). The above concept of the length of time required for carbon to remain sequestered is called *permanence* (Lewandrowski et al., 2004).

Most economic analyses have based C payments on a 15- to 20-year time horizon; a period considerably shorter than the time CO_2 remains in the atmosphere. Unfortunately, most empirical studies of C sequestration in agricultural soils employ static modeling frameworks with one-time decision making (Lewandrowski et al., 2004). As a result, if C payments are made based on the value of permanence, but the C remains sequestered less than the 100-year time frame, then the price paid for C would exceed the appropriate net mitigation value.

Another concept that presents challenges for economic analyses is that, given relatively constant environmental conditions and consistent land management activities, soils will accumulate C until a stabilization threshold is reached (i.e., C-stock equilibrium) (N.D. Farmers Union and U.S. Geological Survey 2003a, b, c; Lewandrowski et al., 2004). However, from a C sequestration perspective, if conditions change (e.g., switching from conventional tillage to no-till), C will increase over time until a new equilibrium is reached. Numerous studies have suggested the time frame required to reach C-stock equilibrium in agricultural soils ranges from 15 to 60 years (Paustian et al., 1998; Dumanski et al., 1998; Bruce et al., 1999; West and Post, 2002; N.D. Farmers Union and U.S. Geological Survey 2003a, b, c).

The concept of C-stock equilibrium has important implications for economic modeling. For any given location, C sequestration has physical limits on its mitigation potential over a finite time period (Lewandrowski et al., 2004). However, an emissions reducing activity (e.g., source capture and direct underground injection of CO_2) sustains its mitigation value as long as the activity is maintained. Also, since incremental C accumulation, under consistent management practices, will eventually decline to zero, C payments also will eventually fall to zero. Economic modeling must account for the possibility that landowners/producers could choose alternative land management or land uses in the absence of incentive payments, and the time frame when those decisions occur is likely to be less than the time frame for permanence (Lewandrowski et al., 2004). Hence, when C-stock equilibrium is reached and incentives (i.e., payment stream) approach zero or when a contract period is completed, landowners will likely choose activities that yield the greatest net return; those future activities may not be consistent with long-term C sequestration.

Another perspective on time in relation to soil C sequestration is provided by Marland et al. (2001) and McCarl and Schneider (2000). They point out that because soil C sequestration can be implemented relatively quickly, it has the potential to play a bridging role in GHGE mitigation policy by reducing the cost of current compliance while technology for reducing GHGE in other sectors is developed. In this context, the volatility (potential lack of permanence) of soil sequestered C may not be as serious a concern as it might initially appear.

Carbon Payment Structures

Issues pertaining to permanence and C-stock equilibrium have implications for both price paid for C sequestered and design of C sequestration policies. Lewandrowski et al. (2004) demonstrated the need to consider two pricing arrangements for terrestrial C sequestration: an *asset price payment structure* for permanent C sequestration and a *rental price payment structure* for temporary C sequestration.

An asset pricing system is appropriate when C is sequestered permanently (i.e., about 100 years). Under an asset pricing system, a producer or landowner would receive a payment for the full mitigation value of the additional C sequestered each year.

A rental payment system is more appropriate when C is not likely to be permanently sequestered. While the mechanics of determining C prices under a rental payment structure can be complicated, essentially, the value of C sequestration is discounted over time, subject to the length of sequestration, the relative value of C over time, and the ratio of the value of temporary sequestration to the value of permanent sequestration over the discount period. The discounting of C prices under a rental payment system accounts for the temporary value of short-term C sequestration. Under a rental payment system, a producer or landowner would receive a payment for the additional C sequestered each year, albeit at a price reflective of the portion of the market value of permanent sequestration that occurred over the contract period (Lewandrowski et al., 2004).

Gross Versus Net Sequestered

Net and *gross* sequestrations are the two most common measures of C storage. With respect to C storage in soils, gross sequestration is simply the amount of C added to soils through changes in land management or land use. *Gross sequestration* does not account for the amount of GHGE generated to accomplish C sequestration, nor does it account for leakage from other activities. Alternatively, *net sequestration* measures both the amount of C sequestered and the amount of emissions incurred during the activity, and, depending upon contract terms or policy designs, may or may not address leakage issues (as earlier defined). Ignoring leakage issues, the appropriate measure of net C sequestration would be the amount of C stored less the amount of emissions generated.

