Economics of Agricultural Soil Carbon Sequestration in the Northern Great Plains

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Abstract

Under the Kyoto protocol of the United Nations Framework Convention on Climate Change the United States is charged with reducing emissions of greenhouse gases to seven percent below their 1990 levels by the period 2008-2012. These reductions could be met from many industries including agriculture. In this paper, an economic simulation model is linked to the CENTURY ecosystem model to quantify the economic efficiency of policies that might be used to sequester carbon (C) in agricultural soils in the Northern Great Plains region. Model outputs are combined to assess the costs of inducing changes in equilibrium levels of soil C through three types of policies. The first is a CRP-style policy that provides producers with per-acre payments for converting crop-land to permanent grass; the second is a policy that provides per-acre payments to all farmers that use continuous cropping, regardless of the land's cropping history; the third is a policy that provides per-acre payments for the use of continuous cropping only on land units that had previously been in a crop/fallow rotation. The analysis shows that a CRP-style policy is found to be an inefficient means to increase soil C resulting in costs that typically exceed $100 per MT (metric ton) of C. In contrast, payments to adopt continuous cropping were found to produce increases in soil C for between $5 to $70/MT depending on the geographic area and degree of targeting of the payments. The most efficient, lowest cost policy is achieved when payments are targeted to land that was previously in a crop/fallow rotation. In this range, soil C sequestration appears to be competitive with C sequestered from other sources.

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Under the Kyoto protocol of the United Nations Framework Convention on Climate Change the United States is charged with reducing emissions of greenhouse gases to seven percent below their 1990 levels by the period 2008-2012. These reductions could be met from many industries including agriculture. Changes in agricultural land use and management practices can sequester (store) carbon (C) in agricultural soils and could reduce U.S. emissions by up to eight percent (Lal *et al.* 1998). However, little if any research to date has assessed how much it would cost to sequester C, except for the case of converting crop-land to trees (McCarl and Schneider 1999; Stavins 1999; Plantinga, Mauldin, and Miller 1999). Other potential means of sequestering C within the agricultural sector are changes in land use, such as conversion of crop-land to permanent grass, and management practices such as the use of no-till and reduced fallow. In the extensive semi-arid area of the Great Plains, these practices are likely to be economically feasible where afforestation—the conversion of non-forest land to forest—is not. Agriculture in the semi-arid regions of the Great Plains also tends to be economically marginal compared to regions such as the Midwest. If agriculture in these locations can produce soil C at a cost that is competitive with other means of sequestering C, farmers in these areas could benefit economically from national and international efforts to reduce atmospheric C.

A precedent exists for using compensation schemes to enhance the environmental benefits from use of agricultural land. Agricultural policies, such as the conservation reserve program (CRP), provide producers with per-acre payments in return for changes in land use and management that provide environmental benefits. However, economists have recognized that per-acre payments are not economically efficient because they fail to account for the site specific nature of the resulting environmental benefits and costs (Feather, Hellerstein, and Hanson 1998; Antle and Mooney 1999). Carbon sequestration differs from other environmental services such as wildlife habitat or recreation in that the value of a ton of C sequestered at all sites has the same marginal social value (say, $V per metric ton) in terms of reducing the risk of climate change. However, the costs associated with changes in land use and management practices, and the potential for each area to sequester C, vary across sites. An economically efficient policy would pay farmers $V for each metric ton (MT) of carbon sequestered on each land unit. Because of difficulties in measuring soil C levels on a site-specific basis, policies are likely to be designed to pay farmers on a per-acre basis for undertaking observable changes in land use or management practices. The more closely these policies are able to target incentives to actions that are more efficient at increasing soil C, the better they will approximate an efficient soil C sequestration policy.

In this paper we link an economic simulation model to the Century ecosystem model to quantify the economic efficiency of alternative policies that might be used to sequester C in agricultural soils in the Northern Plains region. The economic simulation model represents changes in land use and management decisions on a site-specific basis in response to economic incentives provided through a soil C policy (or through a market for carbon emissions reductions). The Century ecosystem model is used to simulate the equilibrium levels of soil C associated with the principal dryland grain production systems in the region, including winter wheat and spring wheat in both crop/fallow rotations and continuously cropped, and for continuous grass (CRP land). Model outputs are combined to assess the costs of inducing changes in equilibrium levels of soil C through three types of policies. The first is a CRP-style policy that provides producers with per-acre payments for converting crop-land to permanent grass; the second is a policy that provides per-acre payments to farmers who use continuous cropping, regardless of the land's previous cropping history; the third is a policy that provides per-acre payments only to those land units that are converted from a crop/fallow rotation.

Agricultural Production and Soil C Sequestration

Agricultural soil C sequestration can be enhanced through changes in land use (e.g., conversion of crop-land to grass) or changes in production practices (e.g., use of conservation tillage, or reductions in fallow) (see Rasmussen and Parton 1994; Tiessen, Stewart, and Betany 1982; Mann 1986; Lal *et al*. 1998). The effectiveness of these changes in sequestering C depends on both cropping intensity and tillage practices. Franzluebbers and Arshad (1996) suggest that soil C will increase slowly over the first 2-5 years of improvements with larger increases between 5-10 years, flattening off thereafter and reaching a finite limit after about 50 years (Lal *et al*. 1998).

Estimates show that 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 (Lal *et al*. 1998). A single land use or management practice will not be effective at sequestering C in all regions. Once a producer reverts to conventional management, stored C is released.[1]

Policy Design

Command and control, incentive based, or market based policy designs could be used to encourage producers to increase soil C (see Antle and Mooney 1999). Under a command-and-control policy farmers would be mandated to use prescribed land use or management practices that result in increased soil C. This is generally an inefficient approach to achieving environmental goals unless each producer is identical, as regulators have a limited ability to tailor mandated technologies to each producer (Council of Economic Advisers, 1990). Incentive based policies, such as the CRP and the Environmental Quality Incentives Program, offer inducements

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[1] Tiessen, Stewart, and Betany (1982); Mann (1986); and Rasmussen and Parton (1994), estimate that 20 percent to 50 percent of soil carbon is lost from the soil during the initial 20 to 50 years of cultivation.

such as subsidies to encourage farmers to engage in desired activities (Osborn 1997; Lynch and Smith 1994). Disincentives, such as a tax, can be used to discourage producers from engaging in an activity. This policy design also is likely to be inefficient for achieving environmental goals as it is based on payments for changes in management rather than achieving the environmental goal.

