Sensitivity of Carbon Sequestration Costs to Economic and Biological Uncertainties

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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 costs of sequestering carbon to uncertainties in the underlying economic and biological parameters of the modeling framework and to scale of analysis. An application is made to the dryland grain production systems of the US Northern Plains under a per-hectare payment policy. We show that the resulting changes in the marginal costs and corresponding quantities of soil carbon sequestered are a nonlinear function of the changes in the soil carbon rates, yields, or economic parameters, and depend upon the spatial heterogeneity of the area. The analysis of changes in yields supports the argument that sequestering soil C could be a long-term win-win situation for producers and society. In the short run, providing incentives to producers to switch production practices in order to sequester soil C could lead to higher productivity in the long run that would induce farmers to maintain these practices without incentives.

Keywords: carbon (C) sequestration; soil C rates; marginal cost of soil C; integrated assessment approach; economic and biophysical uncertainties; scale

Sensitivity of Carbon Sequestration Costs to Economic and Biophysical Uncertainties

In 2002, the Bush Administration announced a plan to decrease the growth of greenhouse gas emissions per unit of economic activity (White House 2002). Along with this program is a mandate for the Secretary of Agriculture to enhance the amount of soil carbon that is sequestered in agricultural soils. Several studies provide evidence that by adopting land use and management practices that 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 and others 1982, Mann 1986, Lal and others 1998). The effectiveness of these changes in sequestering C depends on cropping intensity, tillage practices, and biophysical characteristics of cropland. Lal and others (1998) estimate that approximately 49% of agricultural C sequestration can be achieved by adopting conservation tillage and residue management, 25% by changing cropping practices, 13% by land restoration efforts, 7% through land use change, and 6% by better water management.

These assessments are based on the technical potential for soils to sequester C. An important component of designing programs and policies to sequester soil carbon is to incorporate the economic dimension and ask the key 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 that have focused on the conversion of cropland to forested uses (Adams and others 1993, Parks and Hardie 1995, Plantinga and others 1999, 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 and others 2000, 2003), we quantified the costs of sequestering C from changes in land use and management practices *within* the agricultural sector rather than for reforestation of cropland. We examined 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.

Estimates of the soil C rates and the costs to farmers of changing practices play an important role in the design of government programs or private contracts to sequester soil C, and also play an important role in both buyers' (either government agencies or private entities) and farmers' decisions to enter into contracts. In an earlier study, we examined 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 (Antle and others 2002). We showed that to estimate these costs, soil C rates estimated from an ecosystem model are used in an economic model. Errors from estimates of soil C rates enter non-linearly into the economic model, causing those errors to be magnified. In this paper, we extend this type of sensitivity analysis to consider the impacts of uncertainties in both biophysical and economic parameters and the impacts of spatial scale. The biophysical parameters include soil carbon rates and crop yields, while the economic parameters are the prices for the outputs of the agricultural products being produced. In addition, we consider the impacts of spatial scale by comparing results from an average regional rate of soil carbon accumulation for each production system to results from using carbon rates that are specific to agro-ecozones and production systems.

The paper begins with a description of the assessment framework that integrates the biophysical and economic components for analysis of soil C sequestration costs. Next, 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 to uncertainties in key biophysical and economic parameters, to changes in soil C rates, and to scale of analysis. Finally, we summarize our results and offer some concluding comments.

Integrated Assessment Approach to Modeling Soil C Sequestration Costs

The integrated assessment approach involves linking the output of 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 model estimates 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 provides estimates of the levels of soil C and productivity (yields) associated with each production system. Producers are offered per-hectare payments to adopt production systems that increase the rate of soil C sequestration. 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 to 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. The key implication of this assumption is that there is a farm-level opportunity cost to farmers when they adopt alternative practices that sequester soil C, and farmers will therefore adopt these alternative practices only if there is a perceived economic benefit. In this analysis, this economic benefit comes from a per-hectare payment 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. Alternative policies or contract designs, such as ones that would pay farmers per tonne of carbon sequestered, could also be used (see Antle and others 2003).

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, π_0, are less than the alternative practices plus the C contract payment per hectare, $\pi_C + g$. It is noted that this is true under the assumptions that contracts use a constant rate of soil C accumulation and that farmers have static C price expectations, as discussed in Antle and others (2000).

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. 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.

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

The marginal cost curve for soil C will shift in response to parameters and biological and economic variables that impact the opportunity cost of supplying a tonne of soil C. These include factors that affect both π_0 and π_C such as output prices, yields of alternative production systems, and soil C rates. Errors in these parameters will be translated into errors in estimates of the cost of sequestering soil C and in estimates of the quantities of soil C that can be sequestered. Likewise, this will translate into errors in predicting economic benefits of soil C sequestration for farmers and their participation in soil C contracts.

Crop Productivity Dynamics: Could Soil C Sequestration be a "Win-Win"?

Lal and others (1998) argue that soil C sequestration can be a "win-win" for agriculture, producing benefits for farmers in terms of enhanced productivity, and for society in the form of enhanced environmental benefits (including greenhouse gas mitigation and improved off-farm water quality). If it is true that farmers obtain higher productivity and profitability from the carbon-enhancing practices, then the opportunity cost of the alternative practices is zero or negative – there is a benefit, not a cost, from adoption. Why wouldn't farmers voluntarily adopt such practices? First, we know that the productivity only comes with a time lag – perhaps as long as 5 to 10 years – as soil C is accumulated. Second, farmers may perceive significant uncertainty about the yield gains. Therefore, it is possible that farmers may perceive the economic value of adopting soil C-enhancing practices to be less than their current practices, even though in the longer run they might find the economic value to be positive once they do adopt them. Thus, if farmers perceive that there is a short-run cost to adopting the alternative practices, it may be necessary to provide them a short-run incentive for adoption, even though in the long run they may be willing to maintain these practices ones they have realized that there is a net gain in productivity and profitability.

