The Supply of Terrestrial Carbon Sequestration in Minnesota

Stephen Polasky and Yang Liu

Abstract

This study derives a “supply curve” for carbon sequestration in Minnesota that describes the amount of carbon that could be sequestered for various levels of credit payments. We examine a range of different land-use and land-management practices identified by soil scientists as having potential to sequester large amounts of carbon and having sufficient information upon which to base estimates. These land-use and land-management practices are: land retirement, afforestation, agroforestry, wetland restoration and cover crop adoption. We estimate the costs to landowners of land-use or land-management changes on a per-acre basis. The costs of carbon sequestration include the opportunity costs of agricultural land and conversion costs to alternative practices. We combine information about cost with biophysical information about carbon sequestration rates to calculate the cost of carbon sequestration per ton. We estimate the costs of carbon sequestration for each alternative land-use and land-management practice in each NASS (National Agricultural Statistical Survey) region. The regional supply curve for sequestration is derived by allocating land to the use or practice that gives has the lowest cost per unit of carbon first and sequentially adding in more costly uses or practices. A state-wide carbon supply curve is constructed by aggregating the regional curves. We find that planting a cover crop appears to be the least costly carbon sequestration alternative in most regions. However, the cover crop sequestration rate is based on a single study. This sequestration rate may not be accurate for all soil types or all regions in Minnesota. More research is needed on this option before policy conclusions can be reached regarding this practice. Wetland restoration and afforestation are the next most cost-effective practices. By restoring wetland on wet soils and planting trees on dry soils, more than 20 MMT of carbon can be sequestered in Minnesota annually. This figure is likely to be far higher than can be realized in practice as it assumes a 100% adoption rate. The marginal cost of sequestration ranges from below zero for extremely low-quality agricultural land to $135/MT for the most fertile land.

Contact Information:

Stephen Polasky, Professor
Department of Applied Economics
337e Classroom Office Building, 1994 Buford Ave
St. Paul, MN 55108
Tel: 612-625-9213
Email: polasky@umn.edu

Yang Liu, Research Assistant
Department of Applied Economics
326 Classroom Office Building, 1994 Buford Ave
St. Paul, MN 55108
Tel: 612-625-1724
Email: liux0430@umn.edu

This white paper is one of three papers produced by the Minnesota Terrestrial Carbon Sequestration Project, a research and public forum on biophysical, economic, and policy aspects of terrestrial sequestration. The Project is sponsored by the University of Minnesota Water Resources Center and the Initiative for Renewable Energy and Environment, Xcel Energy Foundation, the Minnesota Department of Agriculture and the Natural Resources Conservation Service. Papers and information are available at the Project’s Web site: http://wrc.umn.edu/outreach/carbon/.

Introduction

The purpose of the economic analysis of the Minnesota Terrestrial Carbon Sequestration Project is to estimate supply curve for carbon sequestration in Minnesota through alternative land-use and land-management practices. We combine biophysical analysis of the carbon sequestration potential, along with economic analysis of the returns, generated by various land-use and land-management practices to estimate a "supply function" for carbon sequestration. The carbon sequestration supply function shows how much carbon can be sequestered at various levels of payments per ton of carbon. The analysis also allows us to calculate the amount of carbon sequestration that can be achieved per dollar invested in various changes in land use or land management, thereby showing what types of investments yield the highest rate of return in terms of carbon sequestered per dollar invested.

