# Sensitivity of Carbon Sequestration Costs to Soil Carbon Rates

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## Abstract

Modifying current agricultural management practices as a means of sequestering carbon has been shown to be a relatively low cost way to offset greenhouse gas emissions. In this paper we examine the sensitivity of the estimates of the amount of soil carbon sequestered and the implied costs of sequestering a tonne of carbon to changes in the rates of soil carbon sequestered for alternative production practices. An application is made to the dryland grain production systems of the U.S. Northern Plains where the marginal costs of soil C range from $20 to $100 per MT. We show that the resulting changes in the marginal costs quantities of C sequestered are not a monotonic transformation of the changes in the soil carbon rates. These results underscore the importance of using a linked economic and biophysical simulation model to assess the economic potential for sequestering carbon in agricultural soils.

**Keywords**: carbon sequestration; soil C rates; marginal cost; integrated assessment approach; wheat

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## I. Introduction

There has been a high level of interest in carbon (C) sequestration as an efficient means for offsetting climate change effects. Several studies provide evidence that by adopting land use and management practices which enhance soil organic matter or by converting agricultural land into forested uses, producers can sequester significant amounts of atmospheric C in soils (Rasmussen and Parton, 1994; Tiessen *et al.,* 1982; Mann, 1986; Lal *et al.,* 1998). The effectiveness of these changes in sequestering C depends on cropping intensity, tillage practices, and biophysical characteristics of cropland. A single land use or management practice will not be effective at sequestering C in all regions. Lal *et al.* (1998) estimate that approximately 49 percent of agricultural C sequestration can be achieved by adopting conservation tillage and residue management, 25 percent by changing cropping practices, 13 percent by land restoration efforts, 7 percent through land use change, and 6 percent by better water management.

These assessments are based on the technical potential for soils to sequester C and ignore the key economic question: would producers be willing to adopt practices that enhance soil C, and if so, at what costs? The economic potential to sequester soil C from changes in agricultural land use has been addressed in a number of studies which have focused on the conversion of cropland to forested uses.(Adams *et al.,* 1993; Parks and Hardie, 1995; Plantinga *et al.,* 1999; and Stavins, 1999). Producers convert land to trees if they are compensated for the agricultural rents of the land. Evidence is provided in these studies that agricultural producers could sequester C through forestation at a cost that is competitive with costs from emissions reductions. Newell and Stavins (2000) examine the sensitivity of the costs of carbon sequestration for conversion to forested uses and conclude that discount rates, agricultural prices and regrowth rates impact these costs .

In earlier work (Antle *et al.*, 2000, 2001) we quantify the costs of sequestering C from changes in land use and management practices *within* the agricultural sector rather than for reforestation of cropland. We examine the relative efficiency of sequestering soil C under alternative payment policies and conclude that the economic efficiency of C sequestration depends on site-specific opportunity costs of changing practices, on the site-specific rates of soil C sequestration, and on the design of the payment policy. Furthermore, in the Northern Plains region of the United States agriculture could sequester C at a cost that is competitive with emissions reductions and afforestation.

In this paper we extend our earlier analysis to examine the sensitivity of the estimates of the cost of sequestering soil C to changes in the rate of soil C sequestration for various production systems. These production systems reflect changes in land use and rotations such as switching from a crop-fallow or permanent grass to a more continuous cropping system. In the absence of on-site monitoring and verification of the changes in soil C, predictions of soil C rates from the ecosystem models are subject to error. Since the economic and ecosystem models are used in an integrated assessment framework, changes in the rates of soil C sequestration translate into changes in the cost of sequestering soil C and changes in the amount of soil C that is sequestered.

Our analytical approach integrates a model of producers' behavioral choices for the land use and management decisions with a crop ecosystem model for determining subsequent changes in soil C levels. The economic and ecosystem models account for the spatial heterogeneity of economic production, land use and C sequestration rates. Our results indicate that the sensitivity of the sequestration costs and corresponding soil carbon levels to changes in carbon sequestration rates depends upon the economic and biophysical conditions in a given region, and is not a monotonic transformation of the changes in the soil carbon rates. These results underscore the importance of using an integrated simulation model to assess the competitiveness of agricultural producers for sequestering soil carbon.

In the next section we describe the assessment framework which integrates the biophysical and economic components for analysis of soil C sequestration costs. In section III we present the simulation results for alternative carbon sequestration rate scenarios and examine the sensitivity of the costs of carbon sequestration and the amount of carbon sequestered in the dryland grain production systems of the northern Great Plains. The results are further discussed in section IV. Finally, section V offers some concluding comments.

## II. Materials and Methods: Integrated Assessment Approach

The integrated assessment approach involves linking two disciplinary models—an economic production model and a crop ecosystem model—to quantify the responses of producers to economic incentives to sequester soil C (Figure 1). The economic production model utilizes economic data on prices and costs of production and yields from the crop ecosystem model to estimate site-specific expected returns to alternative production systems in response to policies that pays producers to change land use or management practices. These expected returns are used to simulate the farmer's choice of production system. The crop ecosystem model (Century) provides estimates of the levels of soil C and productivity (yields) associated with each production system utilizing data on soils and climate. For the analysis in this paper, producers are offered payments to adopt production systems that increase the rate of soil C sequestration. These payment levels are input into the economic production model. The implied marginal cost per tonne of soil C is calculated under a range of alternative payment levels and rates of soil C sequestration.