Impact of Changes in the Soil C Sequestration Rates, Output Prices, and Yields

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 different soil C rates. 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.

If the total increase in soil C over the time period $t = 0$ to T is actually b times the estimate Δc, for $b > 0$, 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 initially 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.

The scale of analysis is an important consideration in policies designed to encourage soil C sequestration for two reasons: estimates of quantities of soil carbon must be verifiable to support contracts between producers and the government or private entities, and the costs of collecting disaggregate physical and economic data over large spatial regions are high (Antle and others 1999b). Therefore, the question of whether the benefits of more disaggregate information exceed the costs becomes relevant to agencies responsible for implementing these programs. In this paper, we address the scale issue in the biophysical dimension by estimating the impacts on the marginal cost curves for soil C when the site-specific soil C rates are replaced by average soil C rates. The differences in the marginal cost curves provides an estimate of the magnitude of the errors that would be made from estimating soil benefits from more disaggregate analysis.

The integrated assessment framework also allows for testing the sensitivity of the costs of sequestering soil C to two other key parameters: prices of agricultural outputs, and changes in yields on the fields where C accumulates. Both of these parameters impact land use decisions and will affect the quantities of soil C sequestered; both of these parameters, as well as the rates of soil C that can be sequestered under alternative production practices, are not known with certainty and will vary due to economic and climatic conditions.

Under a per-hectare payment policy, if the prices of agricultural outputs increase, profits increase and the opportunity cost of switching to the alternative production practice that may sequester more soil C also increases. Using the earlier notation, consider both the profit-maximizing practice and the alternative practice that sequesters greater amounts of C. The opportunity cost is measured as the difference in the profitability of the two land use choices, $\pi_0 - \pi_C$. For a given payment level *g*, fewer fields will be in the program as the output price increases, less carbon will be sequestered, and thus the marginal cost for soil C will increase or shift to the left. Conversely, for a decrease in the output prices, the opportunity cost falls, and more fields enter the program at each payment level. This would imply a decrease in the marginal cost for soil C or a shift in the marginal cost curve to the right. Thus uncertainty with respect to the output prices will ultimately impact the marginal cost curve for soil C and the quantities of soil C that are sequestered within a given area. As prices increase the marginal cost curve for soil C shifts back (left), and as the output price decreases, the marginal cost curve for soil C shifts out (right) holding all other variables fixed. The magnitude of the change in the marginal cost curves for soil C will ultimately depend upon the behavior of the producers' in the region, the combination of production practices that sequester soil C, and on the site-specific biophysical and economic characteristics of the region.

Long-term yield changes may also be associated with increases in soil C. The benefits of sequestering soil C are manifest in terms of reduced greenhouse gases and increases in the long-term productivity of the soil as the organic content of the soil increases. To capture this latter impact, we include a set of scenarios that allow for such a productivity effect on the fields that have entered the program (Table 1). In effect, this increase in yields on fields that are in the program decreases the opportunity cost of being in the program and would tend to shift down (out) the marginal cost curve for soil C. At each payment level, more soil C is sequestered relative to the base scenario of not productivity impact. Once again the magnitude of the shift depends upon the economic as well as biophysical characteristics of the fields.

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 and others 2003, 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 three Major Land Resource Areas (MLRA) in the grain-producing regions of Montana. The MLRAs were stratified into six zones or regions (sub-MLRAs) based on precipitation levels according to historical climate data. In discussion of the results, the terms high and low precipitation are used in a *relative* sense of more or less annual moisture within each region. In truth, the dryland grain regions of the Northern Great Plains are all considered low precipitation zones if compared to other agricultural regions of the United States. 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 and summary statistics are described in Johnson and others (1997) and Antle and others (1999a), and the parameter estimates for the supply and cost equations are discussed in Antle and Capalbo (2001).

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, 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. As a result, the two cropping systems compete closely in terms of net returns.

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 and others 1994, Paustian and others 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. 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. 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.

The variability in the levels of soil C predicted by the Century model for a 20-year horizon is shown in Figure 2. 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 20-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 ith 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.

Simulation Results: Land Use Changes, Soil C Levels, and C Sequestration Costs

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. We provide both the baseline results and the results for the alternative scenarios reflecting changes in soil C rates, changes in output prices, and changes in yields (productivity effect). The scenarios are summarized in Table 1.

Base Scenario 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% more land acreage than permanent grass.

Figure 3 shows the simulated changes in land use shares for each sub-MLRA as payment levels *g* 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 4. 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% 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 20-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 5 for selected sub-MLRAs. The relative homogeneity of land use patterns 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. Sub-MLRA 52-high and sub-MLRA 58a-high are comparable in terms of cropped hectares; the differences in the marginal cost curves are primarily due to productivity of the land. 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.

Soil C Rate Changes: Scenarios 1 and 2

Two alternative soil C rate scenarios are considered in addition to the base scenario ($b = 1$): scenario 1 which increases the soil C rates by a factor of 50% 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% 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 20-year period.

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 5. 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 2 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 5 can be used to infer information 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% higher soil C rates are used (Scenario 1) to under 1.0 MMT when the soil C rates are 50% 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 20-year period. In sub-MLRA 58a-high, a 50% 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.