A third class of policy instrument is market-based trading. A trading scheme for sulfur dioxide emissions has been in place in the United States since 1990 (Petsonk, Dudek, and Goffman 1998; Joskow, Schmalensee, and Bailey 1998) and the agricultural sector is already participating in emerging markets for other environmental goods such as water and water rights (Landry 1996; Colby, Crandall, and Bush 1993). Market-based trading can result in an efficient outcome if the market price reflects the social value of the environmental attribute. Some initial research on carbon trading in agriculture is found in Antle and Mooney (1999) and Sandor and Skees (1999).

Simulation Framework for Analysis of Soil Carbon Sequestration

This section describes the empirical methods used to analyze C sequestration policies in the Northern Plains. The simulation framework consists of two disciplinary models, a field-scale economic model and a biophysical process model. These models are used to simulate changes in land use patterns, input use, and soil carbon under alternative policy scenarios.

Economic Model of Crop Choice and Management Decisions

The field-scale economic model was developed to simulate land use and management decisions in the dryland grain production system of Montana that is typical of the Northern Plains region (Antle *et al.* 1998; Antle and Capalbo 2000). Econometric production models are used to estimate crop supply and variable cost functions for winter wheat, spring wheat, and barley produced with or without fallowing the land in the previous year. These models were estimated using data from a sample of 425 farms that are statistically representative of the USDA’s Major Land Resource Areas (MLRA) in the grain-producing regions of Montana (Figure 1). MLRAs are designed to represent major soil and climatic regions in the United States. These zones were stratified into sub-MLRAs based on whether the area receives high or low precipitation according to historical climate data. Data for the economic model are described in Johnson *et al*. (1997) and the parameter estimates for the supply and cost equations are discussed in Antle *et al.* (1998) and Antle and Capalbo (2000).

A stochastic simulation model of land use allocations and net returns was constructed using the econometric production models and the spatially explicit economic data (Figure 2). This stochastic simulation model is interpreted as generating a statistical representation of the population of production units (fields) in a spatial region as it is based on the stochastic properties of the econometric models and the sample data. The model simulates field scale producer crop choices (winter wheat, spring wheat, barley, or fallow) and the related output and cost of production conditional on that crop choice over several growing seasons. By operating at the field scale, the simulation model can represent spatial differences in crop rotations and productivity that give rise to different economic outcomes in the region. These differences in land use and management are critical for analyzing soil C changes in the Great Plains in response to alternative economic policies.

Each field in the data set is described by its size in acres, location, and an associated set of location-specific prices paid to and received by the farmer (Figure 2). Tillage practices, use of crop insurance, and previous crop initialize the model. These are based on draws from sample distributions estimated from the data. The economic models for each crop are simulated to estimate expected output and cost of production, and to calculate expected returns above short run variable costs of production for each crop alternative.

Biophysical Process Model

Soil carbon estimates are made using Century, a comprehensive biogeochemistry model (Parton *et al*. 1994). Soils and climate data for each of the sub-MLRAs are used as 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 is from the field-scale survey of Montana producers, 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 NASS records of county-level crop yields and changes in soil C derived from the Century database of native and cultivated soils. The initial land use allocation from the Montana survey was used to calculate base C levels for each sub-MLRA. The initial distribution of C in Montana range from 20 to nearly 36 MT per hectare (8 and 14.5 MT per acre) for different production systems and regions. Additional details and references to the data sets are in Paustian, Elliot, and Hahn (1999).

Simulation of Land Use, Crop Choice, and Soil Carbon Levels

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 policy setting ψ_j (e.g., each payment level for conversion of crop-land to grass). The land use patterns are then summarized for each sub-MLRA in the form of proportions $\boldsymbol{s}_i(\psi_j)$ of land allocated to the ith use. The Century model is used to simulate the equilibrium levels of soil carbon for each production system in each sub-MLRA. Letting the level of soil C for each land use be $\boldsymbol{C}_i$, the
level of soil C associated with land use i and policy setting j is then the weighted average

$$(1) \qquad \boldsymbol{C}(\psi_j) = \sum_i \boldsymbol{s}_i(\psi_j)\boldsymbol{C}_i .$$

Empirical Results

We now present the empirical results from analysis of three policies: a CRP-style policy for conversion of crop-land to permanent grass; a policy that pays all farmers on a per-acre basis for land in continuous cropping; and a policy that targets payments for continuous cropping only to acres that were previously in a crop/fallow rotation. Before presenting these results, we shall make two observations about these production systems that help explain the outcomes.

First, the field-level survey data collected for the 1995 crop year, as well as data collected by the Montana Agricultural Statistics Service at the county level, show that under the present policy regime, farmers in Montana allocate roughly one-third of crop-land to the crop/fallow system, one-third to continuous cropping (or to what is referred to as a re-cropping system in which farmers include an occasional fallow into the system), with the residual one-third of the land in fallow. 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 acre 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 over the long-run (Antle *et al*. 1999). Second, simulations of these systems with the Century model show that (i) the levels of soil C under a crop/fallow rotation are about 3-6 MT per hectare (1.2 - 2.4 MT per acre) less than continuous grass, (ii) that soil C levels under grass are 3-6 MT per hectare (1.2 - 2.4 MT per acre) less than under continuous cropping, and (iii) that the levels of soil C under a grass-clover-pasture mix are about 7-10 MT per hectare more than continuous cropping (Figure 3).

Payments per Acre for Conversion of Crop-land to Permanent Grass (CRP-Style Policy)

The economic simulation model was executed for each field in the data set using observed initial conditions (previous crops and prices). Prices were set at values for each location that are representative of long-run averages over the past decade. The land use alternatives were winter wheat, spring wheat or barley (either continuously cropped or fallowed). In addition, the farmer could choose to enter a field into continuous grass (grass, clover, pasture) and receive a payment. In the simulations this payment ranged from zero (the base case) to $75 per acre by $15 increments. Current CRP contracts are in the range of $30 to $40 per acre in Montana. Figure 4 shows the resulting supply curve for land in grass. The largest proportion of land allocated to grass occurs in the sub-MLRAs where crop returns are lowest, and vice-versa (sub-MLRAs 52 High and 52 Low are the most productive areas). The simulation correctly predicts that about 20 percent of crop-land is allocated to CRP when the payments are in the $30 to $40 per acre range. As payments increase, the share of land placed into grass increases sharply for the less productive lands.