### *Conceptual Framework for Assessing the Economic Feasibility of Agricultural Soil C Sequestration*

To incorporate the economic dimension into the soil C sequestration analysis, we begin with the assumption that agricultural producers are initially utilizing land use and management practices that yield the highest economic return. It follows that producers will adopt different practices that increase soil C if and only if there is a perceived economic incentive to do so. In this analysis, we consider a per-hectare payment policy which provides incentive payments to producers for each hectare of land that is switched from a cropping system with a relatively low equilibrium level of soil C to a system that produces a higher equilibrium level of soil C. This per-hectare payment mechanism is similar to existing government programs, such as the Conservation Reserve Program, that provide payments on an area basis to agricultural producers that adopt land use or management practices designed to reduce environmental damages or enhance environmental quality.

Assume that agricultural producers have the opportunity to enter into contracts (either with the government or private firms) to provide C sequestration services for a specified time period by adopting specified land use or other management practices. In this analysis we let a contract pay the farmer $g$ dollars per hectare per year for T years to follow specified management practices that sequester an additional $c$ metric tons of C per year. Under reasonable conditions, producers will enter into contracts on land units that pay $g$ dollars per hectare if and only if $\pi_0 < \pi_C + g$, i.e., if the profits per hectare of their profit-maximizing practices, $\pi_0$, are less than the alternative practices plus the C contract payment per hectare, $\pi_C + g$.[1] Let the total amount of agricultural land in a region be $A$ hectares, and let the share of land in a region that is entered into C contracts be $s(g)$. The total amount of land for which C contracts are profitable is $s(g)A$, and this region would sequester $C(g) = cs(g)A$ metric tons of C per year where C is additional metric tons of C sequestered per hectare each year. The region's marginal cost function for sequestering soil C, $M(C)$, can then be defined as the correspondence between $g/c$ and $C(g)$ where $g/c$ is the implicit price per tone of C sequestered. If C is uncertain, then the marginal cost function for sequestering soil C will also be uncertain. Thus, in this paper we examine the sensitivity of the marginal cost function to uncertainty in C.

The condition for entering into a C contract, $\pi_0 < \pi_C + g$, implies that when a producer switches to alternative practices to comply with a C sequestration contract, he or she will earn a lower profit $\pi_C < \pi_0$ (otherwise, the producer would have already been following these practices). This reduction in profitability, $\pi_0 - \pi_C$, is the opportunity cost of entering into the contract. The upward-sloping marginal cost curve for soil C in a region reflects the fact that different land units have different opportunity costs due to the

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[1] This is true under the assumptions of a linear time path for soil C accumulation and static C price expectations, as discussed in Antle *et al.,* 2000.

spatial heterogeneity of soil and climate conditions and other factors affecting land productivity.

### *Impact of Changes in the Soil C Sequestration Rates*

The impact of changes in the soil C sequestration rates on the marginal costs of sequestering C and on the total quantity of C sequestered in a given region can be calculated using the logic of the decision rules embedded in the economic model. With a per hectare policy, the producer's decision to change practices does not depend on the soil C rates and thus the share of land in a given region that switches to the alternative production system is not affected by them. The soil C rates do however impact the total quantity of soil C that is sequestered in the region and the marginal cost per tonne of C sequestered.

Let the total increase in soil C over the period t = 0 to T be $\Delta c = c_T - c_0$, the average increase is $\Delta c/T = c$ (metric tons per hectare per year). If, however, the total increase in soil C over the time period t = 0 to T is actually $b$ times an estimate, $b > 0$, the average increase in soil C is $b\Delta c/T = bc$ (tonnes per hectare per year). The total amount of land for which C contracts are profitable remains $s(g)A$, however this region would sequester $bC(g) = bcs(g)A$ metric tons of C per year. The region's marginal cost function for sequestering soil C, $M(C)$, can then be defined as the correspondence between $g/bc$ and $bC(g)$. Thus for any $b >$ (<) 1, a given per hectare payment level $g$ will result in a lower (higher) marginal cost per tonne of soil C sequestered and a greater (lower) quantity of soil C relative to the base case where $b = 1$.

Alternatively, one can view this from the perspective of a given marginal cost per tonne and ask how the total quantities of soil C sequestered in a region will change. We can rewrite the marginal cost correspondence between $g/bc$ and $bC(g)$ equivalently as a correspondence between $g/c$ and $b^2C(g)$. This implies that under the per hectare payment policy, the marginal cost function shifts by a factor of $b^2$ in response to a measurement change of $b$ in the soil C rates. If $b > 1$, which implies that the soil C rates were underestimated, the new marginal cost curve will be displaced downward by an amount greater than *b* or alternatively for a given marginal cost per tonne, the level of carbon sequestered in a given region increases by more than *b*. Conversely, if $b < 1$, the new marginal cost curve will increase relative to the initial marginal cost, and the quantity of carbon sequestered in a given region will fall but by less than *b*. These results underscore the importance of using a linked economic and biophysical simulation model to evaluate the sensitivity of the costs of sequestering soil C to changes in soil C rates.

### *Simulation Models for Land Use, Soil C levels, and Costs*

Producers' land use decisions are simulated using an economic simulation model known as an econometric-process model. This type of model was developed to simulate land use and management decisions on a site-specific basis to assess the economic and environmental impacts of changes in agricultural production systems induced by changes in agricultural technology, policy, and changes in biophysical conditions (Antle *et al.,* 2001; Antle and Capalbo, 2001). Site-specific data are used to estimate econometric production models, and these data and models are then incorporated into a simulation model that represents the decision making process of the farmer in a way that is consistent with economic theory and with site-specific biophysical constraints and processes.