Changes in Scale: Scenario 3

The impact that scale of analysis has on the marginal cost curves for soil C are shown in Figure 6 for these same three sub-MLRAs. Scenario 3 uses an average rate of soil C that is representative of the rates for each production system, rather than the site-specific rates used in the baseline scenario. This is a rate that could be used in aggregate policy models that do not capture the spatial heterogeneity of a region, or used for soil C contracts. Use of the average soil C rates tends to overstate the soil C rates in those sub-MLRAs that are less productive in terms of sequestering soil C (sub-MLRA 53a-high) and understate the rates in the more productive regions (sub-MLRA 52-high and 58a-high). The estimated marginal cost for sequestering soil C will also reflect the errors in the soil C rates: for the more (less) productive regions, the use of an average soil C rate will result in a shift to the left (right) of the marginal cost curve for soil C. Within a given sub-MLRA, the horizontal distance between the two marginal cost curves indicates the error in the predicted levels of soil C that would be supplied at given costs. This in turn relates to the potential gains from using a smaller scale for the analysis of the soil C rates. If the cost of collecting the site-specific data is less than these estimated benefits, the government can benefit from a more disaggregate analysis.

Using this type of comparative analysis in a policy setting, one can determine the “cost” of using representative soil C rates. In sub-MLRA 58a-high, for example, the quantity of soil C sequestered at an implicit price offered to producers of $60 per tonne would be approximately 1.5 MMT of C using the representative rates, but in reality would be closer to 2.5 MMT if this price was offered to producers in this region. The implications of this difference in the projected amounts of soil C would be substantial in terms of payouts by the government to producers in this region, and in terms of the distributional predictions of the impacts of a carbon sequestration policy. Errors in estimation of the soil C rates will lead to errors in the government’s soil C sequestration targets for each land unit area.

A similar analysis is being done for the economic dimension of the scale issue, by looking at the sensitivity of the results to using a representative farm/producer for all production systems and all areas. Thus the integrated assessment framework allows us to begin to address between the benefits and costs of analyses conducted at different scales, and the sensitivity of these tradeoffs to the underlying heterogeneity of the production systems.

Changes in Output Prices: Scenarios 4 and 5

Referring back to Figure 1, the output price data are a subset of the economic data that are inputs into the Economic Production Model component. Prices affect net returns and thus the land use and management decisions producers make. If the output prices increase, the land uses that are associated with higher levels of outputs are relatively more attractive, which also implies that the opportunity cost of placing land in a production system that sequesters more soil C but has lower levels of output, increases. In theory, we should observe for these systems that the marginal cost for soil C will increase (shift to left) as the prices of outputs increase, holding all other factors constant. However, the magnitude and ultimate direction of these shifts in the marginal cost curves will depend upon the tradeoffs between mix of crops and grass, and the relative profitability of the production systems. In areas where the alternative systems which sequester more carbon contain a high amount of grass and range lands, and where the profitability of these alternative systems are comparable, the sensitivity of the marginal cost curves to changes in crop prices may be greater, and less predictable. In areas where the alternative systems are largely other crop-based systems, the shifts in the marginal cost curves may be more predictable.

Scenarios 4 and 5 refer to a 10% increase and a 10% decrease in the mean of the estimated sample distributions of output prices respectively. Note that output prices used in the simulation model are drawn from sample distributions estimated from the site-specific data. The results for these two scenarios are shown in Figure 7. Sub-MLRA 52-high has the smallest response to changes in output prices, a result that is predicted by the conceptual model since the alternative soil C sequestering production systems are also highly intensive in grain crops.

Conversely for sub-MLRAs 58a-high and 53a-high, the alternative production systems that sequester more soil C in these two areas have a relatively larger proportion of crops versus grass and rangelands. Indeed, in the more eastern parts of the state, the profit maximizing mix of crops-grass land is more heavily skewed toward the grasses and rangelands. Thus as the crop prices increase, there is an added incentive to switch to the alternative systems, and we observe that more fields entering the program at each payment level, and the overall level of soil C sequestered has increased. The end result is that the marginal cost curve for soil C shifts to the right. Conversely in these same two sub-MLRAs, for a 10% output price decrease, the opportunity cost of switching to the alternative systems that sequester more soil C increases. Producers in these sub-MLRAs respond by switching *less* land areas into the soil C programs at each payment level, and the resulting impact on the marginal cost curves is the shift to the left.

Thus the price scenarios clearly illustrate the importance of having an integrated framework that incorporates site-specific producer decision-making rules in conjunction with biophysical characteristics in determining the sensitivity of the supply curves for soil C. As crop prices change, producers' behavior reflects profit-maximizing decision rules and the direction of shifts in the marginal cost for soil C will depend upon the tradeoffs among the land use alternatives in the region.

Productivity Impacts: Scenario 6

The final scenario that we consider in this paper is the sensitivity of the model to changes in yields. As noted earlier, sequestering soil C has both an immediate impact on reducing atmospheric carbon levels and offsetting GHG emissions, as well as a more long-term productivity impact. These productivity effects are captured in an ad hoc manner in the current simulation model by increasing the yields on those fields that are placed in the soil C program. In Figure 8 we show the sensitivity of the marginal cost of soil C to a 10% increase in the productivity of the fields that are switched to the alternative production systems. The profitability of these fields is enhanced by both the per-hectare carbon payment *g* as well as by the increase in revenues from the higher crop outputs (yields), relative to the non-participating fields. For all three sub-MLRAs, the productivity impacts shift the marginal cost curves outward, implying that the opportunity cost of sequestering soil C has declined, and the curve becomes more inelastic. The magnitude of the shift depends upon the site-specific economic and biophysical characteristics of the areas. Indeed, these results lend credence to the argument that sequestering soil C could be a long-term win-win situation for producers and society. In the short run, supporting producers to switch to less profitable production systems in order to sequester soil C could ultimately be a self-sustaining program, as producers reap the longer term benefits of the buildup of soil C.

Conclusions

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 factors including soil C rates, output prices, and yields, using an integrated assessment approach to simulation modeling. We have also looked at the impact of using more aggregate soil carbon rates on the errors introduced in estimating the marginal cost curves for soil C in given sub-MLRAs. 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.