Figure 5 shows the effects of this payment scheme on equilibrium levels of soil C by sub-MLRA, for the conversion from crops to grass-clover-pasture. The CRP-style payment has a large impact on net soil C levels in those sub-MLRAs that have the steepest supply curve for grass (Figure 4). As shown in Figure 3, the crop/fallow system yields a lower level of soil C than the continuous system, and grass yields a higher level of soil C. When the changes in soil C due to the change in cropping patterns are translated into costs per MT C, the results show that the costs are high, ranging from hundreds to thousands of dollars per MT. At these levels, soil C from crop-land conversion would not be competitive with other sources such as tree planting or industrial sources (Sandor and Skees 1999; Stavins 1999; Plantinga, Mauldin, and Miller 1999).

Payments for Continuous Cropping

We now consider a policy to pay farmers for continuous cropping. Clearly, only land that is switched from crop/fallow to continuous cropping produces an increase in soil C. However, if the policy pays only farmers who switch from crop/fallow to continuous cropping, and not also farmers who already use continuous cropping, the policy creates an incentive for farmers who are currently in continuous cropping to temporarily change to crop/fallow and then back to continuous cropping. Also, farmers in continuous cropping might object to being excluded from the program, on equity grounds. Therefore, in the following analysis we consider two cases: all acres continuously cropped are eligible for payments, regardless of their previous cropping history (nontargeted); and only acres with a history of crop/fallow are eligible for continuous cropping payments (targeted).

Recall that current land allocation (with the CRP in operation) is about evenly divided between the crop/fallow system and continuous cropping, because the two systems yield similar economic returns. This means that a relatively small payment per acre is sufficient to induce farmers to switch land from crop/fallow to continuous cropping. Figure 6 shows that in the base scenario ($0 payments) without any CRP-type payments, approximately 20 percent of the land is in continuous cropping. Payments of $5 per acre increase the percentage continuously cropped to the range of 50 to 65 percent (ignoring sub-MLRA 54a and b). A payment of $10 per acre increases the percentage to 75 to 85 percent; a payment of $15 per acre further increases the percentage to over 90.

Figure 7 shows that these changes in the percentage of land continuously cropped yields increases in equilibrium soil C levels by 2 to 4 MT per acre with a $5 per acre payment. The higher payments ($10 to $15) result in proportionally smaller increments. These soil C levels translate into costs per MT of C ranging from $5 to $70, depending on area and whether the payments are targeted (Figures 8 and 9).

Figure 10 shows the marginal cost curve for carbon sequestered for two sub-MLRAs, 52-h and 53-l, for the targeted and nontargeted scenarios. When the changes in soil C are translated into costs per MT, and it is assumed that all continuously cropped acres are eligible for payments regardless of cropping history (which is the nontargeted case), the costs range from $20 to $40 per MT C with the $5 per acre payment, and increase to almost $60 per MT C in sub-MLRA 53-l and to about $40 per MT in MLRA 52-h with $15 per acre payments. When the payments are targeted to acres that were previously in a crop/fallow rotation, the costs per MT C decline by about $10 per MT with a $5 per acre payment in both sub-MLRA 52-h and sub-MLRA 53-l. This difference narrows as the payments increase to $15 per acre.

Finally, we can calculate the total carbon sequested in the sub-MLRAs for each payment scheme. At a per-acre payment of $2.50, .54 million MT of carbon are sequested. This rises to 4.9 million MT when payments increase to $7.50 per acre and to 10.5 million MT at the highest per-acre payments ($15.00) considered in this research.

Conclusions

Simulations with the Century ecosystem model show that long-term soil C levels associated with a crop/fallow system are less than those for both continuously cropped systems and grass-clover-pasture systems, and soil C levels for grass-clover-pasture are generally greater than for continuously cropped grains. These simulations are combined with results of an economic simulation model that show how land use and management changes respond to policy incentives. The analysis shows that a CRP-style policy is found to be an inefficient means to increase soil C, with cost per MT C ranging from hundreds to thousands of dollars. In contrast, payments to adopt continuous cropping were found to produce increases in soil C at a cost of $5 to $70 per MT C. The most efficient policy is achieved when payments are targeted to land that was previously in a crop/fallow rotation.

A recent study on afforestation in Maine, South Carolina, and Wisconsin estimated the average cost of sequestering C to be between $45-$60 per MT C (Plantinga, Mauldin, and Miller 1999). Stavins (1999) estimated that the average cost per MT C sequestered through afforestation to be in the range of $38 per MT for the Delta states to approximately $70 per MT for the United States as a whole. Sandor and Skees (1999) indicate that early market signals from potential carbon trades are predicting market values between $20 and $30 per MT C. Whether or not the policy is targeted, soil C sequestration from changes in cropping practices appears to be competitive with C sequestered from other sources such as forestry or the energy industry.