In the current application, the econometric production models were estimated using cross-sectional data from a sample of 425 farms and over 1200 fields that are statistically representative of the USDA's Major Land Resource Areas (MLRA) in the grain-producing regions of Montana (see Figure 2). The three MLRAs considered in this study are 52, 53a, and 58a. MLRA 52 is considered to be the most productive grain producing area in the state, hence its nickname of the "golden triangle" area. The three MLRAs were stratified into six zones or regions (sub-MLRAs) based on high or low precipitation according to historical climate data. Log-linear production models consisting of a crop supply and a variable cost function were estimated using nonlinear three stage least squares, for winter wheat, spring wheat, and barley. Data, descriptions of the MLRAs, and summary statistics are described in Johnson *et al.* (1997) and Antle *et al.* (1999), and the parameter estimates for the supply and cost equations are discussed in Antle and Capalbo (2000).

Producers allocate roughly half of cropped land to a crop-fallow system and half to continuous cropping. The econometric analysis shows that, in a given year, where the crop is grown, the crop-fallow system provides higher yields and lower average variable costs of production, and thus higher returns per hectare on average relative to the continuous cropping system. However, these higher returns must be traded off against the opportunity cost of a forgone season of returns while the field is fallowed and thus yields are zero. As a result the two cropping systems compete closely in terms of net returns averaged over a two-year period.

The econometric-process simulation model uses the estimated production models to simulate the farmer's discrete choice among production systems, and the related output and cost of production for that choice, at the field scale, over space and time. By operating at the field scale with site-specific data, the simulation can represent spatial and temporal differences in land use and management, such as crop rotations, that give rise to different economic outcomes across space and time in the region. Moreover, because of the detailed representation of the production system, the econometric-process model can be linked directly to the corresponding simulations of the crop ecosystem model to estimate the impacts of production system choice on soil C.

Each field in the sample is described by area, location, and a set of location-specific prices paid and received by producers, and quantities of inputs. Using sample distributions estimated from the data, draws are made with respect to expected output prices, input prices, and any other site-specific management factors (e.g., previous land use). The econometric production models are simulated to estimate expected output, costs of production, and expected returns. The land use decision for each site is made by comparing expected returns for each production activity. These spatially and temporally explicit land use decisions are combined with simulated outputs of the crop ecosystem model to assess changes in levels of soil C.

The crop ecosystem model known as Century is utilized to represent the processes controlling crop growth, water, nutrient, and organic matter dynamics that determine the productivity of agricultural ecosystems (Parton *et al.,* 1994; Paustian *et al.,* 1999). Century simulates C (i.e., biomass), nitrogen and other nutrient dynamics and includes submodels for soil biogeochemistry, growth and yield submodels for crop, grass, forest and savanna vegetation, and simple water and heat balance. For use in agricultural ecosystems, the model incorporates a large suite of management options including crop type and rotation, fertilization, tillage, irrigation, drainage, manuring, grazing, and burning. The model employs a monthly time step and the main input requirements (in addition to management variables) include monthly precipitation and temperature, soil physical properties (e.g., texture, soil depth) and atmospheric nitrogen.

Soils and climate data for each of the sub-MLRAs are used as Century model inputs in addition to management variables such as crop type and rotation, fertilization and tillage practices.[2] Baseline projections of soil C are made using historical climate and land use records. These projections are compared to USDA National Agricultural Statistics Service records of county-level crop yields and changes in soil C derived from the Century database of native and cultivated soils. The land use allocation from the 1995 Montana production survey was used to calculate base C levels for each sub-MLRA.

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[2] The Parameter_elevation Regressions on Independent Slopes Model (PRISM) data set was used to determine weather-related data. Information on current management systems from the field-scale survey of Montana producers, is augmented with the USDA National Agricultural Statistics Service (NASS) database, the National Resources Inventory (NRI) database, and county_level databases of the National Association of Conservation Districts (NACD). Soil characteristics are determined using the Advanced Very High Resolution Radiometer (AVHRR) database (USGS_Earth Resources Observation System (EROS) Data Center), the State Soil Geographic Database (STATSGO) and the NRI database.

The variability in the levels of soil C predicted by the Century model for a twenty year horizon is shown in Figure 3. Simulations of the crop-fallow, continuous cropping, and permanent grass production systems show that the equilibrium levels of soil C under a crop-fallow rotation are about 3–6 MT per hectare less than continuous grass over a twenty year horizon, and that soil C levels under permanent grass are 3–5 MT per hectare less than under continuous cropping. The variability across sub-MLRAs reflects the heterogeneity in biophysical and climatic conditions, which translates into differences levels of soil C for the production systems.

The economic simulation model selects the land use that maximizes expected returns for each sample field for each policy scenario that is investigated. The economic simulation is executed over a time horizon sufficient to reach an equilibrium for each per hectare payment level $g$. The land use patterns are then summarized for each sub-MLRA for each policy setting in the form of proportions $\boldsymbol{s}_i(g)$ of land allocated to the i$^{th}$ use. The Century model is used to simulate the soil C levels and flows for each land use in each sub-MLRA over a given time horizon. For a range of payments, we simulate the changes in land use within each sub-MLRA based on maximizing expected returns, and calculate the levels of soil C sequestered and the resulting C sequestration costs using the procedures discussed earlier.

## III. Results

We now present the empirical results for simulating the econometric process model and the Century ecosystem model for changes in land use, changes in soil C levels, and the costs of sequestering soil C under a per hectare payment policy. The per hectare payment policy provides payments for switching from a crop-fallow or permanent grass system to a continuous cropping system. Producers are offered payments that range from a low of $5 per hectare per year and increase by $5 increments to $50 per hectare per year.