Changing the soil C rates, output prices and crop yields 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 as we increase soil C rates. This corresponds to the earlier results on sensitivity of estimates of costs and quantity of soil C that can be sequestered in response to uncertainties with respect to biophysical estimates of soil C rates for alternative cropping systems (Antle and others 2002). With output prices, the changes in the marginal cost depend upon the relative profitability of the alternative production systems within each sub-MLRA. Changes in the productivity of the fields which sequester additional soil C are shown to both decrease the opportunity cost of sequestering soil C and decrease the responsiveness of the land use changes to the implicit prices offered for a unit of soil C.

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 emissions, or where policy makers are concerned with the amount of government outlays for sequestering soil C, the accuracy of estimates of soil C rates, prices and productivity effects plays a critical role. Our analysis shows that the competitiveness of the agricultural sector as a mitigator of greenhouse gases or a carbon sink, and the estimates of the total amount of C that could be sequestered, are highly dependent upon these factors. This argues for further assessment of the benefits and costs of more accurate measurement of the key variables, including soil C rates and the potential productivity impacts of increasing soil C.

Finally, 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 incorporating the sensitivity of policy design to both scale and these key simulation model parameters.

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Table 1. Scenario Descriptions

Base Scenario	Base estimates of the land use and soil C levels in each sub-MLRA using site-specific soil C rates.
Soil C Rate Scenarios:	
Scenario 1	Increases the soil C rates by a factor of 50% in all sub-MLRAs and for all cropping systems ($b = 1.5$).
Scenario 2	Decreases the soil C rates by a factor of 50% in all sub-MLRAs and for all cropping systems ($b = 0.5$).
Scale Scenario:	
Scenario 3	Uses an average rate of soil C that is representative of the rates for each production system, rather than the site-specific rates used in the base scenario.
Output Price Scenarios:	
Scenario 4	A 10% increase in the mean of the estimated sample distributions of output prices respectively.
Scenario 5	A 10% decrease in the mean of the estimated sample distributions of output prices respectively.
Yield Scenario:	
Scenario 6	A 10% increase in yields for fields that are in the program.

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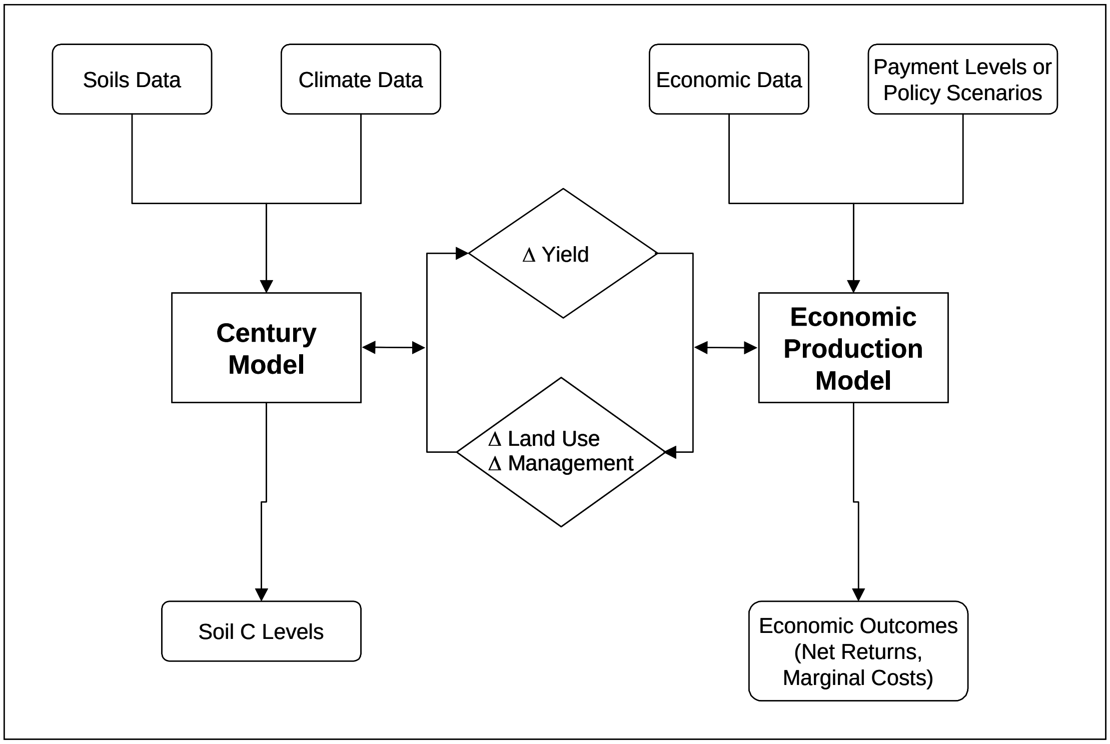