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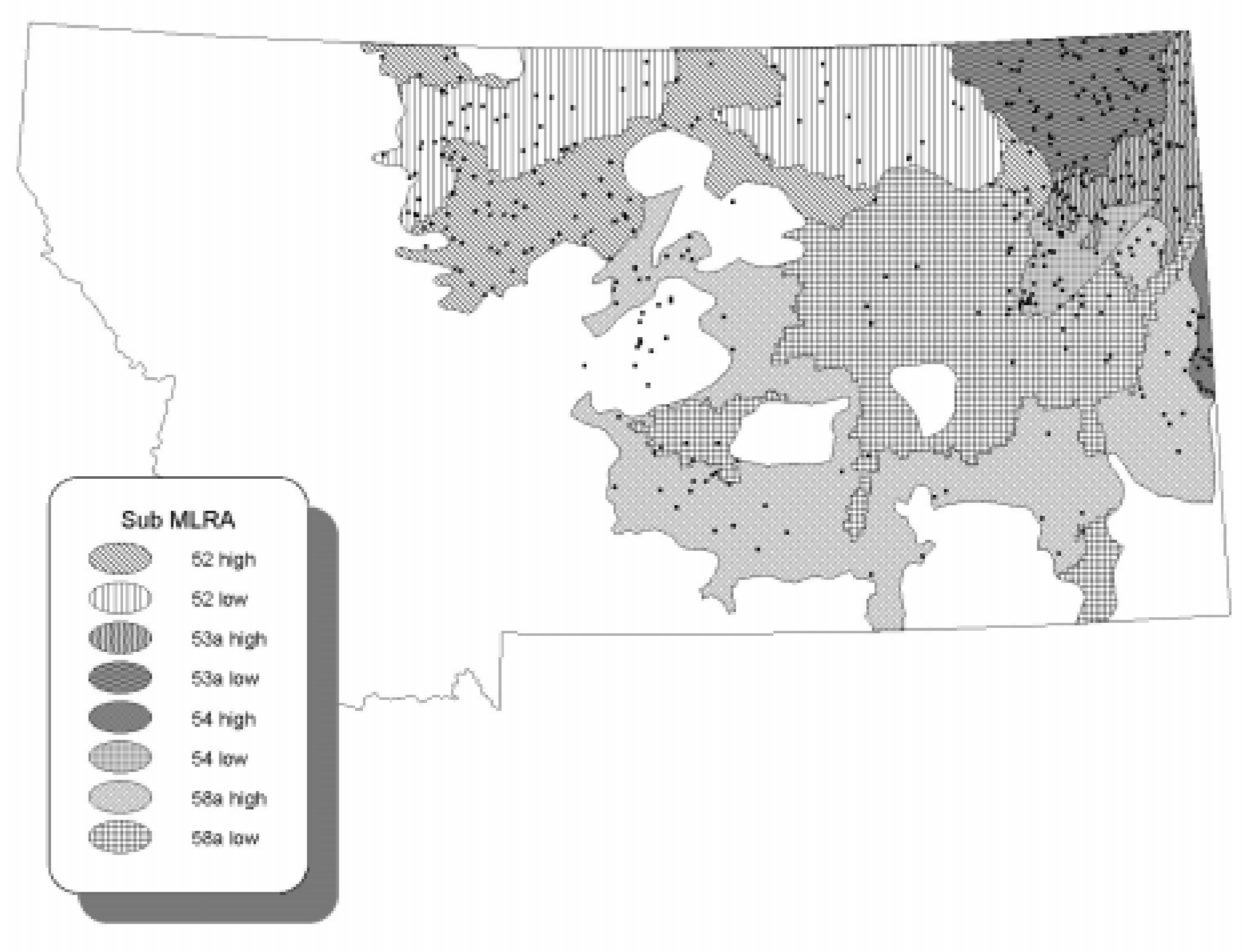
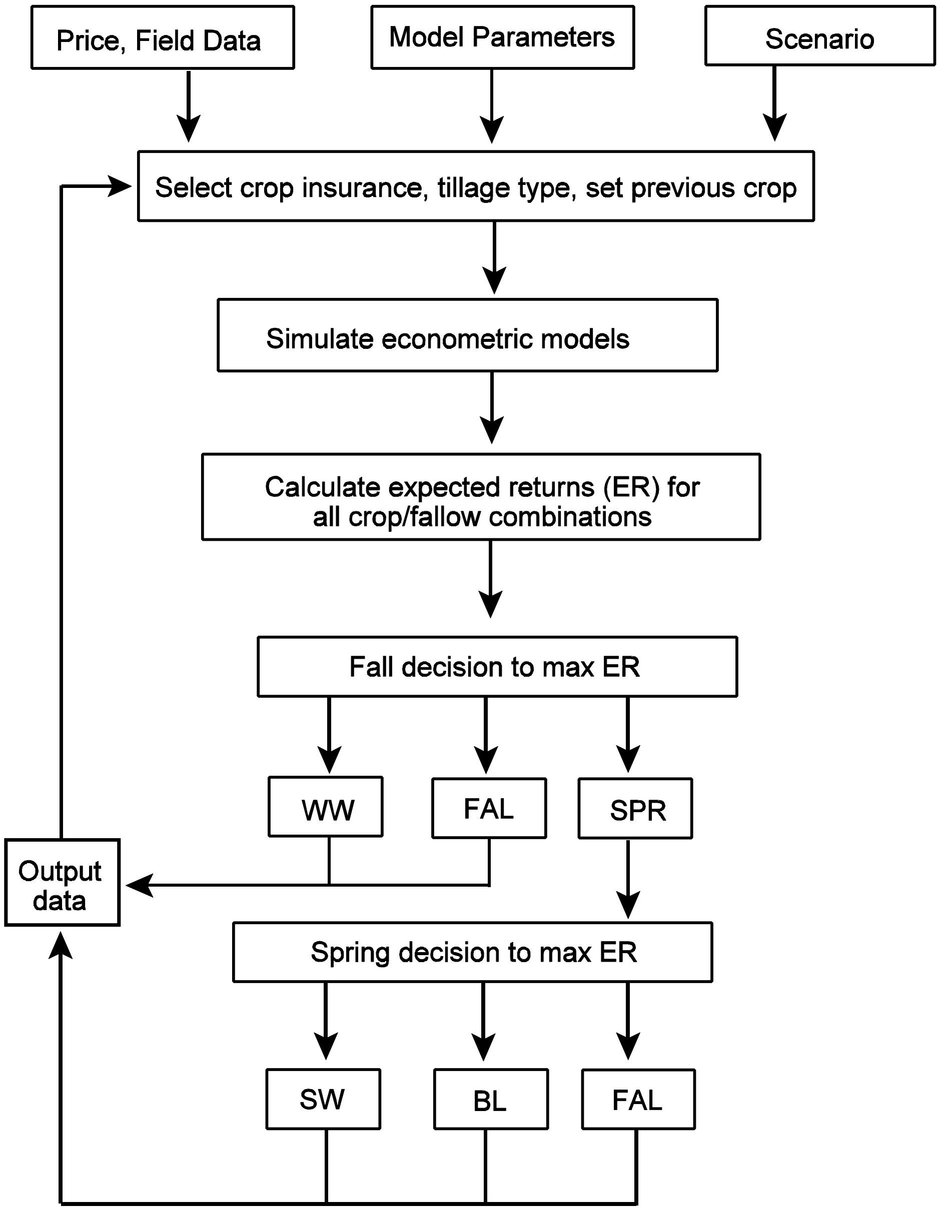


Figure 1. Sample Points by Sub-MLRA



SPR = Spring planting decision
WW = Winter wheat
BL = Barley
FAL = Fallow
SW = Spring wheat