Three soil C rate scenarios are considered: a base scenario (*b* = 1) which uses the soil C rates shown in Figure 3; scenario 1 which increases the soil C rates by a factor of 50 *percent* in all sub-MLRAs and for all cropping systems ( *b* = 1.5); and scenario 2 which decreases the soil C rates by a factor of 50 *percent* in all sub-MLRAs and for all cropping systems ( *b* = 0.5). For each of these scenarios, the simulation model described above is run and the results used to derive a marginal cost curve for soil C sequestration, in which the marginal costs per tonne of soil C are plotted against the quantities of carbon sequestered in each sub-MLRA over a twenty year period.

### ***Base Scenario (b = 1) Results***

When payments are set equal to zero (*g=0)* the simulation generates base estimates of the land use and soil C levels in each sub-MLRA . The economic simulation model was executed for each field in the data set using observed conditions for land use, and prices set at mean levels to reflect long-run averages over the past decade. The land use alternatives simulated in the model were winter wheat, spring wheat, and barley in either a continuous cropping or a crop-fallow rotation, and permanent grass. The initial land use patterns indicate that permanent grass is a more attractive alternative relative to continuous cropping in sub-MLRAs 58a-high, 58a-low, and 53a-high. These areas in the eastern and southeastern part of the state have lower levels of moisture relative to the more productive areas sub-MLRAs 52-high and 52-low. In these latter two areas, continuous cropping accounts for approximately 50 percent more land acreage than permanent grass.

Figure 4 shows the simulated changes in land use shares for each sub-MLRA as payment levels increase. All sub-MLRAs exhibit a similar pattern of land use change under the per hectare policy, reflecting the fact that the opportunity cost of switching from crop-fallow or grass to a continuous cropping system is fairly similar. The effects of these changes in land use on the levels of soil C are shown in Figure 5. The amount of soil C sequestered varies depending upon the land area, land use, and the relative productivity of each cropping system to sequester soil C. The largest change in soil C sequestered in response to changes in payment levels occurs within sub-MLRAs 52-high and 52-low, which comprise an average of 50 percent more acreage than the other areas. The increases in soil C become smaller as payment levels increase, reflecting the diminishing rates of land use change shown in Figure 3. Under the highest payment level, the average amount of carbon sequestered in each sub-MLRA range from 0.8 to 1.1 tonnes/hectare. Over the six sub-MLRAs considered, the total C sequestered ranges from 4.8 MMT to 17.7 MMT over the twenty-year period.

The simulated marginal cost curves embody the combined effects of land use changes, soil C productivity differences, and differences in the payment levels. These are shown in Figure 6 for the sub-MLRAs: 52-high, 53a-high, and 58a-high. The relative homogeneity of land use patterns shown in Figure 4 means that the observed differences in the marginal costs of C sequestration under the base scenario across the three sub-MLRAs are explained largely by the spatial differences in the productivity of the soils to produce soil C and by the size of the sub-MLRA. The patterns of land use change imply that initially the marginal cost curves are inelastic; above \$100 per tonne, these marginal cost curves become very inelastic in response to the limitations on the quantity of soil C that can be sequestered when all acreage is in continuous cropping.

### ***Results for Scenarios 1 and 2 for Selected Sub-MLRAs***

The marginal cost curves for soil C for scenario 1($b = 1.5$) and scenario 2 ($b = 0.5$) for three sub-MLRAs are also shown in Figure 6. Policy payments in excess of \$50 per hectare do not add appreciably more soil C since the share of land in the alternative production system at the highest payment considered in this analysis accounts for nearly all of the cropland. In sub-MLRA 52-high, the \$50 per hectare policy payments ($g = \$50$) translate into a marginal cost for soil C of approximately \$90 per tonne under the base scenario, and \$60 per tonne and \$180 per tonne under scenarios 1 and 2, respectively.

The corresponding quantities of soil C sequestered in sub-MLRA 52-high are 4.3 MMT, 6.6MMT and 2.2 MMT for these three scenarios over the 20-year period.

In sub-MLRA 53a-high, the soil C rates are on average less than the rates in sub-MLRA 52-high and 58a-high and the total land in crops is less. Furthermore, the gains in soil C resulting from a switch from permanent grass to continuous cropping are small as indicated in Figure 3 and the opportunity cost is high. As a result, the simulated marginal cost for each payment level is greater than the other sub-MLRAs and the quantity of soil C sequestered is less. In sub-MLRA 58a-high, the pattern of changes in soil C rates across cropping systems is similar to sub-MLRA 52-high and the implied marginal costs are in a similar range. The corresponding quantities of soil C sequestered in sub-MLRA 58a-high are lower due in part to the lower acreage in this region.

In a market for carbon trading, the attractiveness of US agricultural producers as suppliers of carbon credits hinges on the marginal costs and the quantities of soil C that can be sequestered. The marginal costs shown in Figure 6 can be used to infer informaiton about the quantities of soil C that would be sequestered, or the number of C credits that would be sold, at alternative market prices for carbon. At a marginal cost of approximately $50 per tonne of soil C, the quantity of soil C sequestered over 20 years in sub-MLRA 52-high varies from just under 3.0 MMT in the base scenario to over 6.0 MMT when 50 percent higher soil C rates are used (Scenario 1) to under 1.0 MMT when the soil C rates are 50 percent lower than the base (Scenario 2). In sub-MLRA 53a-high, our analysis predicts that producers would not participate in a C market if the price per tonne was $50 per tonne under the base scenario and scenario 2, and thus the variations in the amount of soil C that would be sequestered at this price ranges from zero to 1.0 MMT over the twenty year period. In sub-MLRA 58a-high, a 50 percent increase in soil C rates results in the amount of carbon sequestered at a price of $50 per tonne to more than double relative to the base scenario, while a comparable percentage decrease in estimates of soil C rates results in no participation of producers and zero levels of soil C.