The economic implications are different for net versus gross sequestration. Generally, the mitigation value of C storage is overstated in gross sequestration measurements, as the emissions generated to sequester C are not included. Net sequestration is more accurate in measuring the mitigation effect of C sequestration; however, most economic literature has not considered agriculture to be a likely candidate for emission limits because of prohibitively high transaction costs (Lewandrowski et al., 2004). Thus, in a system of offset emission trading, measures of net sequestration are not likely to apply to agricultural activities.

Leakage is a term referring to unintended actions resulting from changes in market conditions that undermine the amount of C sequestered or produce an increase in GHGE. In the case of terrestrial C sequestration, leakage occurs from market adjustments associated with C incentives (Lewandrowski et al., 2004). In the case of soil C sequestration, leakage can occur both from activities within and outside of the agricultural sector.

An example of leakage outside of production agriculture is the potential effects on the management of existing forests that arise from decreases in market prices of forest products due to increasing supplies of lumber associated with afforestation of marginal agricultural lands. Much of the concern with leakage between production agricultural and forestry stems from competition for the same land resource (Adams et al., 1999; Alig et al., 1997; Plantinga et al., 1999; Stavins, 1999; Murray et al., 2004).

Leakage within production agriculture is usually caused by changes in net returns for alternative land management and/or land use. These adjustments are usually the result of changing commodity prices. If sufficient agricultural land is removed from crop production, corresponding increases in commodity prices may cause a change in management on land not currently associated with C sequestration or may provide sufficient economic incentive to discontinue C-friendly practices on other lands. For example, net returns from placing grazing lands (e.g., tillable pastureland) into crop production may be higher than net returns from managing those lands for livestock production. Another example is if higher crop prices resulting from initial changes in agricultural land use or management entice shifts from conservation tillage to conventional tillage on other cropland where the cost savings associated with conservation practices are exceeded by revenue advantages related to conventional tillage (Lewandrowski et al., 2004).

Payment Mechanisms

The economic literature primarily has used two approaches for distributing C payments or providing C incentives. A *market-based system* has been discussed in which landowners or producers would either negotiate directly or collectively with purchasers of C offsets (Willey, 2004). Prices would be determined through public markets, operated either domestically or internationally. In essence, C offsets would become a tradable commodity (McCarl and Schneider, 2000; Thomassin, 2003; Young, 2003). Producers and landowners would be sellers of C offsets, while greenhouse gas emitters would likely be purchasers. Although the concept of a carbon or GHGE market is relatively straightforward, numerous details of the rules and stipulations associated with terrestrial C sequestration transactions have yet to be resolved in the United States. The impetus required for a C or GHGE market to establish hinges on some sort of mandated reduction in emissions, either through international treaty or domestic regulation. The absence of international or Federal involvement in emission reductions within the United States does not preclude the possibility that individual state governments may implement their own limits on emissions (Young, 2003). In the absence of such regulatory action, few market incentives exist for companies to substantially reduce their emissions (Banerjee et al., 2003; Thomassin, 2003).

The Chicago Climate Exchange is currently experimenting with a voluntary market for trading GHGE, although the participants are cooperating without international or domestic mandates to reduce emissions (Chicago Climate Exchange, 2004). The domestic sulfur dioxide market may provide a potential blueprint for how a C market might be structured under international or domestic mandates (Joskow et al., 1998; EPA, 2003). It is possible the Chicago Climate Exchange could become a major market under international treaty or domestic regulation on GHGE (Banerjee et al., 2003).

The second approach has been to use Federal *government programs* to provide and distribute sequestration incentives. Specifics of these programs have been loosely defined and generally range from a separate C sequestration policy to a component of a broader U.S. energy policy to a provision of existing U.S. agricultural policy. Despite the widespread use of some type of hypothetical government program, the literature does not address the likelihood that C payments or incentives will flow from Federal programs.

Some economic analyses have patterned a C sequestration policy after CRP (Parks and Hardie, 1995; Alig et al., 1997; Plantinga et al., 1999; Stavins, 1999; Lewandrowski et al., 2004). Other studies have used direct payments or government subsidies that serve as financial incentives for producers (Antle et al., 2001; McCarl and Schneider, 2001).

Eligibility requirements are a key factor when either CRP-based C sequestration policies or other government-based incentives are assumed. Two approaches have been developed with regard to eligibility requirements. One option is to pay all producers who practice a specified activity covered by a program, often termed the *good actor* approach. Another option is to pay only producers who are willing to switch to the specified activity, often referred to as the *new adopter* approach.