Figure 2. Simulation Model Structure

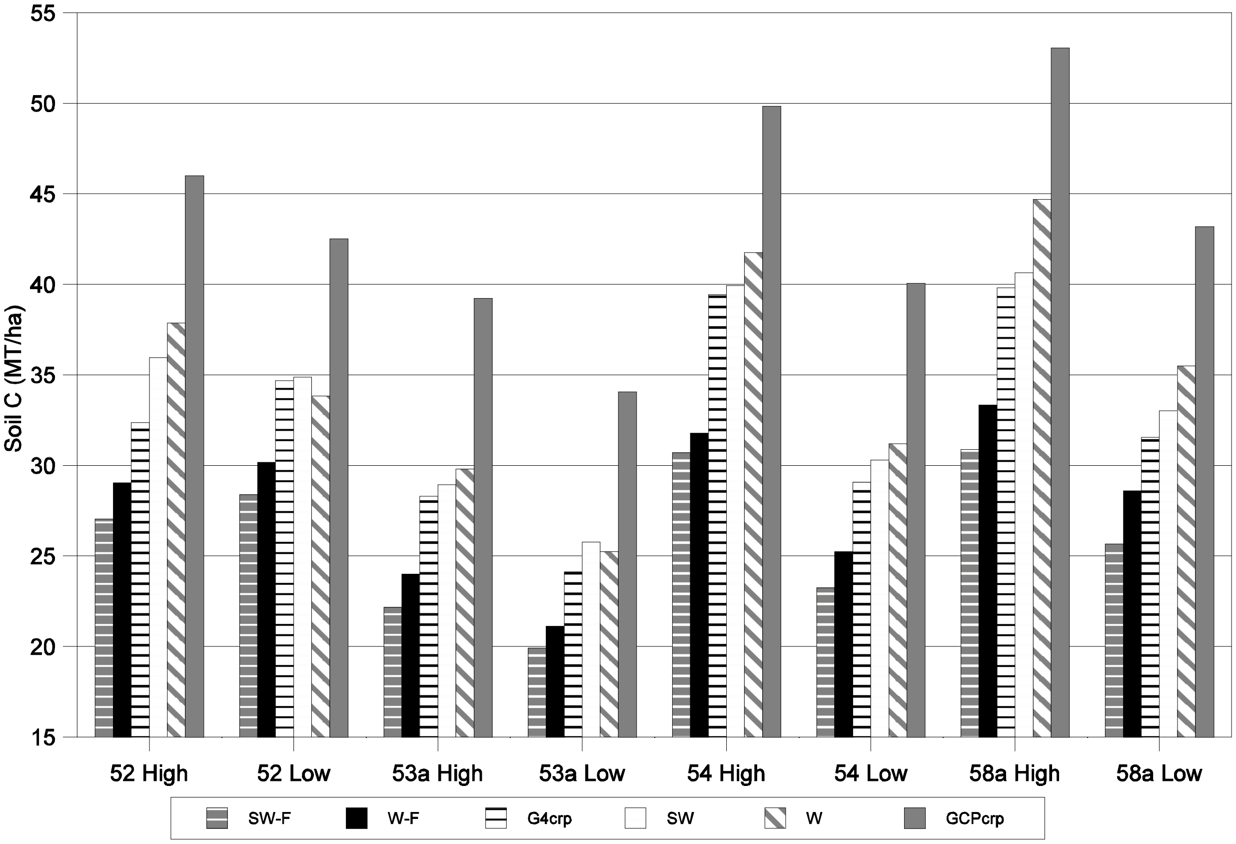


Figure 3. Soil C Levels Predicted by Century Model for Cropping Systems in Montana