## IV. Discussion

Previous studies of C sequestration have considered the conversion of agricultural land to forests, or changes in the management and land use patterns within the agricultural production systems. In this paper we have examined the sensitivity of the carbon sequestration costs to changes in a key factor, soil C rates, using an integrated assessment approach to simulation modeling. Our analysis of dryland grain production systems in the Northern Plains shows how land use responds to policy payment incentives and induces changes in soil C. This economic response combined with data on soil C levels allows for derivation of the marginal cost of sequestering soil C. The analysis shows that a policy that provides payments to adopt continuous cropping were found to produce increases in soil C at a marginal cost ranging from \$12 to \$140 per MT of C even in the less productive regions of the northern Great Plains. For this policy, the average costs do not exceed \$50 per MT of C. These estimates are in the range of the costs reported for Iowa agriculture. A comparison of the costs and carbon potential in Iowa and Montana is made in Antle, Capalbo, and Mooney (2001).

Our analysis shows that soil C sequestered by grain producers in the northern Great Plains region could be competitive with C sequestered from afforestation or through industrial emissions reductions. A recent study of afforestation in Maine, South Carolina, and Wisconsin indicates that the average cost estimates are in the range of \$45–\$60 per MT of C (Plantinga, Mauldin, and Miller, 1999). A study by Stavins (1999) estimates that the average cost per MT of C sequestered through afforestation to be in the range of \$38 for the Delta states to approximately \$70 for the United States.

Changing the soil C rates used in the simulation model changes the quantity of soil C sequestered per unit of land placed in the program, and changes the marginal cost per tonne of soil C. As the soil C rates increase, the impact on the quantity of carbon sequestered at each marginal cost increases in proportion to the square of the increase in soil C rates. Thus in a setting where carbon trading markets are being explored as a basis for sequestering soil C in order to meet international agreements for mitigation of greenhouse gases (GHG) emissions, or where policy makers are concerned with the amount of government outlays for sequestering soil C, the accuracy of estimates of soil C rate information plays a critical role. Our analysis shows that the competitiveness of the agricultural sector as a mitigator of GHG or a carbon sink, and the estimates of the total amount of C that could be sequestered, are highly dependent upon the rates of soil C. This argues for better measurement of soil C rates as well as greater attention being paid to the use of frameworks that reflect integrated economic and biophysical models.

## V. Conclusions

The focus of this study has been on methods to address the sensitivity of estimates of the marginal costs of sequestering a tonne of soil C to changes in biophysical estimates of rates of soil C that can be sequestered by changing management practice. What is evident from this analysis is that (i) measures of marginal costs of sequestering soil C are based upon integrating a biophysical model of the physical potential to sequester soil C with an economic model that captures the behavior of producers with respect to changes in land use; and (ii) the marginal costs are affected by biological and economic parameters, both of which are measured with some degree of uncertainty.

The results in this paper are derived using a per hectare payment policy as the incentive mechanism for producers to switch to production practices that sequesters higher levels of soil C. A future research area would involve exploring the sensitivity of both policy design and soil C rates to estimates of the costs of sequestering C and quantities of C sequestered.

Finally, it is important to note that agriculture is both a sink for C as well as a major emitter of $CO_2$ and two other potent GHG, nitrous oxide and methane (McCarl and Schneider, 2000; Robertson, Paul, and Harwood, 2000). Both methane and nitrous oxide are also likely to be influenced by land use and other management practices. Thus an area for future research would be to account for the total mixture of emission and sequestration fluxes of GHG caused by a farmer's altered land use and management practices. This extension poses formidable measurement problems because methods and models to quantify nitrous oxide and methane emissions are, to date, not as well developed as those for C.

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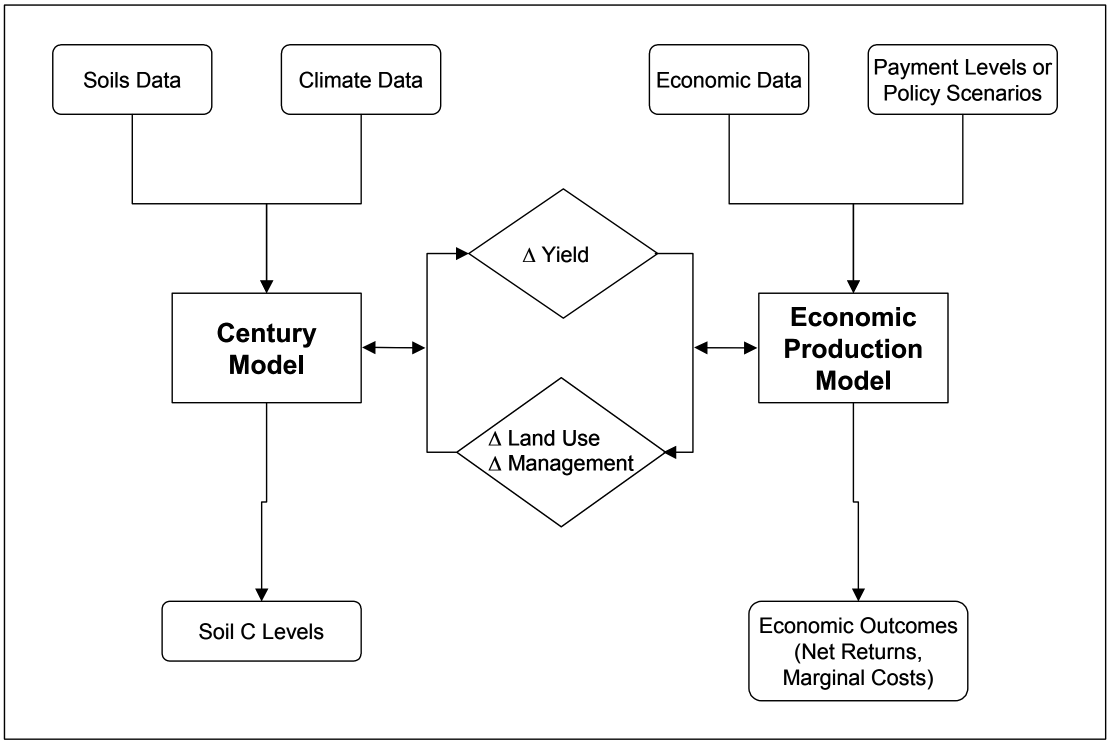