Figure 1. Linkage between Century Model and Economic Production Model

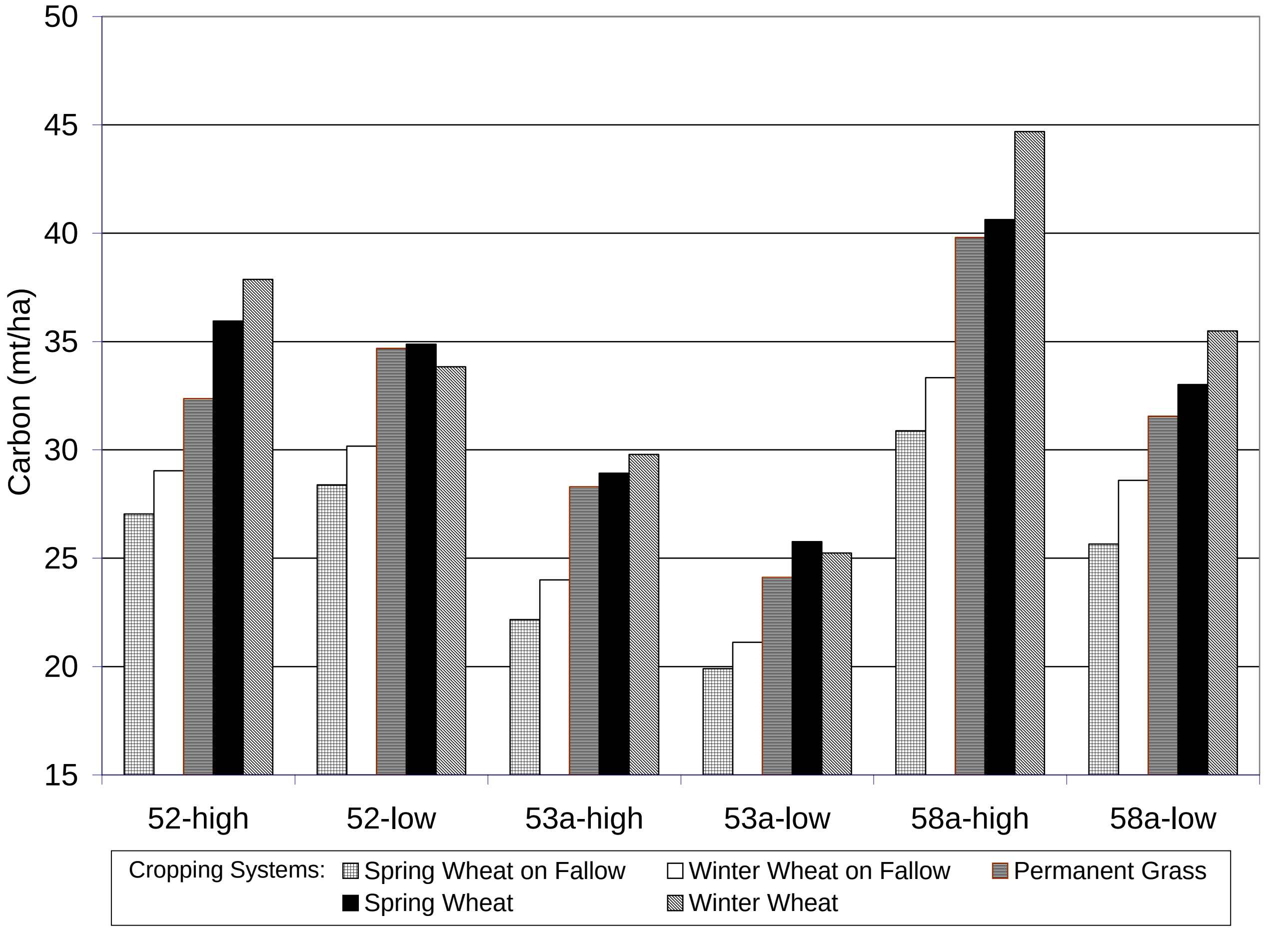


Figure 2. Soil C Levels Predicted by Century Model for Alternative Cropping Systems in Montana

