Sensitivity of the Century model for estimating sequestered soil carbon using coarse- and fine-scale map data sources in north central Montana
by Ross Stanley Bricklemyer

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Resources and Environmental Sciences
Montana State University

Abstract:
The use of agricultural best management practices, most notably the adoption of no-till systems, has become a potential technique to sequester (store) carbon in soils and help mitigate the effects of global warming. Efficient sampling designs and the use of process-based soil organic carbon (SOC) dynamics models are potential methods of monitoring and verifying soil carbon change. This research combined field-scale soil sampling and the use of the Century model to explore field-scale SOC variability and the effects of soil texture input data sources (STATSGO and SSURGO databases) on predicted SOC dynamics in north central Montana. Using soil-landscape associations for field stratification and sampling of micro sites for paired management comparisons was an efficient design for measuring SOC (CV = 8-13%). An optimal sampling design of 4 microsites by 2 cores or 3 microsites by 3 cores provided reliable detection of a tillage effect on SOC, given the magnitude of differences (1.3 to 5.1 t C ha^-1) and degree of variability measured. Including the effects of soil clay content as a covariant may provide unbiased estimations of the effects of tillage on SOC among sites, particularly for coarse scale comparisons. The Century model accurately predicted SOC content at five sites using site-specific soils data (10% deviation from measured values). Neither the STATSGO (1:250,000 scale) nor SSURGO (1:24,000 scale) databases adequately predicted soil textures, nor supplied adequate soil textural information for use in the Century model and so introduced potential error to field-specific predictions. Century proved to be sensitive to the effects of clay content when predicting the amount of SOC in a particular field; however the model was insensitive to the effects of soil texture on C sequestration as a result of no-till management. The methods used to measure SOC and the Century model proved to be useful tools for determining carbon stored due to no-till management. Additional research is needed to determine if a consistent relationship exists between soil texture and the effect of tillage on SOC and thus determine if adjustments are needed to the Century model's treatment of soil texture.

SENSITIVITY OF THE CENTURY MODEL FOR ESTIMATING SEQUESTERED SOIL CARBON USING COARSE- AND FINE-SCALE MAP DATA SOURCES IN NORTH CENTRAL MONTANA

by

Ross Stanley Bricklemyer

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2003

APPROVAL

Of a thesis submitted by

Ross Stanley Bricklemyer

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Dr. Perry R. Miller (Signature) 4/21/03 Date

Approved for the Department of Land Resources and Environmental Sciences

Dr. Jeff Jacobsen (Signature) 4/21/03 Date

Approved for the College of Graduate Studies

Dr. Bruce McLeod (Signature) 4-21-03 Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature Ross S. Bi[illegible]

Date 4/21/03

Dedicated to my loving and supportive family

Ross Joseph, Helen Marie, and Scott Arnold Bricklemyer

Thank you for your support and patience.

ACKNOWLEDGMENTS

I would like to thank Dr. Perry R. Miller for the opportunity to conduct this research and for his challenging questions, guidance, and endless patience throughout this experience. Secondly, I wish to thank the other members of my advisory committee, Dr. Keith Paustian, Dr. Thomas Keck, Dr. Gerald Nielsen, and Dr. John Antle for all of their comments, suggestions, expertise, and invaluable advice. Finally, I would like to thank Dr. Brian McConkey for his insightful discussions.

I am grateful for the opportunity to meet and interact with the following cooperating producers: Mr. Lester Johnson, Mr. Steve Keil, Mr. Steve Matheson, Mr. and Mrs. Carl and Janice Mattson, Mr. Bob Mattson, Mr. Hugh Mc Farland, Mr. Steve McIntosh, Mr. Brian Morse, Mr. Mark Peterson, Mr. Ken Romain, and Mr. Glen Stewart. I would like to thank them for their interest and participation in this study. Without their help this study would not have been possible.