**Figure 1. Linkage between Century Model and Economic Production Model**

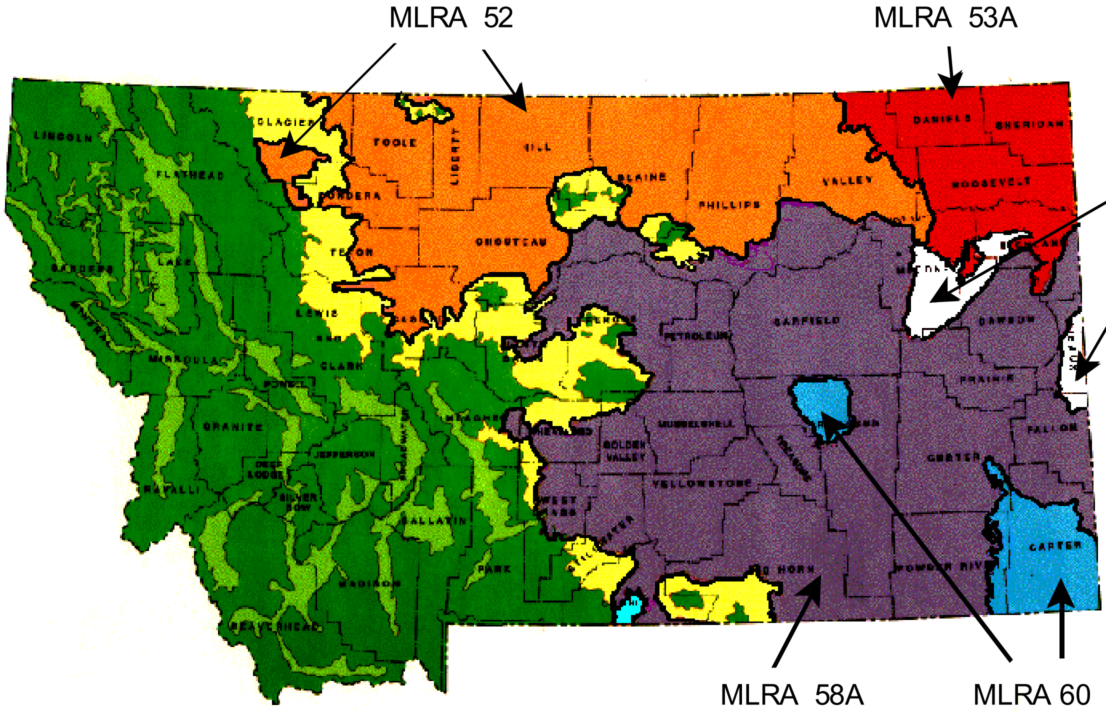
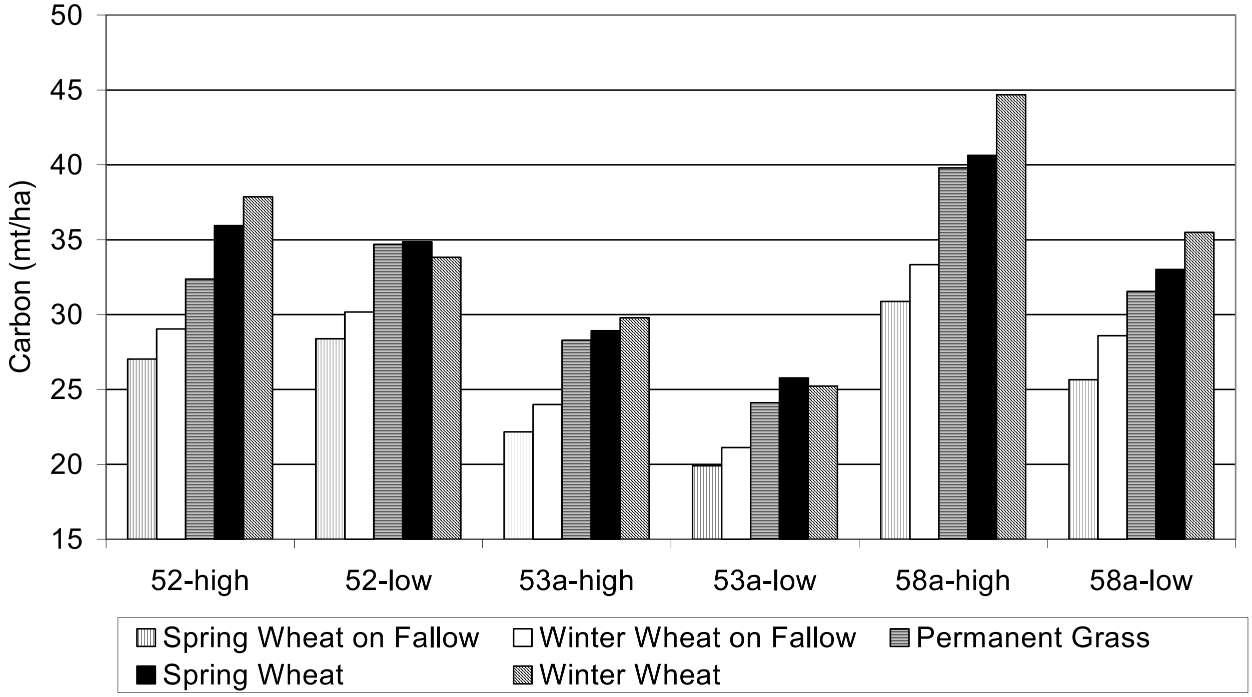