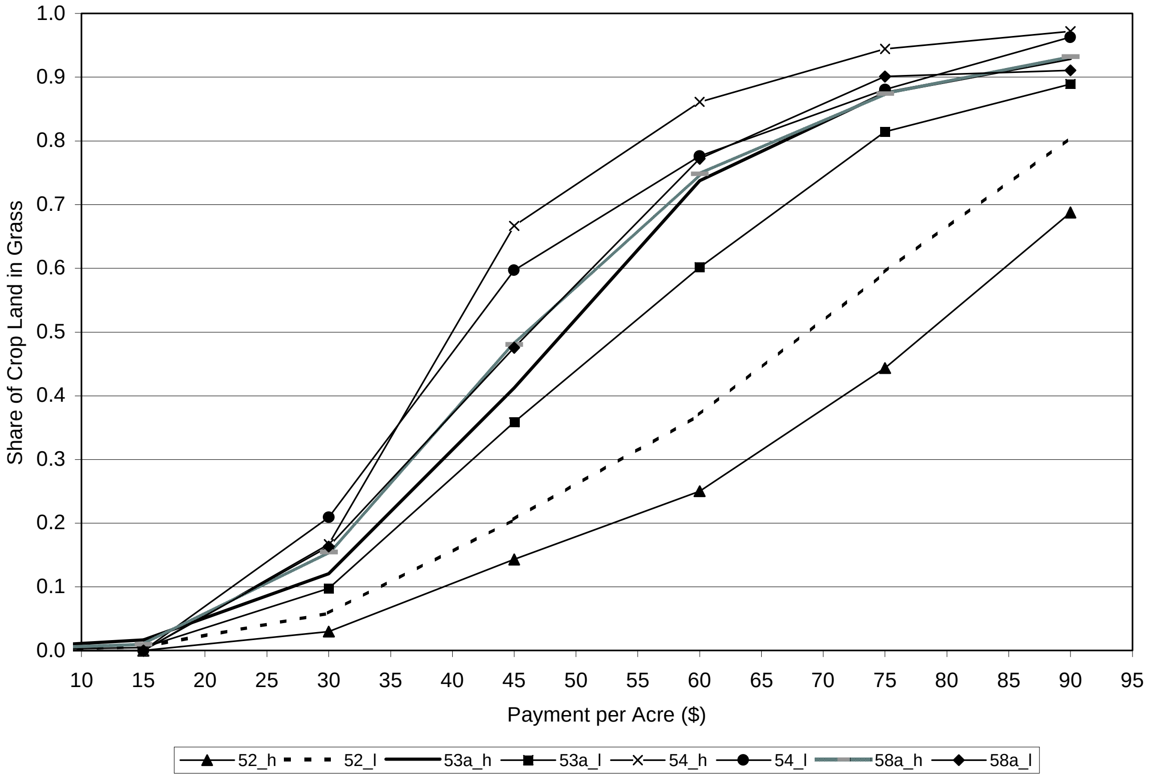


Figure 4. Share of Crop Land in Grass with Payments per Acre for CRP

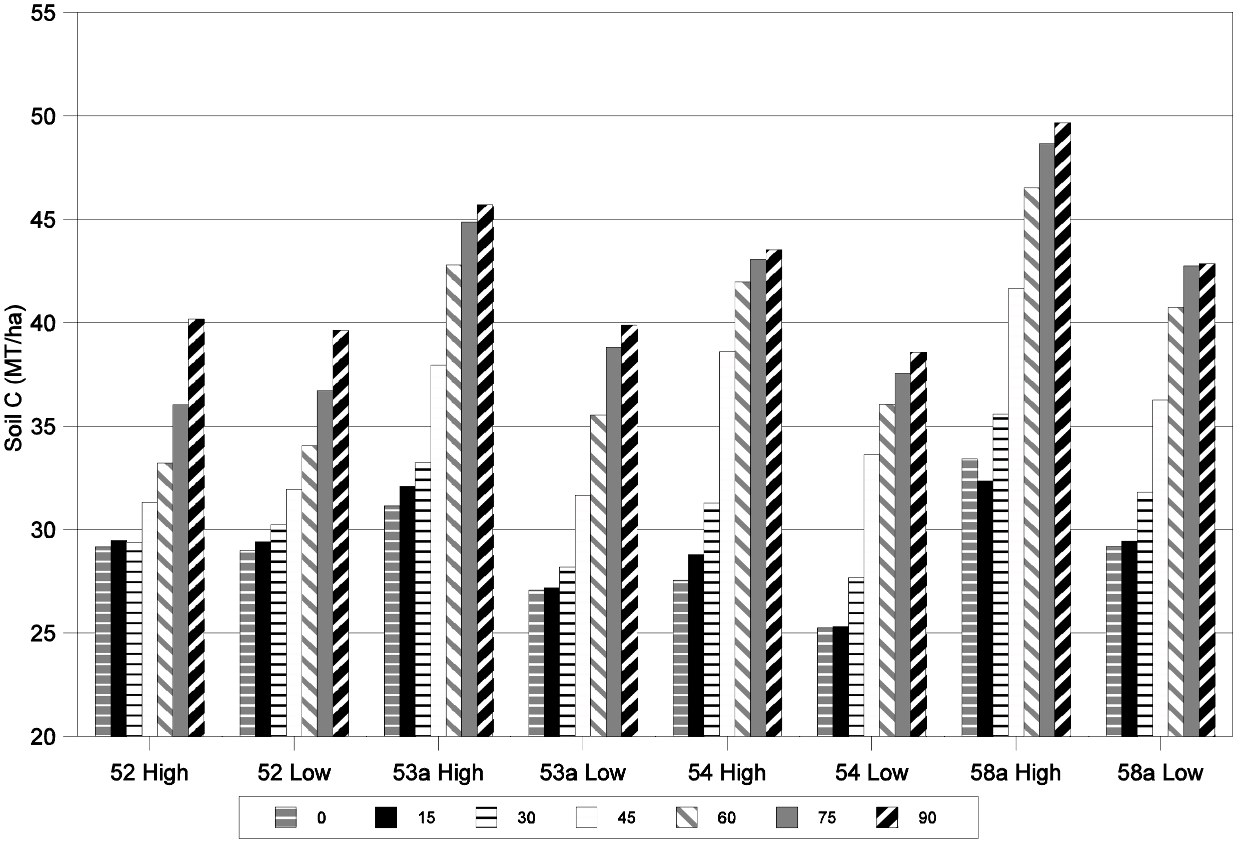


Figure 5. Soil C Levels for Conversion from Crops to Grass

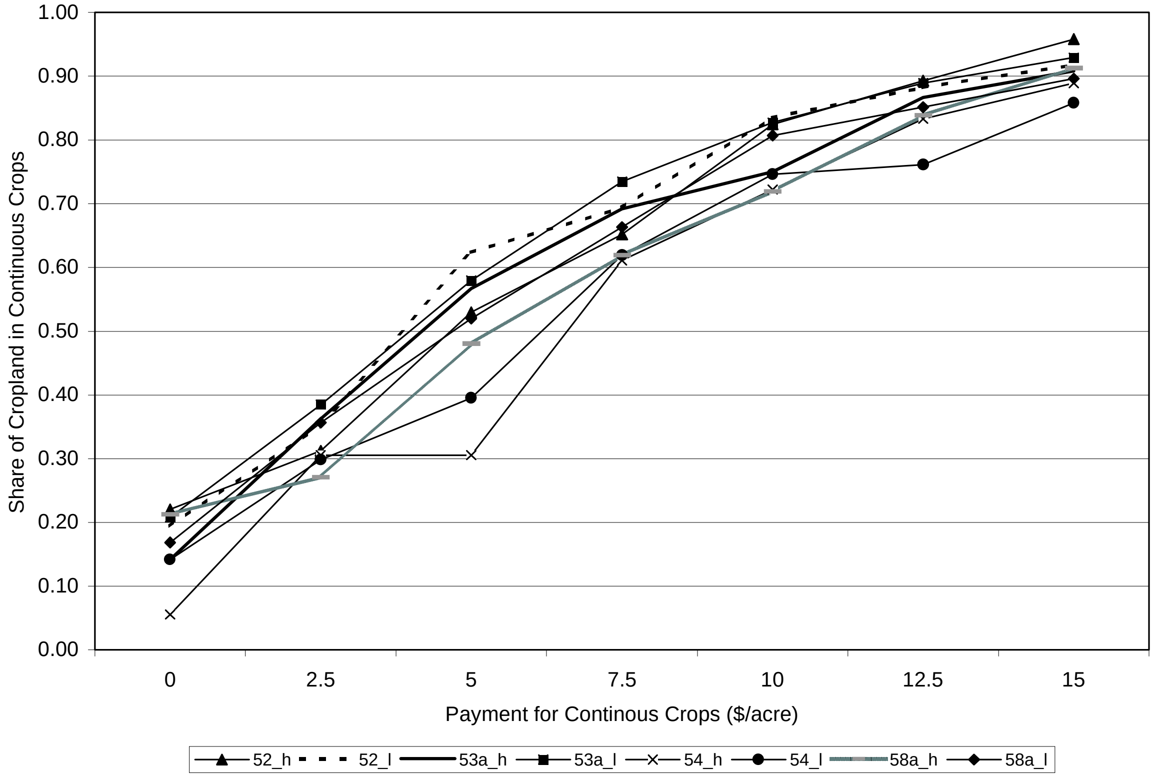


Figure 6. Share of Crop Land in Continuous Crops with Payments per Acre for Continuous Crops