The good actor approach does not penalize producers who adopted an activity or practice before external compensation was available. Supporters of the good actor approach suggest that it avoids *moral hazard* (Lewandrowski et al., 2004). Moral hazard, in the context of C sequestration, refers to a situation where a producer switches from C-friendly practices to undesirable activities in order to qualify for financial compensation. For example, if only land previously farmed under conventional tillage is eligible for payments associated with practicing reduced tillage, operators who had previously adopted conservation tillage might be tempted to revert to conventional tillage to qualify. Moral hazard is a concern since policies which may indirectly encourage that behavior must be capable of observing and penalizing such actions. Arguments against the good actor approach are based mostly on overall program cost and cost-effectiveness measurements, assuming moral hazard issues are adequately addressed (Lewandrowski et al., 2004). For example, a national program providing financial compensation for those practicing conservation tillage could be prohibitively expensive, since Vesterby and Krupa (2001) and the U.S. Department of Agriculture (1998) estimated that 420 million acres of privately owned forest land and 100 million acres of privately owned cropland are currently managed with conservation tillage.

The new adopter approach limits financial incentives to producers who choose to switch to a specified activity. Those already practicing the desired activity would be ineligible to receive program incentives. Under the above framework, payments would only cover the additional C sequestered relative to a prepolicy or preprogram baseline (Lewandrowski et al., 2004). Much of the support for a new adopter approach is based on program costs and cost-effectiveness measurements. A new adopter approach does not reward producers who already found it economically advantageous to implement the desired activity(s), and by doing so, the program only pays producers who need an incentive to adopt C sequestration practices. The disadvantage of the new adopter strategy is that moral hazard behavior becomes an issue, and moral hazard issues can undermine program/policy goals and increase program costs because of policing and monitoring.

Results from Selected Studies

Because the literature dealing with soil C sequestration has proliferated in recent years, an exhaustive review of past work is clearly beyond the scope of this report. Rather, the intent here is to briefly summarize key findings and conclusions from selected studies that examine 1) the role of agriculture and agricultural soil C sequestration in GHGE mitigation, 2) selected national and regional analyses of the economics of soil C sequestration, and 3) studies specific to the PCOR Partnership region.

Role of Agriculture in GHGE Mitigation

Overviews of the potential role of agriculture in GHGE mitigation are provided by McCarl and Schneider (2000), Marland et al. (2001), Murray (2004), Gray and Fulton (2003), and Rosenberg and Izaurralde (2000), among others.

McCarl and Schneider (2000) provide an overview of the issues and concerns associated with GHGE mitigation and review the potential role(s) of agriculture in GHGE reduction. These include providing biofuels (biomass for power plants, ethanol, and biodiesel) and soil sequestration. The authors point out that extensive use of agricultural lands for sequestration could lead to both positive and negative externalities. Positive externalities include increases in soil organic matter, which may reduce the need for irrigation water and chemical fertilizers; increased wildlife populations as cropland is converted to grass or forest; and reduced soil erosion and runoff, as a result of either reduced tillage or cropland conversion. Negative externalities could include increased food prices and/or reduced agricultural exports as a result of cropland conversion. The potential of soil C sequestration is believed to be substantial as several studies have identified the potential for appreciable amounts of sequestration at costs of less than $100 per ton of C, which appears to be quite competitive with opportunities in other industries. Nevertheless, attention must be given to factors affecting farmer/landowner adoption of GHGE mitigation measures and policy measures to reduce leakage and ensure maintenance of sequestered C stocks over time. Finally, the authors point out that soil C sequestration appears able to fill a critical bridge role in a longer-term GHGE mitigation strategy, as it offers several options that can be quickly implemented, before major technological breakthroughs are available in other sectors.

Marland et al. (2001) discuss, under ten themes, policy and economic issues that will determine whether programs of C sequestration in agricultural soils can succeed. These issues involve contexts for implementation, economics, private property rights, agricultural policy, and institutional and social structures. Ultimately, success will depend on the incentive structure developed and the way in which C sequestration is integrated into the total fabric of agricultural policy. Specific points of note include the potential of soil C sequestration to play a bridging role in mitigation policy by reducing the costs of current compliance while technology for reducing GHGE in other sectors is developed. In this context, the volatility (potential lack of permanence) of soil sequestered C may not be as serious a concern as it might initially appear.