I am indebted to Philip Turk for his enduring friendship and support, and his honest statistical guidance. Finally, I would also like to thank Tina Harding and Annie Sisk for their help in sample preparation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The use of agricultural best management practices, most notably the adoption of no-till systems, has become a potential technique to sequester (store) carbon in soils and help mitigate the effects of global warming. Efficient sampling designs and the use of process-based soil organic carbon (SOC) dynamics models are potential methods of monitoring and verifying soil carbon change. This research combined field-scale soil sampling and the use of the Century model to explore field-scale SOC variability and the effects of soil texture input data sources (STATSGO and SSURGO databases) on predicted SOC dynamics in north central Montana. Using soil-landscape associations for field stratification and sampling of microsites for paired management comparisons was an efficient design for measuring SOC (CV = 8-13%). An optimal sampling design of 4 microsites by 2 cores or 3 microsites by 3 cores provided reliable detection of a tillage effect on SOC, given the magnitude of differences (1.3 to 5.1 t C ha^{-1}) and degree of variability measured. Including the effects of soil clay content as a covariant may provide unbiased estimations of the effects of tillage on SOC among sites, particularly for coarse scale comparisons. The Century model accurately predicted SOC content at five sites using site-specific soils data (10% deviation from measured values). Neither the STATSGO (1:250,000 scale) nor SSURGO (1:24,000 scale) databases adequately predicted soil textures, nor supplied adequate soil textural information for use in the Century model and so introduced potential error to field-specific predictions. Century proved to be sensitive to the effects of clay content when predicting the amount of SOC in a particular field; however the model was insensitive to the effects of soil texture on C sequestration as a result of no-till management. The methods used to measure SOC and the Century model proved to be useful tools for determining carbon stored due to no-till management. Additional research is needed to determine if a consistent relationship exists between soil texture and the effect of tillage on SOC and thus determine if adjustments are needed to the Century model's treatment of soil texture.

REVIEW OF LITERATURE

Global Warming

Responding to mounting evidence of increasing atmospheric carbon dioxide (CO_2) concentrations contributing to global warming, the nations of the world have come together in the United Nations Framework Convention on Climate Change to begin reducing atmospheric CO_2 concentrations (UNFCCC, 1994). The desirability of sequestering carbon in terrestrial ecosystems to mitigate global warming has been emphasized by recent political developments, most notably the Kyoto protocol (Masood 1997). If ratified, the Kyoto Protocol would have required the USA to reduce its net carbon dioxide emissions to 7% below 1990 levels (UNFCCC, 1997). When negotiated in 1997, Kyoto recognized direct CO_2 reductions and considered agricultural sinks (i.e. offsets) only provisionally, as a means to meet target CO_2 reductions. In the subsequent Conference of Parties (COP 6.5) in Bonn, Germany (July 2001), political agreement was reached to recognize agricultural sinks as emissions offset and is worded as "application of net-net accounting (net emissions or removals over the commitment period less net removals in the base year) for agricultural activities (cropland management, grazing land management and revegetation)" (COP 6.5: Bonn Agreement). More recently, at the COP 7 meeting in Marrakech, Morocco (November 2001), emission offsets were termed "emission removal units". The Kyoto Protocol has spawned the idea of emission removal credits to offset greenhouse gas emissions which have become a topic of interest in the production agriculture and agroeconomics sectors. The recent decision of the U.S. government to withdraw from the Kyoto Protocol does not exempt the USA. from addressing its CO_2 emission problem. The Bush administration has committed the USA to address the global carbon issue and U.S. policy includes emission reductions and emission removals (i.e. carbon sequestration) as a part of that effort. An 18% reduction in *greenhouse gas intensity,* which is a measure of emissions per unit gross domestic product (GDP), has been set as a target (Pianin 2002). National incentives, such as "green" payments for agricultural management changes and a potential market-based carbon credit trading system are being developed that will likely coincide with the 2008-2012 targeted emission reduction commitment period scheduled in Kyoto.