**Figure 2. Major Land Resource Areas in Central and Eastern Montana**



Note: Soil C levels for barley are the same as spring wheat.

**Figure 3. Soil C Levels Predicted by Century Model for Cropping Systems in Montana**

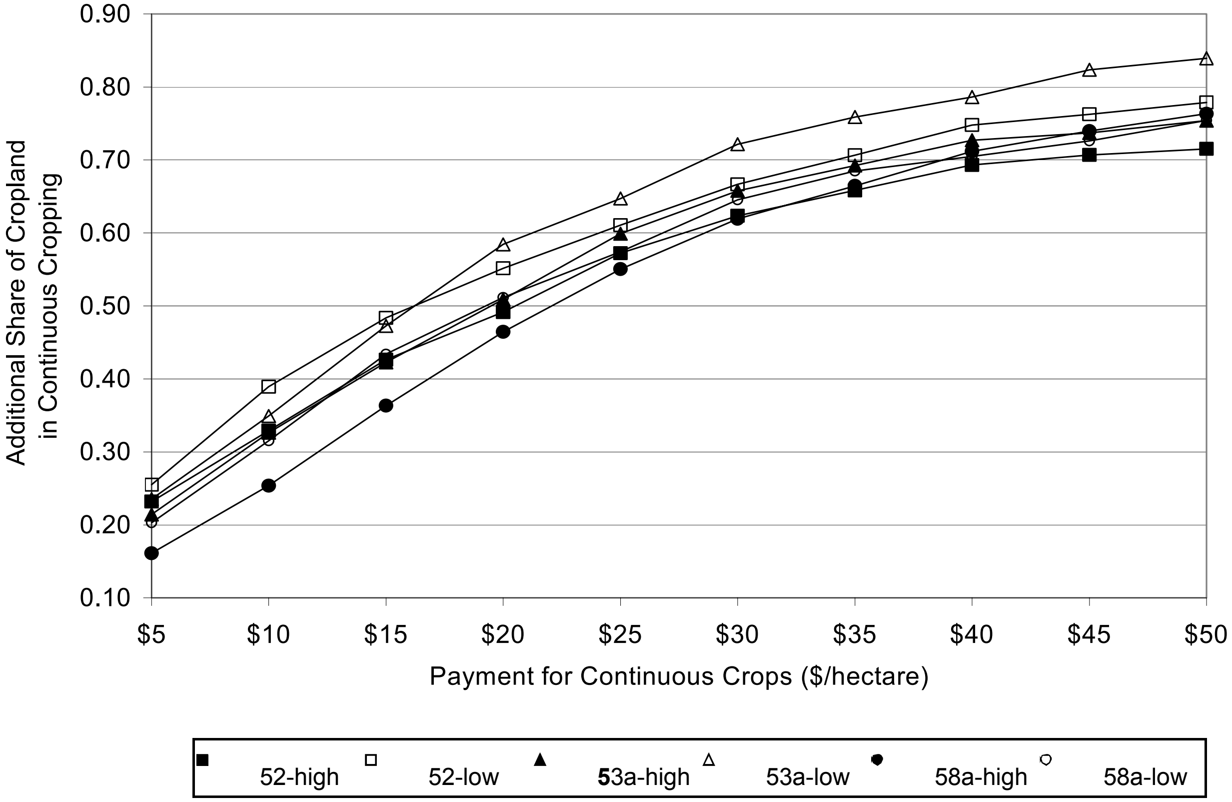


**Figure 4. Additions to the Share of Cropland in Continuous Cropping by Sub-MLRA: Base Scenario**

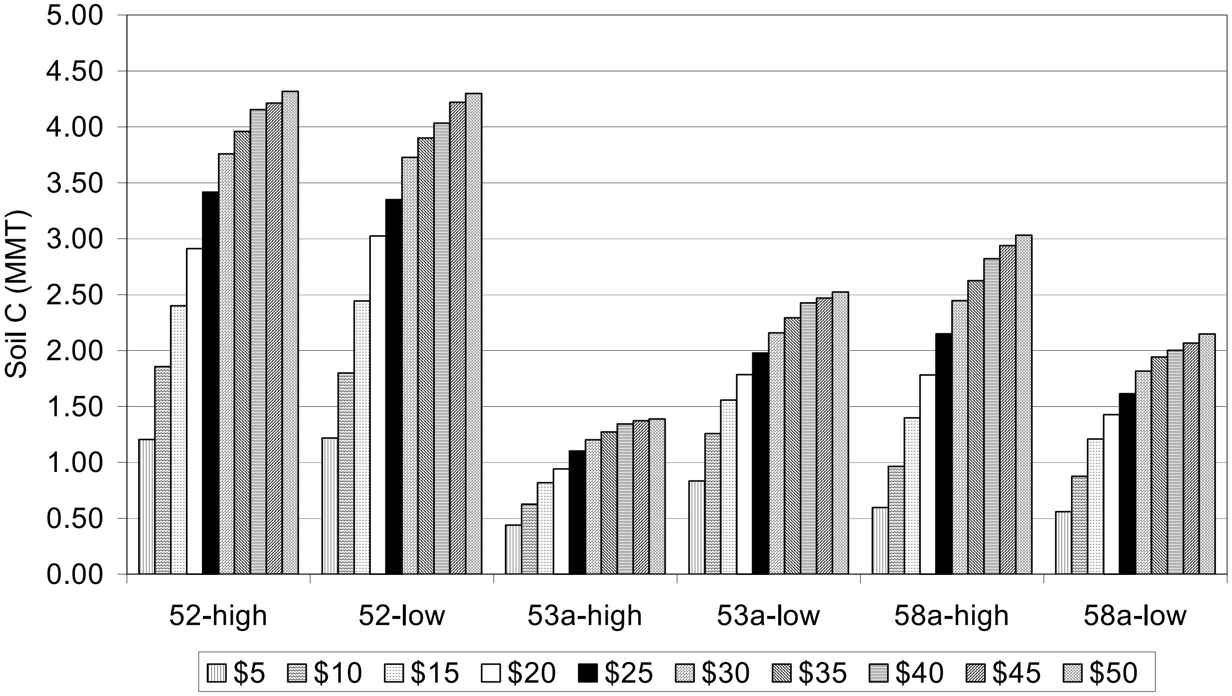
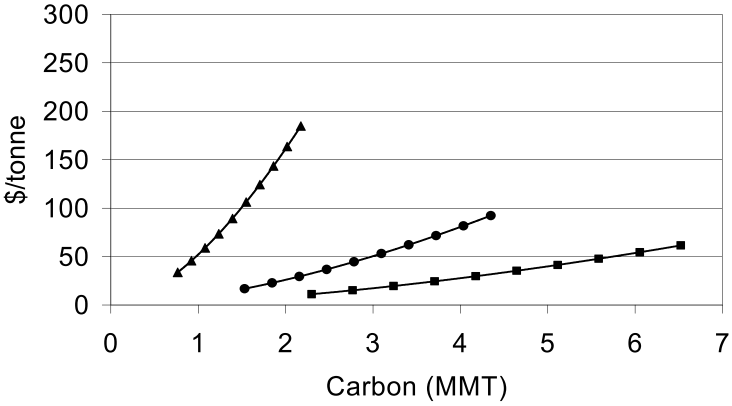