Murray (2004) provides a brief overview of the types of agricultural and forestry activities that could be undertaken to sequester or reduce GHGE emissions. The author reports that because the U.S. agricultural and forestry sectors operate on extensive land bases, the biophysical (technical) potential for GHGE mitigation is quite large. Current net C sequestration by U.S. agricultural soils and forests is estimated at 70 MMT of CO_2 equivalent annually, over 90 percent of which is from forests. This offsets 10 percent of national GHGE. The biophysical potential to sequester C in U.S. cropland ranges from 300 to 550 MMT of CO_2 equivalent per year. Afforestation can store up to 5 to 10 MT of CO_2 (1.4 to 2.7 MT of C) per acre per year over a timber rotation. The author also reports on a recent study of the economic potential to sequester C. At a low price ($5 per MT of CO_2 equivalent), both agricultural soil C sequestration and forest management are competitive, each collectively sequestering more than 100 MMT of CO_2 equivalent per year. At prices for CO_2 above $15 to $30 per MT, afforestation and biofuels become the dominant sequestration options. GHGE accounting issues, such as leakage and defining a baseline, also are discussed.

Rosenberg and Izaurralde (2000) overview soil C sequestration and conclude that soil C sequestration can provide an important opportunity for limiting the increase in atmospheric CO_2. Their report summarizes findings from a 1998 workshop where 100 scientists and policy makers determined that a need exists for further research on the mechanics of soil C sequestration, as well as a need for a rapid, economical, and reliable method to verify and monitor soil C sequestration and for a more comprehensive understanding of the social, economic, and environmental implications of incentives that might lead to widespread adoption of soil C sequestration practices. A major finding is that soil C sequestration can play a pivotal role in GHGE mitigation over the first three or four decades of the 21st century, thus buying time for development of technological advances in alternative energy sources and other means of limiting emissions.

National/Regional Studies

A comprehensive study of C sequestration in the U.S. agricultural sector was recently conducted by the Economic Research Service (ERS) of USDA (Lewandrowski et al., 2004). Their analysis adapted the ERS U.S. Agricultural Sector Model (USMP) to include emissions and sequestration parameters. The USMP model disaggregates the United States into 45 regions based on ten USDA farm production regions and 26 land resource regions. The model includes ten major crops and 16 livestock commodities. The objective function maximizes the sum of producer and consumer surplus across all commodity markets. Input markets for cropland, pasture land, family labor, hired labor, and irrigation water are modeled at the regional level with upward-sloping supply curves, while 23 other farm input markets are modeled at the national level, with perfectly elastic supply functions.

Based on the sequestration/emission parameters, alternative designs of carbon incentive payments were implemented. Three sequestering activities were studied: 1) afforesting cropland or pasture, 2) shifting cropland to permanent grass, and 3) increasing the use of reduced tillage and other "carbon positive" production practices. The total U.S. agricultural land base formed the scope for analysis, and incentive payments were based on a 15-year contract. Incentive payments ranged from $10 per MT of C to $125 per MT. Other key assumptions included the following:

- In shifting cropland to grassland, carbon is assumed to have been depleted to 0.7 of equilibrium and can return to 0.9 (90 percent) in 20 years.

- Shifting either cropland or pasture to forest is not an option in the Great Plains or mountain regions.

- No revenue from coproducts (forage, hunting) is assumed from cropland converted to grass.

Carbon sequestration rates in the PCOR Partnership study region ranged from 0.085 to 1.331 metric tons per acre per year for selected changes in land use/management (Table 1).

Key results from the ERS study include the following:

- Nationally, at $10 per MT of C, 0.4 to 10 MMT could be sequestered annually. At $125 per MT, from 72 to 160 MMT could be sequestered (offsetting 4 to 8 percent of gross U.S. emissions in 2001).

- Farmers in most regions would not convert cropland to grass up through $125 per MT of C (however, this is based on no value for coproducts).

- The economic potential to sequester C is substantially less than the technical potential.

It is important to account for permanence when analyzing soil C sequestration. For example, at a 5 percent discount rate, a practice that stores C for 15 years and then releases it is worth about 0.354 of the "full" value of a CO_2 emission reduction.

Several recent studies address coproducts or cobenefits associated with C sequestration. Plantinga and Wu (2003) examine cobenefits of afforestation in Wisconsin. Major environmental benefits from afforestation included reduced soil erosion and reduced water pollution from nitrates and herbicides (e.g., Atrazine). Using an econometric model of land use that quantifies the relationship between aggregate (county) allocations of land to agriculture and forestry and average returns to alternative land uses, land quality, and other variables, the study

Table 1. Carbon Sequestration Rates in the PCOR Partnership Study Region for Selected Changes in Land Use/Management (Lewandrowski et al. [2004])

	metric tons/acre/year			
Region	Cropland to Forest	Pasture to Forest	Continuous Crop to Grassland	Continuous Crop to Conservation Tillage
Northern Plains (ND, SD, NE)			0.378	0.134
Mountain (MT, WY)			0.249	0.085
Lake States (WI, MN)	1.331	1.240	0.425	0.150
Corn Belt (IA, MO)	0.938	0.847	0.491	0.170

simulated the response by private landowners to subsidies for converting agricultural land to forest, yielding estimates of total acreage of afforested land in each county for each subsidy level. The National Resources Inventory (NRI) and the Soil Interpretation Record System (SOILS5) were then used to predict the location of parcels converted to forest and their environmental characteristics (e.g., soil type, slope). Given the physical characteristics of the converted land, environmental "production functions" are used to estimate the associated increases in sequestered C and wildlife habitat values and decreases in soil erosion, nitrogen, and herbicide pollution.