> "And we will look for ways to increase the amount of carbon stored by America's farms and forests through a strong conservation title in the farm bill. I have asked Secretary Veneman to recommend new targeted incentives for landowners to increase carbon storage."
>
> President George W. Bush - February 14, 2002

Greenhouse Gases

Gases that contribute to the greenhouse effect or the radiative forcing of the atmosphere include water vapor, carbon dioxide (CO_2), nitrous oxide (N_2O), methane(CH_4), ozone (O_3), chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons

(HCFCs). Of these gases, water vapor, CO_2, N_2O, CH_4 and O_3 are naturally occurring, however it is generally accepted that anthropogenic sources of CO_2, N_2O and CH_4 emissions in addition to man-made gases such as CFCs and HCFCs, are resulting in a rapid increase in global temperatures (Levitus et al. 2001). According to a greenhouse gas (GHG) emissions inventory released by the U.S. Environmental Protection Agency (U.S. EPA), CO_2, CH_4, and N_2O comprised 98% of the U.S. greenhouse gases in 1999 (U.S. EPA 2001). Global warming potentials (GWP) of all greenhouse gases are standardized relative to CO_2 and are reported in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.). The GWP of CO_2, CH_4, and N_2O are 1, 23, and 296, respectively, for a 100 yr time period (IPCC 2001). This means that one unit mass of N_2O has 296 times the atmospheric radiative forcing as one unit mass of CO_2. Total U.S. GHG emissions rose from 6,038 Tg CO_2 EQ to 6,746 Tg CO_2 EQ with an annual growth rate of 1.2% from 1990 to 1999. Individually, total CO_2 and N_2O emissions increased from 1990 to 1999, whereas total CH_4 emissions decreased slightly (U.S. EPA 2001).

Role of Agriculture

Greenhouse Gas Emissions

According to the EPA's greenhouse gas emissions inventory, agriculture plays a significant role in greenhouse gas emissions. In 1999, agriculture contributed 488 Tg CO_2 EQ, which is 7.2% of the total GHG emissions in the U.S.A. (U.S. EPA 2001). Most of the agricultural emissions are associated with CH_4 and N_2O. Agriculture has direct and indirect sources of fossil fuel derived CO_2 emissions associated with fuel use, N fertilizer production and lime application (Lal et al. 1999). CO_2 emissions also occur through oxidation of soil organic matter in cultivated soils especially from organic (i.e. peat and muck) soils (Eve et al. 2002a). However, overall agricultural soils were a net sink for CO_2, sequestering 77 Tg CO_2 EQ in 1998 and 1999 (US EPA 2001).

The agriculture industry was responsible for 28% of the U.S. total methane emissions and 69% of U.S. total nitrous oxide emissions (US EPA 2001). Methane emissions were primarily from enteric fermentation and manure management in agriculture. Enteric fermentation is a natural process in ruminant digestion and, therefore the majority of CH_4 emissions are from dairy and beef cattle production. The management of livestock and poultry manure that promotes anaerobic decomposition is not only a significant source of methane; it is also, to a smaller degree, a source of nitrous oxide (US EPA 2001).

The single largest source of N_2O is agricultural soil management. Microbial processes of nitrification and denitrification naturally produce nitrous oxide in soils. The addition of nitrogen through synthetic and organic fertilizer use, manure application, and legume crop production enhances N_2O emissions. Soil management practices that affect the flux of N_2O and other GHGs include irrigation, drainage, tillage, fertilizer application, and fallowing of cropland. No-till management has been reported to emit less NO_2 as compared to more intensively tilled systems when spring thaw conditions on fallow are considered (Lemke et al. 1999). In a controlled split-plot experiment in the Parkland region of Alberta, annual losses of NO_2-N from intensively tilled management ranged from 0.1 to 4.0 kg N ha^{-1} with highest overall losses occurring on fallow ground followed by N fertilizer treatments and pea residues (Lemke et al. 1999).

Soil Organic Carbon

Agriculture plays an important role in U.S. soil carbon dynamics. The U.S. land area in cropland is approximately 170 million hectares or about 19% of the total U.S. land area. The amount of historic soil organic carbon (SOC) lost from the U.S. cropland carbon pool is estimated at 5000 Tg (Bruce et al. 1999). Therefore, there is a potential to sequester, or store, nearly 5000 Tg of carbon from the atmosphere in U.S. cropland alone if soil C levels were rebuilt to original levels. However, the economic potential to sequester C in soil (the amount that could be sequestered at a plausible cost) is lower (45 to 100 Tg yr^{-1}) and is dependant on the market price of carbon relative to the cost associated with implementing carbon sequestering practices (McCarl et al. 2002).