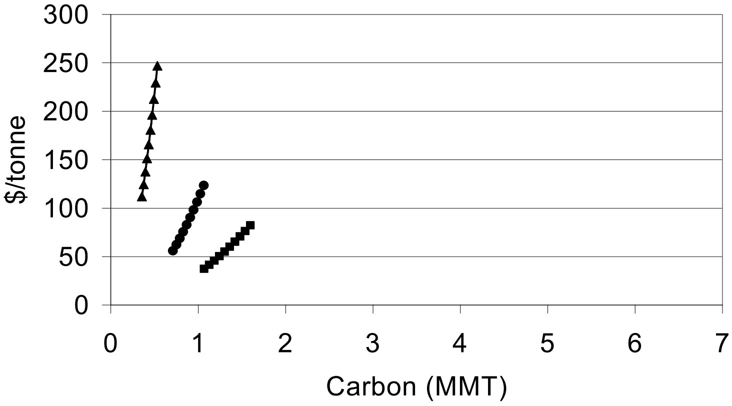


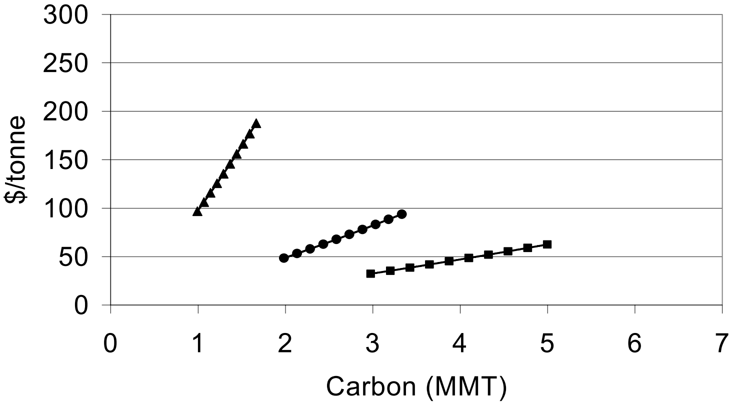
**Figure 5. Changes in Soil C over a Twenty-Year Time Horizon by Sub-MLRA: Base Scenario**



**a. MLRA 52-High**



**b. MLRA 53a-High**



**c. MLRA 58a-High**

▲ Scenario 2: Soil C rates are 50% of base scenario
● Base Scenario (b = 1.0)
■ Scenario 1: Soil C rates are 150% of base scenario

**Figure 6. Marginal Costs for Soil C for Selected Sub-MLRAs: All Scenarios**