The structure of the hypothesized program is similar to CRP—landowners enroll their land in exchange for a subsidy plus a payment covering establishment (i.e., tree planting) costs. No timber harvesting occurs on enrolled land. A uniform subsidy is given for each unit of land converted from agriculture to forest. Five subsidy values are selected to achieve conversion of 5 percent, 10 percent, and up to 25 percent of baseline agricultural land. Acreage afforested at the highest subsidy was projected at 3.08 million acres statewide. Costs per acre increase from $200 at the lowest enrollment target (5 percent – 0.62 million acres) to $600 at the highest (25 percent – 3.08 million acres). Carbon sequestration increases to 4.1 MMT annually for the highest target (3.08 million acres), compared to 0.24 MMT annually for the baseline. The sum of estimated benefits from soil erosion reduction and improved wildlife habitat is $103 million annually, compared to estimated program costs of $101 to $132 million per year. Corresponding C prices ranged from $23 to $30 per MT. If the cobenefits were credited (even partially) against the program costs, the net costs of C sequestration would be even less.

Kurkalova et al. (2003a) examined cobenefits of a conservation tillage-based C sequestration program in Iowa. The study was based on an econometric model, described by Pautsch et al. (2001), that estimates the probability of adopting conservation tillage. A physical process model (EPIC) is used to estimate changes in C sequestration, nitrogen runoff, and soil erosion resulting from adoption of conservation tillage (>70 percent residue cover), rather than conventional tillage (<30 percent residue cover). Reductions in nitrogen runoff, wind erosion, and water erosion were considered *cobenefits* of adopting conservation tillage. Data for the analysis were obtained from the 12,000+ NRI observation points in Iowa. The authors examined two program options: 1) a *practice-based* policy (instrument) where bids are taken to place tracts into conservation tillage to maximize acres enrolled and 2) a *performance-based* policy where payments are based on the quantity of C sequestered. Both practice-based and performance-based programs are maximized using an objective function given a set budget. Forty different budget levels were specified to trace out supply relationships. The study concluded that the practice-based policy provides high proportions of the benefits (e.g., C sequestration, nitrogen runoff, erosion), relative to the performance-based policy. Targeting any one of the benefits provides a high proportion of the other benefits, compared to amounts obtained by targeting them directly. Although the authors do not attempt to value the cobenefits, their value appears to be substantial.

van Kooten et al. (2002) examined the transaction costs associated with achieving landowner adoption of carbon-positive practices. While many studies have evaluated the cost of afforestation and other forms of terrestrial sequestration, these have generally assumed the transactions to be costless (i.e., the only costs of afforestation would be the opportunity cost to the landowner of the foregone land use and the actual costs of planting the trees). However, *transaction costs*, which include the costs of discovering exchange opportunities, negotiating contracts, and monitoring and enforcing implementation, are real and hence need to be considered in evaluating the feasibility of various sequestration options. Some sources of transaction costs include *search costs* (finding potential suppliers of land/buyers of C offsets and learning about the services they can offer), *bargaining/negotiation costs* (the process of achieving common understanding of the main attributes of the contract and reaching agreement about the obligations of the parties), and costs associated with *monitoring* and *contract enforcement*. A cooperative might be one means by which a group of landowners could reduce the transaction costs associated with afforestation.

The willingness of landowners in Canada's grain belt to engage in C-sequestering practices was assessed through a mail survey (182 usable surveys: <10 percent response). Canadian farmers indicated a greater willingness to create C offsets through changes in tillage activities than from converting cropland to tree production (Table 2).

Survey participants were familiar with (i.e., had participated in) other types of contracts. Respondents indicated they had participated in crop share lease arrangements (62 percent), arrangements restricting cropping practices (9.3 percent), and contracts to prevent crop production (5.5 percent). If respondents were to create/sell carbon credits, they would prefer to enter into tree-planting contracts with a government agency, with their next preference being a contract with a large CO_2 emitter. Selling C credits in a market or contracting with an environmental nongovernmental organization were less preferred options.