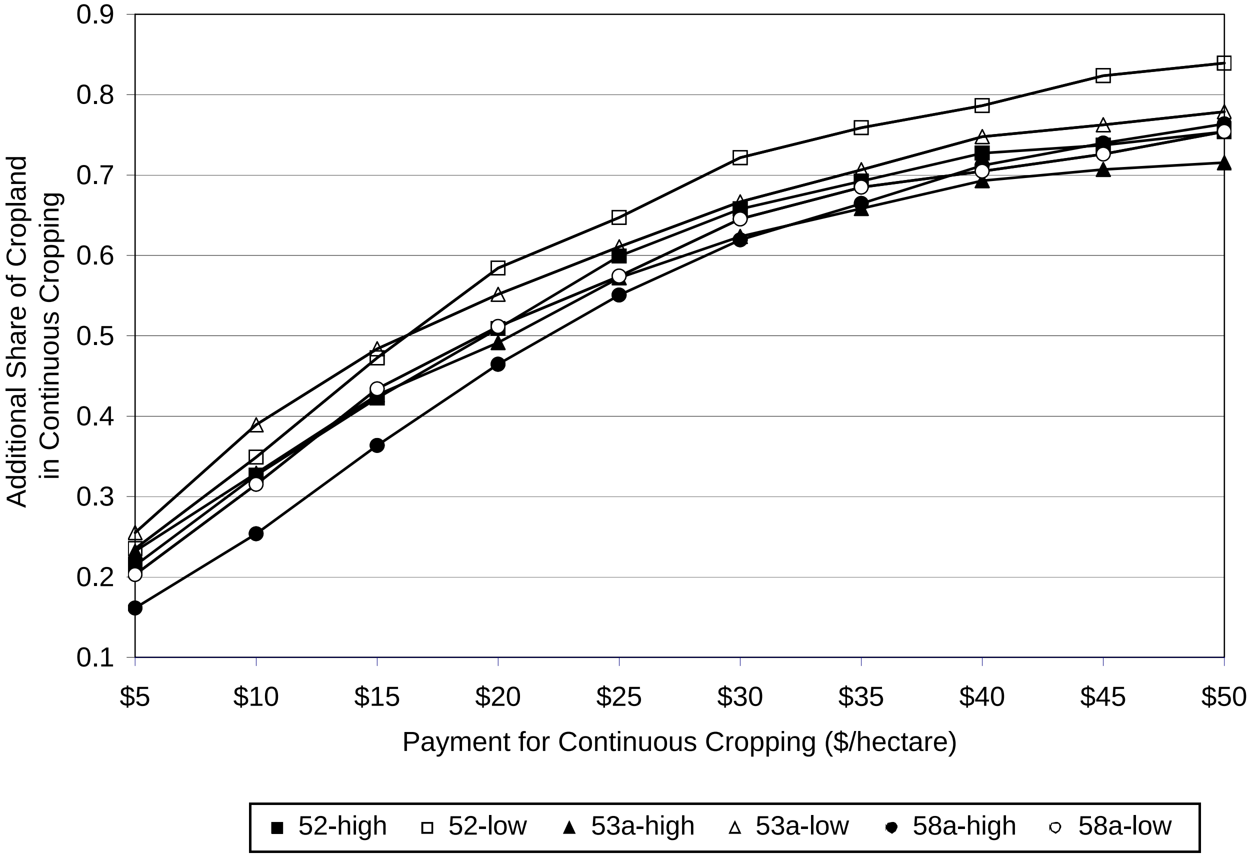


Figure 3. Additions to the Share of Cropland in Continuous Cropping by Sub-MLRA: Base Scenario

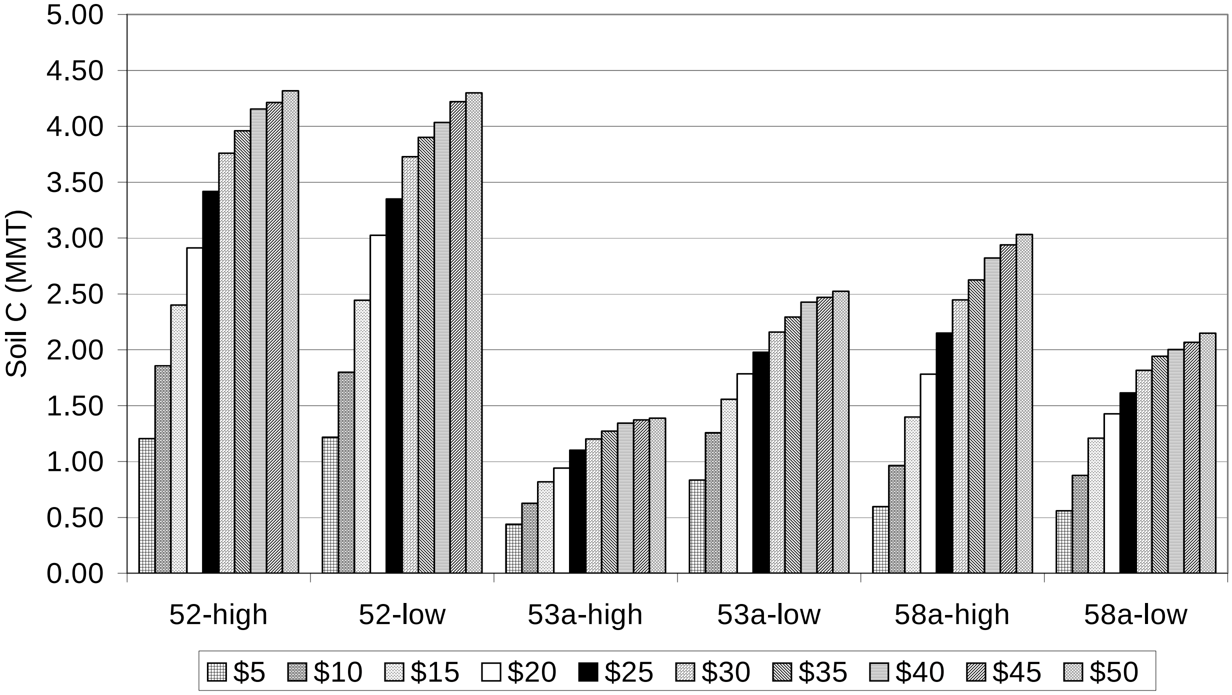
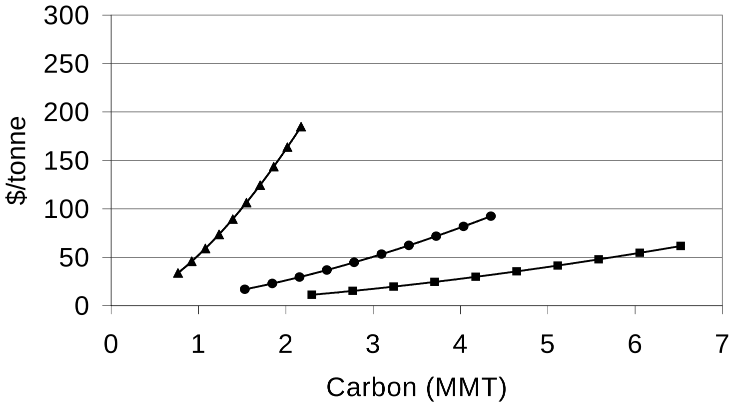
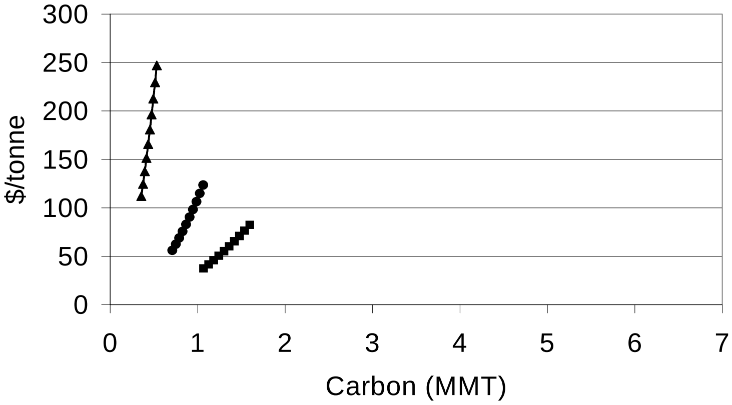