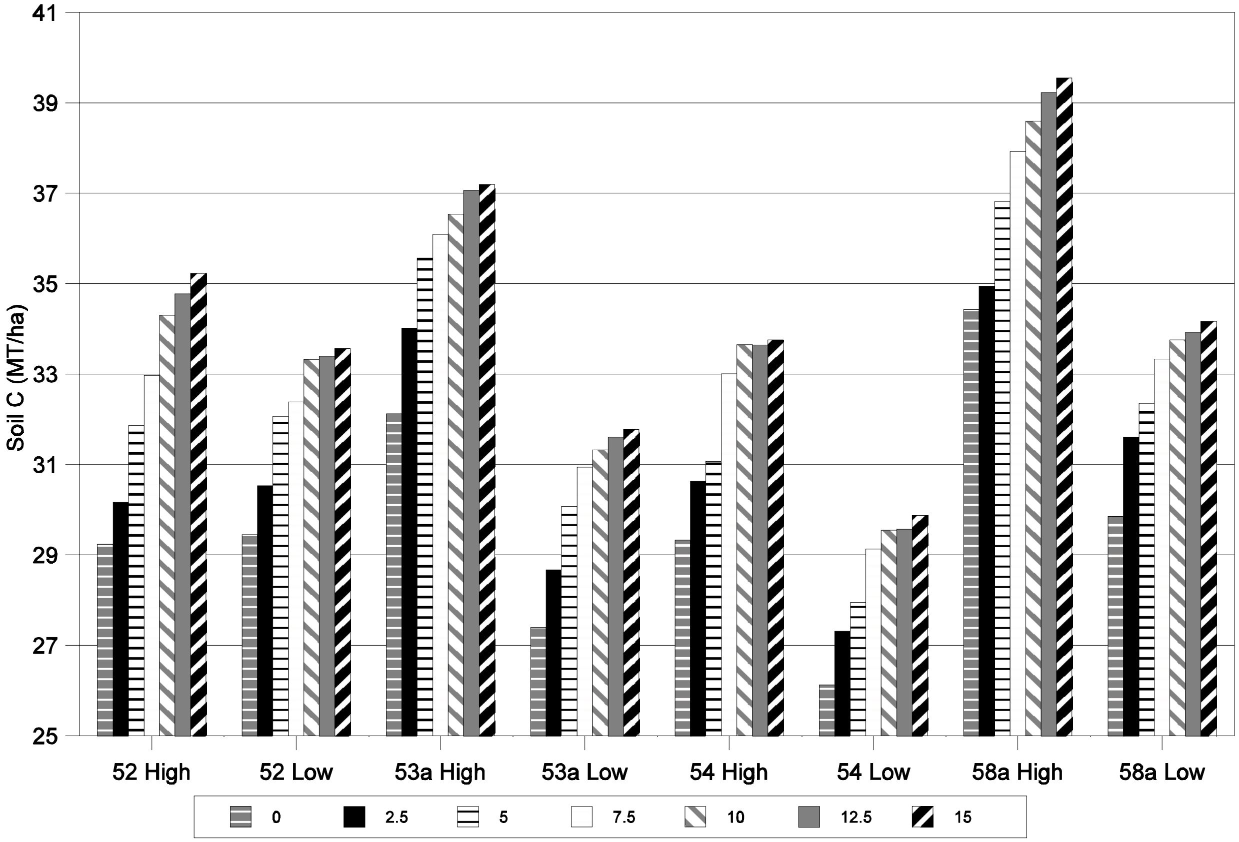


Figure 7. Soil C Levels with Per-Acre Payments for Conversion from Crop/Fallow to Continuous Cropping

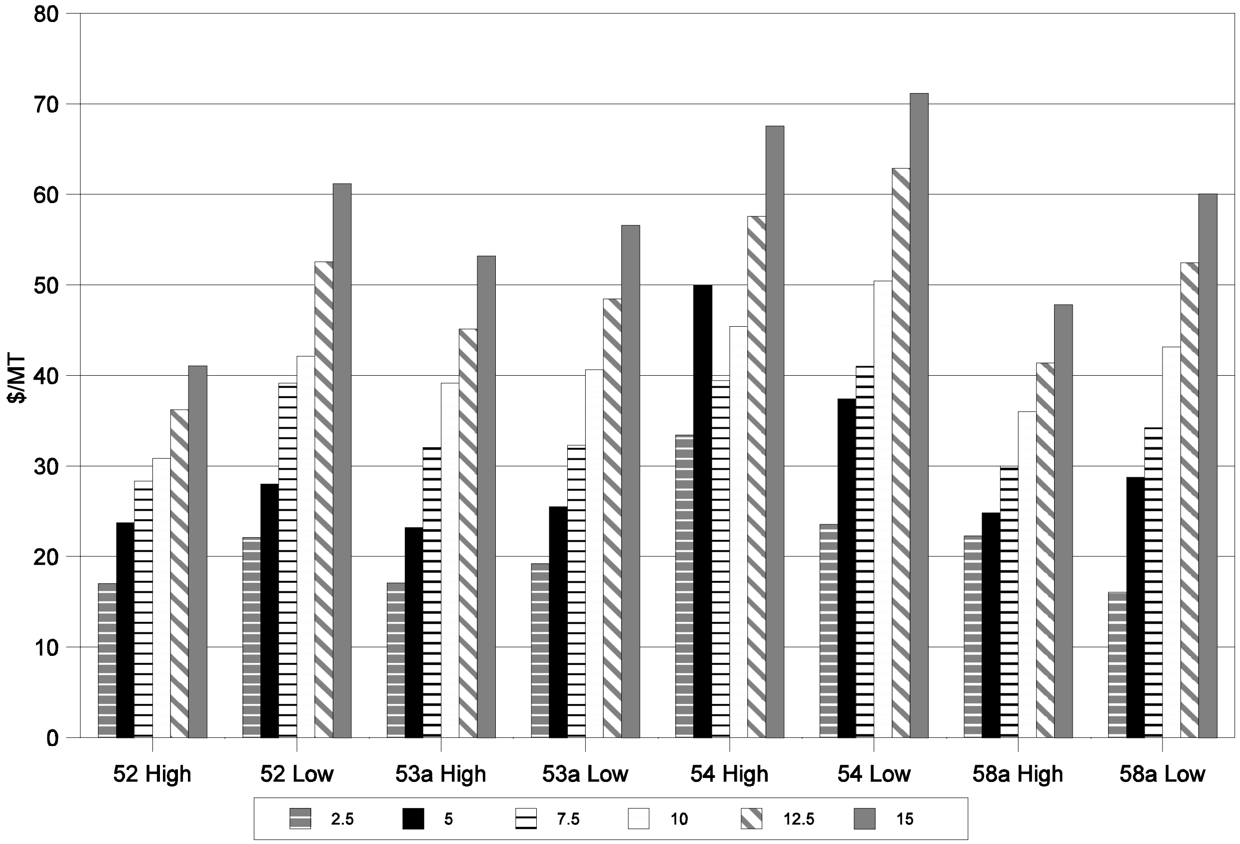


Figure 8. Costs per MT C for Non-Targeted Payments for Conversion from Crop/Fallow to Continuous Cropping