Of the respondents, 82 percent would be willing to join a cooperative to sell carbon-offset services. However, 25 percent indicated they would never voluntarily enter an agreement to plant trees in large blocks. The authors speculated that reasons for this reluctance may include landowner hesitation to make long-term commitments, investments in agricultural equipment and facilities, and lack of familiarity with forestry.

Studies Specific to the PCOR Partnership Region

Antle and his associates have reported a series of analyses for the grain-producing region of eastern Montana (Antle et al., 2001, 2002, 2003; Capalbo et al., 2004).

Table 2. Willingness of Canadian Farmers to Engage in C Sequestration Activities, Survey Results, 2002 (van Kooten et al. [2002])

	Percentage of Respondents
Reduce Tillage Operations	60.7
Plant Shelterbelts or Individual Trees	57.8
Reduce Summer Fallow, Increase Crop Intensity	54.1
Replace Summer Fallow with Chemical Fallow	47.4
Plant Fast-Growing Trees (15 yr) in Large Blocks (>40 acres)	23.7
Plant Native Trees (40 yr) in Large Blocks	20.7

Their analytical approach is based on field-level econometric models for winter wheat, spring wheat, and barley, in continuous cropping and summer fallow rotations, as well as permanent grass. These models are incorporated into a simulation model that approximates producer decisions on land allocation and input use in response to policy shocks. The CENTURY (crop ecosystem) model was used to determine the net effect on soil C. The study area is three MLRAs (major land resource areas) in eastern Montana. The database is 1995 survey data from 425 farms and 1200 fields. Three production practices considered are 1) crop fallow, 2) permanent grass, and 3) continuous cropping. Based on the CENTURY model, equilibrium levels of soil C are 1.21 to 2.4 MT per acre less under crop fallow than under permanent grass over a 20-year horizon, and soil C levels are 1.21 to 2.02 MT per acre *less* under permanent grass than under continuous cropping. Thus the implication is that the highest sequestration rates occur when producers switch from crop fallow to continuous cropping. The studies showed that conversion from summer fallow to continuous cropping results in C sequestration at marginal costs of $12 to $140 per MT and average costs not exceeding $50 per MT. The authors reported that these costs are similar to costs estimated for C sequestration associated with changes in agricultural land management in Iowa. They also indicated that costs per MT of C in Montana are competitive with costs associated with afforestation in other regions (Plantinga et al. 1999; Stavins, 1999). In considering these results, it is worth noting that the summer fallow production practice has been substantially replaced by continuous cropping in the plains region. For example, in North Dakota, summer fallow acreage statewide fell from 6.6 million acres in 1986 to 1.7 million in 2002. Also, permanent grass was not economical at the C prices evaluated; however, values of coproducts from permanent grass were not included in the analyses.

A group of Iowa researchers also have reported a series of analyses based on increased adoption of conservation tillage (Pautsch et al., 2001; Kurkalova et al., 2003b; Feng et al., 2004). They use an econometric model, described by Pautsch et al. (2001), which estimates the probability of adopting conservation tillage as a function of net returns to conventional tillage, local soil characteristics, and regional temperature and precipitation variables. Production possibilities include 14 rotations consisting of mixes of corn, soybeans, wheat, sorghum, and hay. A physical process model (EPIC) is used to estimate changes in C sequestration, nitrogen runoff, and soil erosion resulting from adoption of conservation tillage (>70 percent residue cover), rather than conventional tillage (<30 percent residue cover). They estimated that the average cost of sequestering 1 MMT ranges from $207 to $1089 per MT among the state's four regions. Program costs are substantially lower if only new adopters are targeted, and the program's cost-effectiveness increases if payments can be based on the amount of C sequestered, rather than a flat per acre payment to all adopters of no-till systems. Of the study sample, 62 percent of the fields already were being farmed with conservation tillage practices.

Feng et al. (2004) extended the analysis to examine the cost-effectiveness of *working lands* (WL) programs compared to *land retirement* (LR) programs to achieve environmental benefits, specifically C sequestration and reduction in soil erosion. The authors indicated that LR programs, particularly CRP, have dominated agri-environmental programs for the past two decades. However, the 2002 Farm Bill provided additional funding for conservation programs on WL, including the Conservation Security

Program (CSP). The authors examined the C sequestration implications of 1) a WL program providing incentives for adoption of conservation tillage and 2) a LR program (expansion of CRP). They used the modeling framework and NRI database described by Pautsch et al. (2001) and others. Results indicated that the WL program (conservation tillage) is substantially more cost-effective than LR in sequestering C. If a $100 million budget were available for C sequestration, the optimal allocation would be to use 99.6 percent of available resources for WL programs. This allocation of resources would result in sequestering 2.8 MMT of C annually at an average cost of $35.60 per MT.