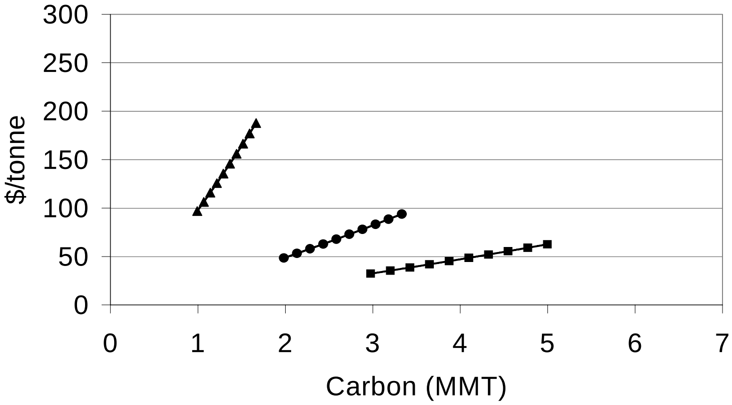
Figure 4. Changes in Soil C over a 20-Year Time Horizon by Sub-MLRA: Base Scenario



a. Sub-MLRA 52-high



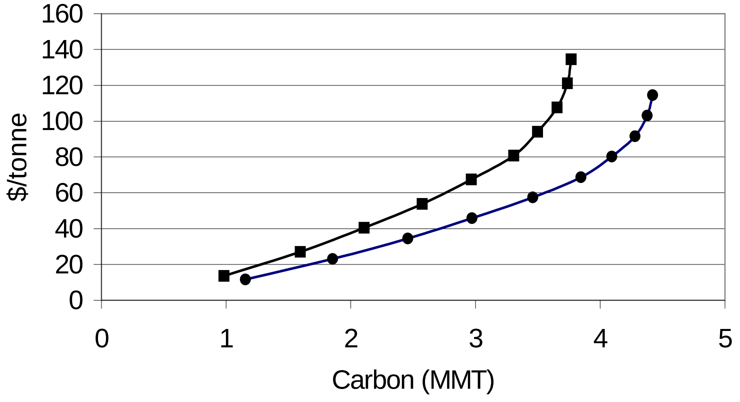
b. Sub-MLRA 53a-high



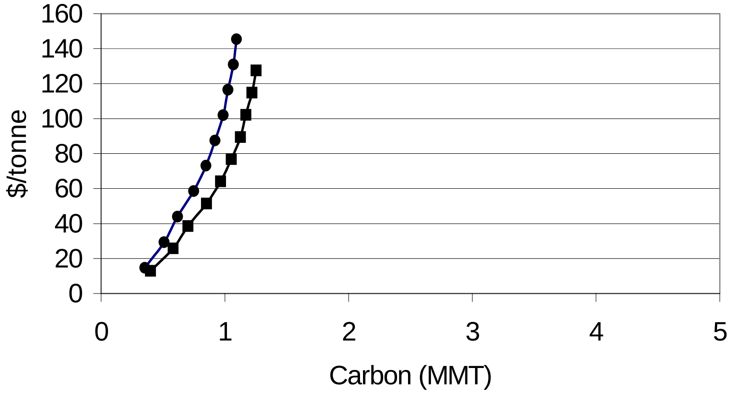
c. Sub-MLRA 58a-high

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

Figure 5. Marginal Costs for Soil C for Selected Sub-MLRAs: Soil C Rate Scenarios



a. Sub-MLRA 52-high



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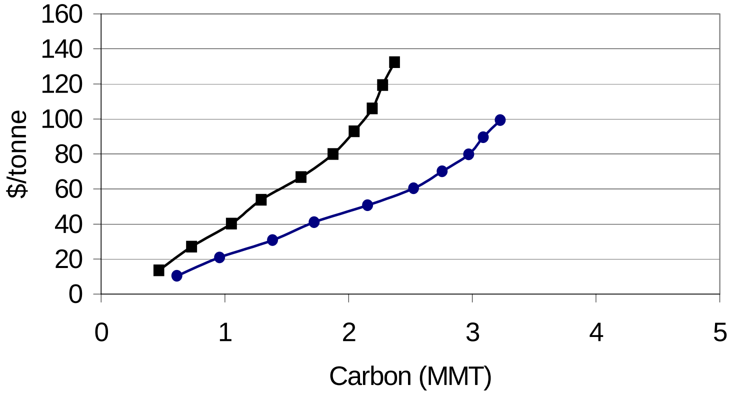
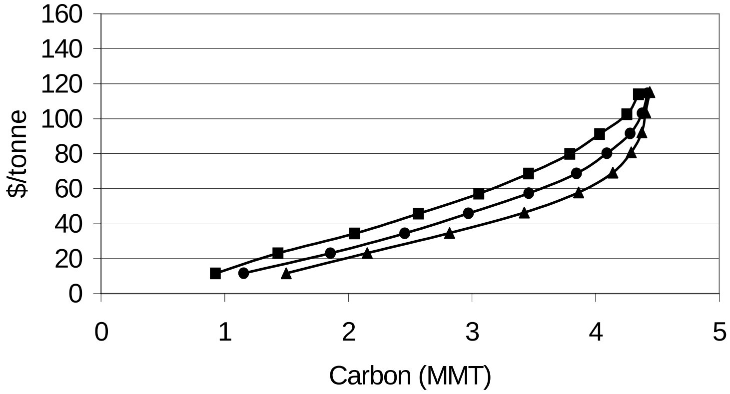
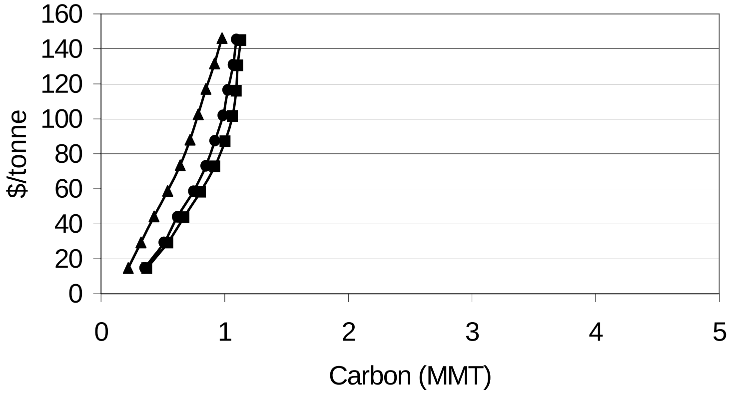