Land sinks have become an emission removal consideration because CO_2 consumed by plants and sequestered in soils is a large part of the global carbon cycle (Lal et al. 1998). The global terrestrial carbon pool (2.1×10^6 Tg C) is approximately three times larger than the atmospheric carbon pool (0.75×10^6 Tg C) (Flach et al. 1997). Photosynthesis by plants converts CO_2 from the atmosphere into carbon-based organic materials (i.e. stems, leaves, grain, roots, etc). The residual plant materials are converted by biophysical reactions to soil organic matter, which is comprised of approximately 58% carbon. Carbon sequestration in agricultural systems is carbon dioxide removed from the atmosphere by plants and stored in soil via biological processes (McConkey et al. 1999). Land management changes have the potential to sequester C and restore soil organic carbon in the soil (Paustian et al. 1997a; Peterson et al. 1998). Management practices that promote carbon sequestration in cropland include reduction of soil tillage and erosion, crop residue management, increased cropping intensity, diversification of crop rotations, and efficient fertilizer management (Campbell et al. 2000a,b; Liang et al. 1999; Lal et al. 1998; Peterson et al. 1998; Potter et al. 1997).

Terrestrial ecosystems might prove to be a net sink for atmospheric carbon, however, the notion of significant reductions in atmospheric CO_2 as a result of agricultural management changes has met some skepticism. Full accounting of CO_2 flux should be considered when estimating annual SOC gains and developing carbon policy. Certain changes in agricultural management increase the amount of SOC but there is a carbon cost associated with all agricultural operations. The carbon cost associated with fuel use, production and application of N fertilizer and lime, irrigation, and application of manure should be discounted from their net contribution to carbon sequestration (Schlesinger 2000). In some cases, the C cost associated with the afore mentioned operations significantly reduces the net storage of C (Schlesinger 2000). Additionally, a full accounting of agriculturally related greenhouse gases should be included in the overall potential of management practices to not only reduce atmospheric carbon dioxide but also to reduce net greenhouse gas emissions (Robertson et al. 2000). Tillage in concert with the practice of summerfallow has been shown to release significant amounts of nitrous oxide as compared to no-till management during the spring thaw in Alberta (Lemke et al. 1999).

Tillage Effects

Tillage promotes soil C losses due to increased erosion and microbial decomposition. Removal of grain and crop residues, and the practice of summerfallow reduces the overall amount of C input. Physical disturbance by tillage breaks down soil aggregates in the surface horizon, thus increasing the potential for soil erosion. Tillage also increases the potential for microbial decomposition rates due to greater bioavailability of organic matter and increasing aeration (Paustian et al. 1997a). After a tillage event, soil microorganisms rapidly metabolize soil organic matter and release CO_2 as a metabolic byproduct (Reicosky 1997). Continued tillage over many years has reduced the overall organic carbon content of soil by 20 to 50 percent (Tiessen et al. 1982; Rasmussen and Parton 1994; Lal et al. 1998).