CONCLUSIONS

The general consensus within the economic literature is that 1) agricultural soils can provide low-cost C sequestration when compared to current abatement costs for nonagricultural industries and 2) the economic potential of agricultural soils to store C is considerably less than the technical potential (Lewandrowski et al., 2004; Pretty et al., 2003; McCarl and Schneider 2000; Marland et al., 1999). Nationally, McCarl and Schneider (2001) estimated the maximum economic potential of C sequestration in agricultural soils to be about 70 MMT annually based on a C value of $500 per MT. The economic potential of agricultural soils to sequester C appears to range from 22 to 78 percent of technical capacity.

Specific Findings

- At $125 per MT of C (a common upper limit placed on C prices in economic studies), agriculturally based C sequestration is likely to offset only 4 to 8 percent of total U.S. 2001 CO_2 emissions.

- At low payment rates (<$25 per MT), land management practices (e.g., switch from conventional tillage to conservation tillage) are the primary sequestration activities.

- At high payment rates ($125 per MT), afforestation becomes the dominant source of additional C sequestration.

- Temporal and regional differences must be accounted for when assessing the economics of C sequestration. Incentive levels sufficient to elicit desired responses from producers in one region do not guarantee similar actions in other regions. Also, not all desired C-sequestering activities are equally adaptable to all production regions in the United States (e.g., afforestation is not practical in the upper Great Plains, no-till systems may not be agronomically feasible with some specialty crops). Additionally, location-specific factors will influence the rate of C sequestration, and studies attempting to evaluate C sequestration on a national scale have used data which are not likely to match specific regions or locations within the United States.

- Switching agricultural land from crop production to permanent grass has not been economically viable in many studies primarily because of the treatment of coproducts. Most studies have attempted to replicate CRP-based restrictions on the management activities allowed on cropland converted to permanent grass. Rules on how CRP lands can be managed historically have been very restrictive, and many economic analyses have maintained those restrictions. In 2002, restrictions on CRP lands were lessened to allow some haying and/or grazing (U.S. Congress, 2002). Adopting strict CRP-based rules for cropland converted to permanent grass has substantially diminished the economic potential of that land use alternative for C sequestration.

Remaining Issues and Future Research Needs

Most economic assessments of soil C sequestration have assumed that producers/landowners are profit maximizers. Further, producers have been assumed to be both willing and able to readily adopt C sequestration activities, providing the net income from those activities is shown to be greater than what can be achieved from alternative activities. However, as has been suggested by McCarl and Schneider (2000) and Marland et al. (1999), a number of issues pertaining to acceptance rates and behavioral impediments to adopting C sequestration activities have yet to be adequately addressed. Research by van Kooten et al. (2002) recently examined some of the above issues; however, that work primarily focused on Canadian producers. A thorough understanding of the issues pertaining to adoption/behavior impediments associated with agricultural C sequestration will require additional research on the following topics:

- Producer risk (production, contractual).
- Financial feasibility (constraints due to cash flow, debt capacity).
- Management requirements.
- Producer and landowner willingness to take on long-term commitments, transfer or continuation of those commitments upon retirement, exodus from farming, or sale of land.
- Property rights and land leasing obstacles between operators and land owners.
- Producer acceptance of contractual obligations (governmental versus private markets).

Most studies have indicated that transaction costs will influence the economics of C sequestration, especially if C incentives stem from a private market-based system. While economists recognize the implications of transaction costs on producer-level decisions to partake in C sequestration activities, estimates of those costs have been mostly absent from the economic literature. Research by van Kooten et al. (2002) discussed transaction costs and the different factors and components that are likely to be included, but the research did not provide estimates of those expenses. Mooney et al. (2004) presented a framework for assessing transaction costs between contracts based on parcel size or carbon units. They conclude that, for any given region in the United States, measurement costs can either increase or decrease as the population sampled increases. One of the reasons for largely omitting transaction costs in the economic literature is that the future mechanism(s) for facilitating C sequestration in the United States remains uncertain (i.e., C sequestration may involve government-sponsored programs or private markets). Also, since few private transactions within the United States have occurred, sufficient data are not readily available to forecast likely future transaction costs. Finally, many technical aspects of a market-based contract for soil C sequestration remain unknown. For example, costs of monitoring and verification remain difficult, if not impossible, to accurately assess since no universally acceptable framework has been developed. Additional insight into how transaction costs may influence C sequestration in agricultural soils would require some quantification of those expenses and some understanding of how those costs may be shared among buyers and sellers in a private market.