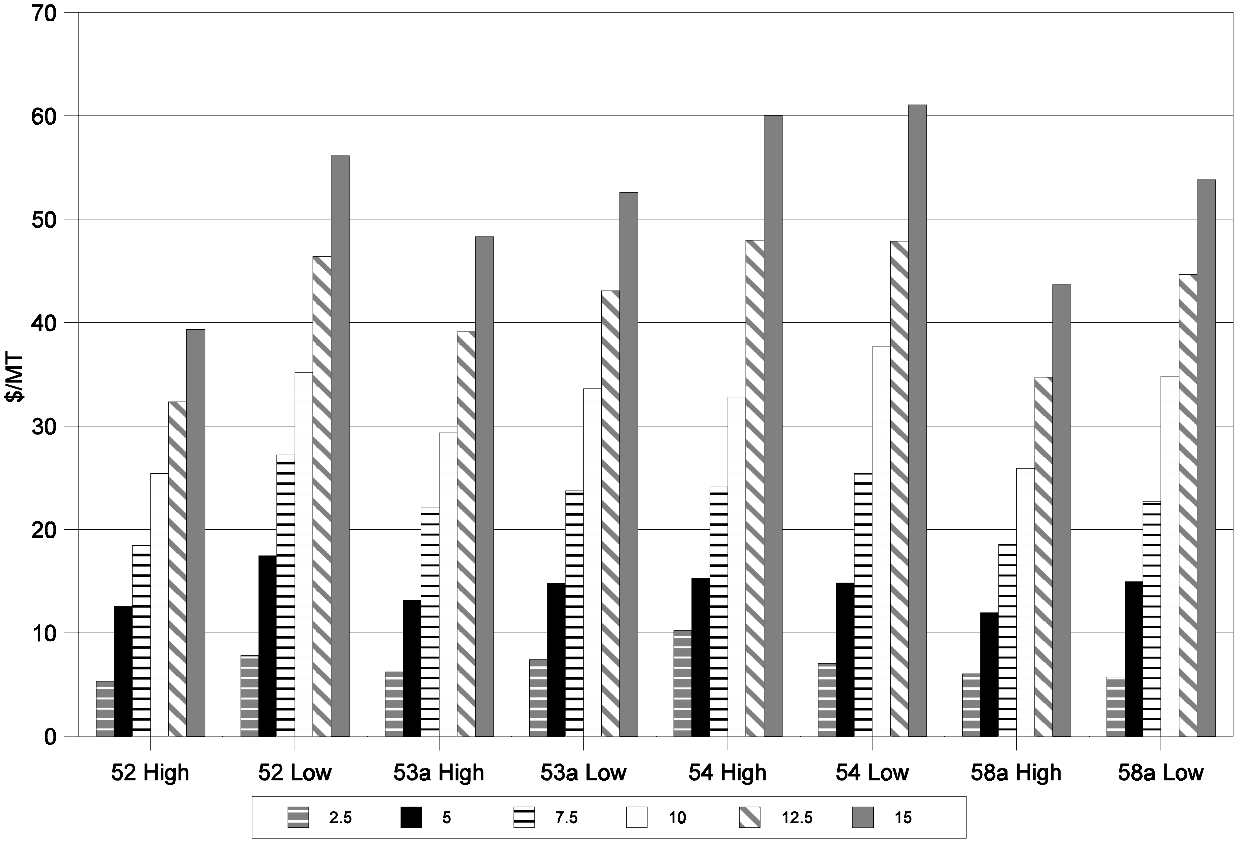


Figure 9. Costs per MT C for Targeted Payments for Conversion of Crop/Fallow to Continuous Cropping

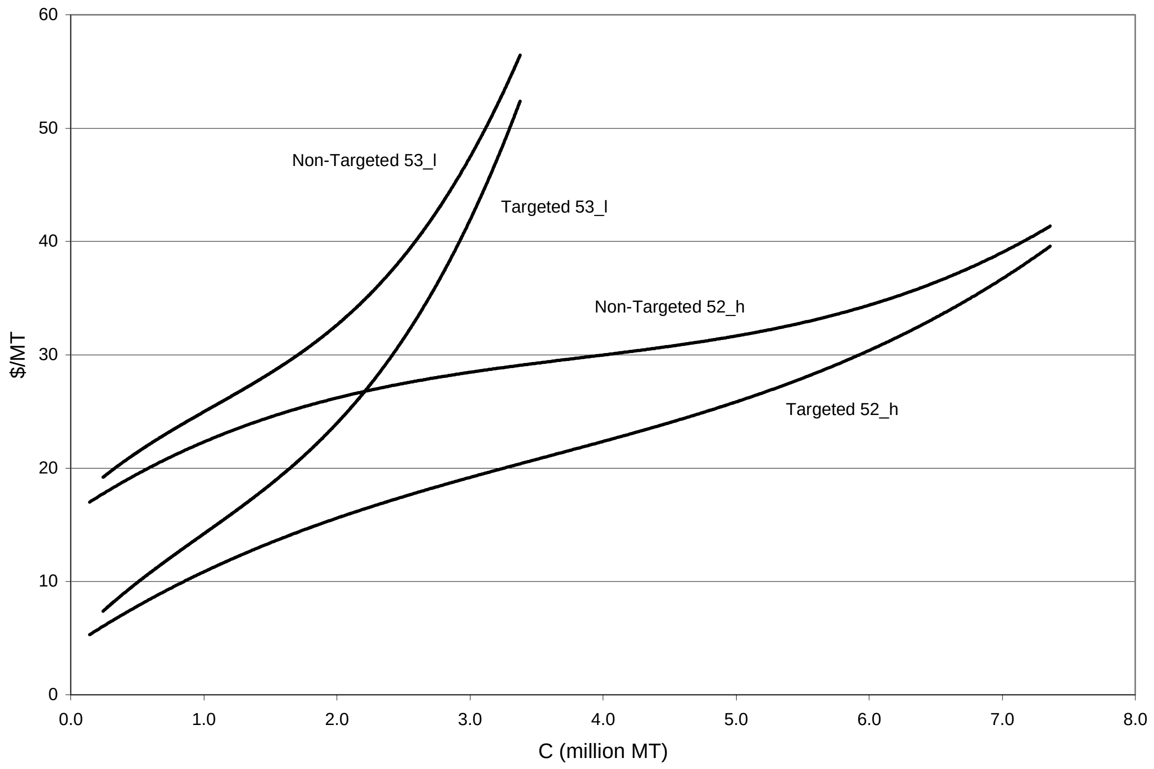


Figure 10. Marginal Cost Curves for Soil under Non-Targeted and Targeted Payments for Two Sub-MLRAs in Montana