It is generally accepted that reduction in soil disturbance in production agriculture promotes carbon storage. Not only can the reduction or elimination of tillage increase the amount of organic carbon in soil (Yang and Kay 2001, Paustian et al. 1998; Kern and Johnson 1993), but tillage also influences the distribution of C in the soil profile. In a comparison of chisel plowing versus moldboard plowing, Yang and Kay (2001) found no significant difference in the total amount of SOC in the 0-20 cm depth. However, SOC levels were greater in the 0-10 cm depth and less in the 10-20 cm depth with chisel plowing compared to moldboard plowing whereas the latter had a more evenly distributed SOC content from 0-20 cm. Conservation tillage, including zero till or no-till management (NT) is considered a best management practice that promotes carbon sequestration and increases soil organic carbon in fields that were previously managed with tillage. In 39 paired comparisons of no-till and convention tillage effects on soil C, no-till averaged 8% greater SOC than conventional tillage in the mineral soil (Paustian et al. 1997b). Similarly, organic C concentrations were higher in coarse- and fine-textured soils (13 and 44%, respectively) under stubble mulch as compared to moldboard plowing, respectively. Using the IPCC inventory method of estimating soil C change, conversion from conventional tillage to no-till has been estimated to increase soil organic C at a rate of 0.20 Mg C ha^{-1} yr^{-1} for 20 yr in the mountain region of the United States (includes Montana, Idaho, Colorado, Wyoming, Utah, Arizona and New Mexico) (Eve et al. 2002b). Reviews by Paustian et al. (1997a) and West and Marland (2002) estimated that a conversion to no-till from conventional tillage in the U.S. could increase SOC by 0.3 and 0.34 Mg C ha^{-1} yr^{-1}, respectively, over a 20 yr period. In another review, Follet (2001) estimated that initial C sequestration rates resulting from a change from conventional tillage to no-till could be 0.3 to 0.6 Mg C ha^{-1} yr^{-1} for the U.S. Great Plains and 0.1 to 0.5 Mg C ha^{-1} yr^{-1} for the Canadian prairies. In a modeling study of the Canadian prairies, the Century model estimated C sequestration rates of approximately

0.13 Mg C $ha^{-1}yr^{-1}$ (Smith et al. 2001). The adoption of no-till management carbon across the U.S. has the potential to sequester significant amounts of carbon, 275-763 Tg CO_2 Eq. annually (Lal et al.1999; Bruce et al.1999) which represents approximately 4 to 11% of the U.S. total GHG emissions in 1999. Management changes associated with the adoption of no-till agriculture commonly involve a concert of operational changes that contribute to increased soil carbon. Changes that commonly occur with adoption of no-till systems in semiarid regions are management of crop residues, varying crop rotations, fertilizer application, and increasing cropping intensity (McConkey 1999). Adequate fertilization, coupled with increasing cropping intensity, increases crop residues and thus carbon inputs, a major factor influencing SOC change in no-till systems (Campbell et al. 2001a). Decreasing fallow frequency in concert with fertilized wheat production showed carbon gains whereas unfertilized wheat showed little or no change after 10 to 30 years (Campbell et al. 2000a; Campbell et al. 2001b). The role of fertilizer use and it's contribution to NO2 emissions in agroecosystems is not well understood and is currently being debated (Lemke et al. 1999; Robertson et al.2000). Annual SOC gains due to increased cropping intensity and fertilization in semiarid southwestern Saskatchewan were measured at 0.32 Mg C $ha^{-1}yr^{-1}$ for continuous wheat with nitrogen and phosphorus added (N+P), 0.28 Mg C $ha^{-1}yr^{-1}$ for a wheat-lentil rotation (N+P), and 0.23 Mg C $ha^{-1}yr^{-1}$ for a fallow-fall Rye-wheat rotation (N+P) (Campbell et al. 2000a).

Policies and Incentives for Soil C Sequestration

Agriculture can contribute to greenhouse gas reductions by emission reductions and greenhouse gas removals. Emission reductions do not reduce the present amount GHGs in the atmosphere; rather reductions refer to lowering the amount of GHGs that are released into the atmosphere from agricultural activities such as fossil fuel use, livestock production, and application of fertilizers. It is important to remember that significant levels of GHGs are still emitted even after emission reductions. Greenhouse gas removals actually reduce the present concentration of GHGs in the atmosphere relative to 'business as usual', partially offsetting increases from other sources. Presently, biological sinks, including carbon sequestered in agricultural soils, are the only method of removing greenhouse gases such as CO_2. After a management change, soil carbon will increase until the system reaches a new equilibrium (Fig. 1.1). At this point soil will no longer sequester additional carbon provided that management practices continue unchanged. This is when the issue of *permanence* and the risk associated with maintaining the sequestered carbon stock becomes apparent. Fig. 1.1 models hypothetical gains in SOC due to a change in management. Time, in this schematic represents, 10 to 30 yr. Carbon that has been sequestered in agricultural soils can be a source of CO_2 with a return to the previous conventional management system (Fig. 1.1). To deal with the maintenance risk of the new carbon stock, policy makers must account for treatment of C sequestration liability.