The concept of leakage is often discussed in the economic literature. While the implications of leakage are well understood, specifics on how to handle the issue and the costs of enforcement remain relatively scarce. As discussed by Marland et al. (1999), leakage associated with private agricultural and forestlands in the United States could occur from a variety of activities:

- Conversion of private forestland back into agriculture.

- Conversion of preexisting grass and wetlands back into crop production.

- Failure to prevent farmers who do not participate in C practices from reverting to less C-friendly practices or activities.

- A need exists for policy or regulatory provisions to prevent discontinuation of C sequestration practices in the case of land transfer, changing lease arrangements, incentives once C-stock equilibrium is reached, changing technological factors (e.g., biotechnology), and changing global demand for wood and food products, in addition to other potential factors affecting long-term commitments to agriculturally based C sequestration.

Most economic studies of C sequestration on agricultural soils have focused on cropland. Although Campbell et al. (2004) recently examined the economics of adopting C sequestration activities on rangeland in a case study of a single ranch in north central Wyoming and Lewandrowski et al. (2004) and others have included the afforestation of pastureland in their national assessments, producer-level economics of C sequestration on rangeland largely have been omitted from recent literature. The United States has substantial acreage of rangeland (approximately 524 million acres), and the technical potential of rangeland to sequester C has been estimated at 29 to 110 MMT per year (Follett et al., 2001). Despite this potential, little focus has been placed on the economics of C sequestration on grazing lands.

From a national perspective with regard to government policies aimed at C sequestration, Lewandrowski et al. (2004) identified several topic areas for future research:

- Expand the scope of financial incentives provided by a government-based policy to include rangeland and pasture management.

- Expand the scope of incentives to encompass other greenhouse gases (e.g., methane and nitrous oxide).

- The interaction between the agriculture and forestry sectors should be examined more holistically. Some analysts suggest that the potential leakages associated with afforestation of agricultural lands and changes in management of existing forestlands should be more accurately measured. Preliminary analysis of the interaction between afforestation of agricultural lands and forestland management suggests that C emissions would be increased because of changes in timber harvest on existing forestlands. If the potential leakage between the two sectors is not fully understood, it is likely that C sequestration achieved from afforestation of agricultural lands will be overstated.

- A thorough assessment of program costs associated with measuring, monitoring, and verification and contract compliance needs to be performed across a wide array of alternative financial incentives to appropriately determine cost-effective policy provisions. How expensive would various policies be when all the costs are included? Unfortunately, economic studies to this point have not measured institutional costs of the governmental programs that have been modeled.

Economic assessments of soil C sequestration have to this point pertained only to the management and use of private agricultural lands. Little attention has been paid to changes and potential economic trade-offs in the use of public lands to sequester C. No attention has been given to answering how current multiple-use management of public lands would be affected by the addition of C sequestration goals or mandates.

Issues in the PCOR Partnership Region

Many of the national economic issues associated with C sequestration are of relevance and importance to stakeholders in the PCOR Partnership region. The larger C sequestration issues, such as the economic relationships (leakage and competing resource use) between forestry and agriculture and the development of Federal policies to influence soil C sequestration on croplands, are sufficiently broad that specific solutions are likely to be debated at national levels and would require a coordinated approach that includes both consideration of region-specific factors and national strategies.

More specific issues of direct relevance in the PCOR Partnership Region that have yet to be fully explored include the following:

- Economics of C sequestration in wetlands. The PCOR Partnership region has a substantial number of permanent and temporary wetlands in the Prairie Pothole Regions of North Dakota, South Dakota, Minnesota, and the provinces of Manitoba and Saskatchewan, Canada.

- Economics of C sequestration on grazing lands. The PCOR Partnership region has substantial acreage of rangeland and pastureland throughout the Partnership states and provinces.

- Economics of C sequestration on croplands. While several studies have examined various aspects of C sequestration on cropland in the PCOR Partnership region, a number of economic questions still remain unanswered for many crop-producing areas within the Partnership states and provinces. How does the cost of soil C sequestration change as production systems and land productivity vary within the PCOR Partnership region?

- Producer acceptance and behavior impediments to adopting C sequestration activities remain largely undocumented. Questions remain regarding the willingness of producers and landowners to take on long-term commitments, how will carbon contracts or government policies handle the transfer or continuation of those commitments upon retirement or exodus from farming, and what happens to contractual obligations when the land is sold or the land changes tenants?

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