c. Sub-MLRA 58a-high

Figure 6. Marginal Costs for Soil C for Selected Sub-MLRAs: Scale Scenario



a. Sub-MLRA 52-high



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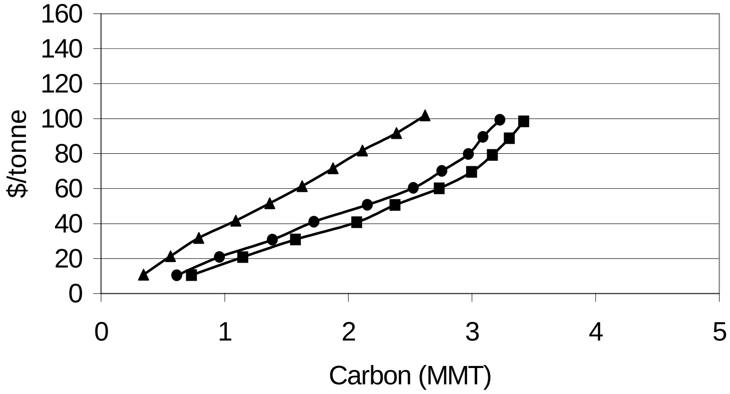


c. Sub-MLRA 58a-high

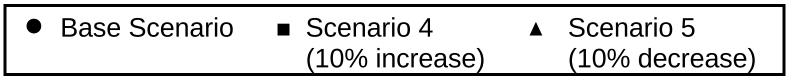
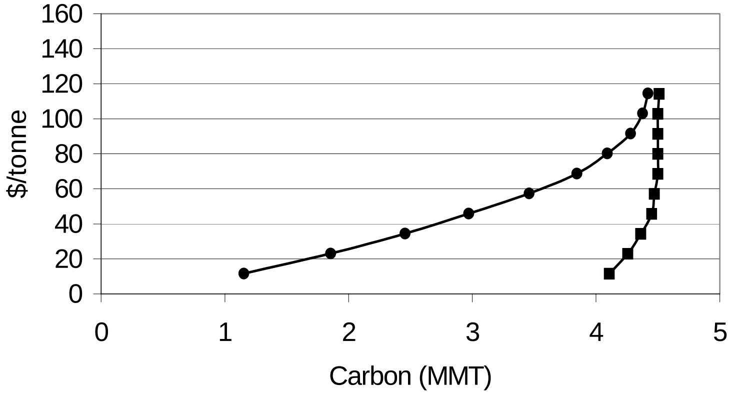


Figure 7. Marginal Costs for Soil C for Selected Sub-MLRAs: Output Price Scenarios



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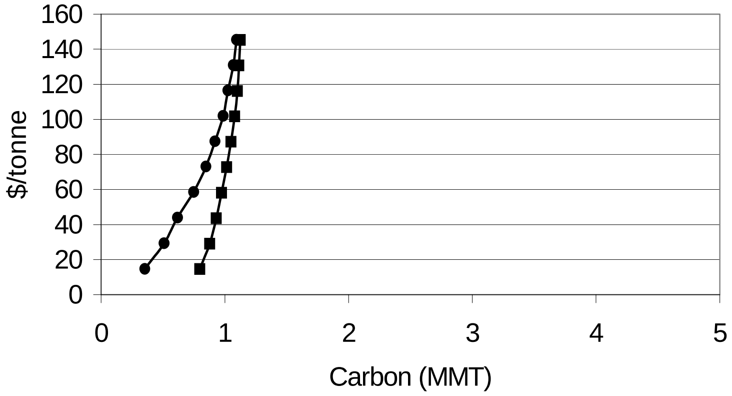

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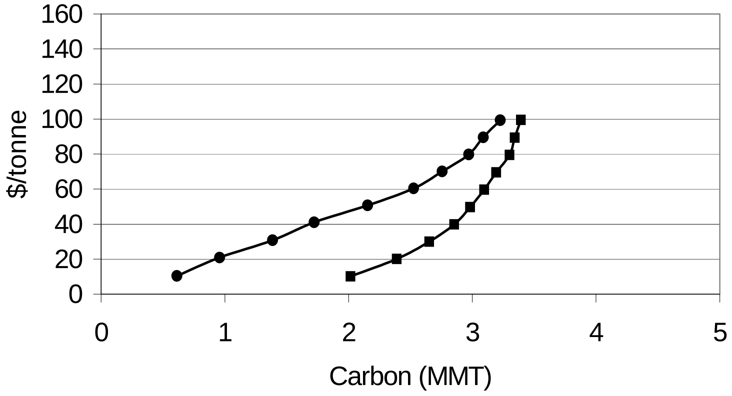

c. Sub-MLRA 58a-high

● Base Scenario ■ Scenario 6 (10% yield change)

Figure 8. Marginal Costs for Soil C for Selected Sub-MLRAs: Productivity (Yield Increase) Scenario