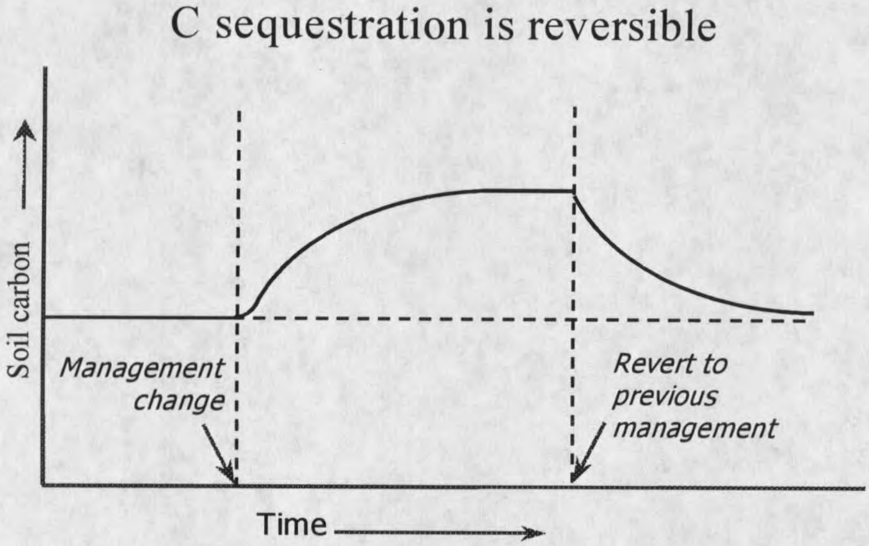

Figure 1.1. General schematic of carbon sequestration dynamics showing management changes in relationship to carbon storage (J. Bennett, pers. comm., 2002; graph adapted from Janzen et al. 1998).

Two scenarios addressing the permanence issue have been proposed. Discussion of the liability issue is easily understood if we present the treatment of sequestered carbon as a commodity or a service, understanding that carbon sequestered in agricultural soils is a service provided by farmers rather than a commodity to be sold. As a commodity (Fig. 1.2), farmers would assume the responsibility of sequestering and maintaining the carbon stock. In the case that the production system should fail, farmers could be forced to repurchase the removal credits defined in the contract. In this scenario, permanence risk is transferred to the farmer. Sequestering carbon as a service (i.e. carbon banking) would minimize the permanence risk to farmers (Fig 1.3). If removal units are treated as an emission storage service and the system should fail, the farmer forfeits only the added value created by the carbon stored (Bennett 2002). Reversion to management previous to no-till is not anticipated once carbon contracts have been fulfilled. If ancillary long-term benefits (in addition to C storage) due to the adoption of best management practices occur, reversion to previous management would be unlikely regardless if C incentives are maintained. Whether carbon sequestration is treated as a commodity or a service, the policy must be efficient for successful implementation.

Designing efficient policies to sequester carbon in cropland is critical if significant amounts of greenhouse gases are to be reduced. There are three general designs that could feasibly be implemented to sequester carbon (Antle and Mooney 2001). Command-and-control policies could be used to force agricultural producers to use specific management practices. This system of regulation would be inefficient due to the heterogeneity of farm management practices and distribution of soil resources. It would not be feasible to prescribe mandatory management practices to individual producers that would fit their specific farm capital and soil resources to grow the crops suitable to their agricultural environment.

C sequestration as a Commodity

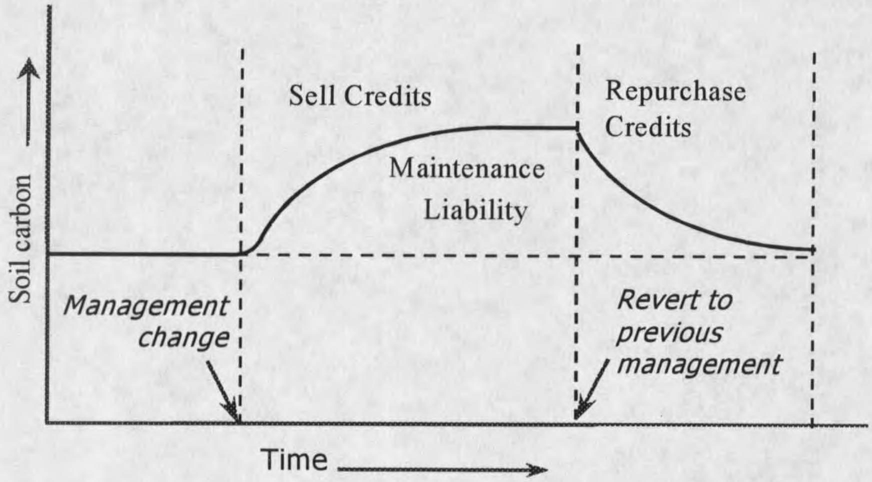

Figure 1.2. General schematic of carbon sequestration loss liability treated as a commodity with the farmer assuming the risk of maintaining the carbon stock (J. Bennett, pers. comm., 2002, graph adapted from Janzen et al. 1998).

C Sequestration as a Service

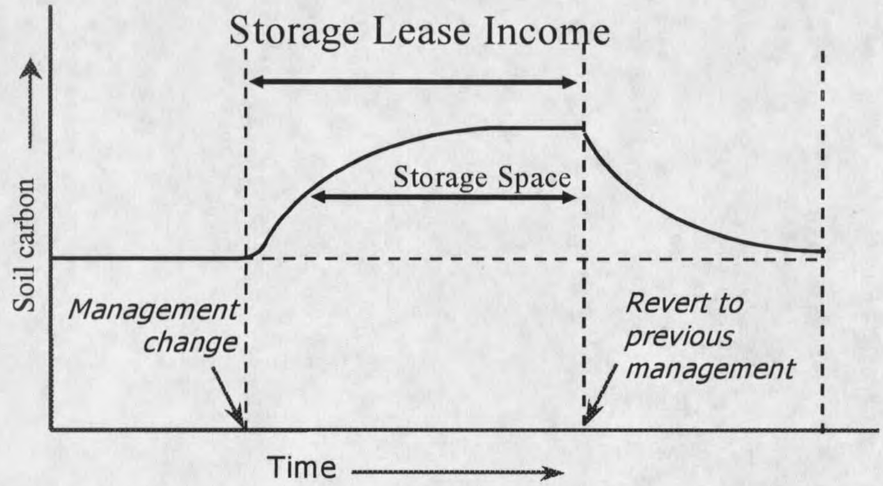

Figure 1.2. General schematic of carbon sequestration loss liability treated as a service with the service buyer assuming the risk of maintaining the carbon stock (J. Bennett, pers. comm., 2002, graph adapted from Janzen et al. 1998).

Secondly, incentive policies could 1) be used to encourage producers to engage in carbon sequestering practices through subsidies and 2) discourage carbon releasing practices using taxes. This method could also be an inefficient policy because it is based on management practices rather than reducing greenhouse gases. Adopting certain practices could reduce atmospheric CO_2 by storing carbon in the soil, however, those same practices may release other, more potent greenhouse gases as a result (i.e. "Leakage"). Some incentive-based policies are already being used to enhance agricultural environmental quality. These volunteer programs, the Conservation Reserve Program (CRP), Wetland Reserve Program (WRP), and Environmental Quality Incentives Program (EQUIP), offer payments and other financial support to farmers who participate.

The third potential policy for sequestering carbon is a market-based system for trading carbon. Economic analysis of carbon sequestration in Montana has shown that increasing SOC would be more efficient if conducted on a market-based "per tonne" of carbon payment rather than a governmental subsidy to producers on a "per acre" basis such as the CRP (Antle et al. 2001; Antle and Mooney 2002). Costs would also vary as a function of the types of management practices used. For example, estimated marginal cost for carbon sequestered on a per acre payment to producers to seed land into permanent grass ranges from \$34 to \$500 t^{-1} C, compared to \$12 to \$150 t^{-1} C in a system that would compensate farmers for adopting a continuous cropping system (Antle et al. 2001, 2002; Antle and Mooney 2002). The theory behind "per tonne" market-based carbon credits is that CO_2 emitters can purchase carbon that is being sequestered