We analyzed alternatives to the current dominant agricultural land-use of growing corn and soybeans. After initial investigation of the carbon sequestration potentials of different land-uses and land-management practices in Minnesota, five major alternative land uses were identified as having both a large potential for carbon sequestration and an adequate knowledge base on which to base further investigation and integration with the economic analysis. These five alternative land-uses and land-management practices are: land retirement, afforestation, agroforestry, wetland restoration, and cover crop adoption. The first four alternatives involve converting agricultural land to alternative uses. Land retirement converts cropland to grassland that is not managed for any type of crop production. This alternative follows the program requirements of the Conservation Reserve Program (CRP). The owner of CRP land receives CRP rental payments as well as any potential carbon credits for that land. Afforestation refers to a land use change from cropland or pasture to forestry, without timber harvesting. Agroforestry is a land-use system that involves introduction and periodic harvesting of trees or other woody perennials. In Minnesota, agroforestry mainly includes hybrid poplar. We assume that poplar plants will be harvested every 12 years. In the rest of the paper, we will use poplar and agroforestry interchangeably. For wetland restoration, only restoration on hydric soil is considered. Wetland creation on non-hydric soils is very costly (it can be as expensive as over $7000/acre), so it is excluded from the analysis. The final alternative, cover crop, involves a change in management but not land use. A cover crop is planted between major crop rotations. There has been limited research on the use of cover crop, but a recent study in Minnesota on winter rye demonstrates its potential for carbon sequestration.

Literature review

There have been several prior economic studies on the costs of carbon sequestration through afforestation (Alig et al. 1997; Park and Hardie 1995; Lubowski, Plantinga and Stavins 2006; Plantinga, Mauldin and Miller 1999; Stavins 1999), a few prior economic studies on the costs of carbon sequestration through land retirement (Antle et al. 2001; Feng et al. 2004), and virtually no prior studies on the costs of carbon sequestration through wetland restoration or cover crop adoption. However, the underlying theory is very similar for each practice. Economists evaluate the costs and benefits of each land-use/land-management practice, and compare them with the current (baseline) agricultural use. The costs of land conversion include the opportunity costs of agricultural land, establishment costs of the new practice and maintenance costs after conversion. Establishment costs and maintenance costs are assumed fixed across the state for each practice.

There are, however, large differences in the opportunity costs of agricultural land, which vary with geographic location and land productivity. There are three major approaches to costs estimation by economists: engineering costs study, sectoral optimization models and econometric analysis.

Engineering cost study (bottom-up)

The engineering model generally uses reported land prices to estimate the social cost of converting land from one use to another (Park and Hardie 1995). A marginal cost curve is constructed using information on revenues and costs of production for alternative land uses assuming representative types or locations of land, then sorting these data in ascending order of costs. Usually researchers need to estimate available land area, forest carbon accumulation rates, land values and planting costs for hypothetical sequestration programs. They can also use the observed sale and rental prices of agricultural land instead of the forgone net revenue, if they are available. This approach assumes that farmers will maximize their profits given the information on costs and benefits of alternative practices.

The bottom-up approach does not address the issue of leakage, which refers to decreasing carbon sequestration or increases in greenhouse gas emissions induced by price changes associated with market adjustments in response to carbon incentives. For example, when more people convert agricultural land to forests in the project area due to the carbon credit incentive they receive, the supply of timber products increases and the price of timber products will likely drop. This price drop may drive other landowners to convert forestry to agricultural practices as they see agricultural production is now more profitable than timber harvest. The CO_2 emissions that result from this deforestation could partially or completely negate the benefits of afforestation in the project area.

Sectoral optimization models (FASOM)

When the leakage problem is significant, a two-sector (agriculture and forestry), multi-period model can be used. Two-sector models can address the question of how landowners will respond to changes in prices caused by changes in policies or other perturbations, and can predict consequent land-use changes between agriculture and forestry (Alig et al. 1997). The opportunity costs of land are calculated as one component of the optimization process. In this model, prices are no longer fixed, but are updated each period according to market supply and demand. Landowners respond to price changes and land conversions can go in either direction, from agriculture to forestry, or forestry to agriculture, depending upon which land use is most profitable for the landowner. Both the engineering model and the sectoral optimization model assume that landowners' decisions are entirely driven by profit maximization. In reality, of course, this is not true. Landowner decisions typically factor in other considerations such as a conservation ethic or past experience rather than strictly being driven by observable benefits and costs.

Econometric studies, the revealed-preference approach

Econometric studies are based on observed choices among alternatives rather than assuming profit maximizing choices (Lubowski, Plantinga and Stavins 2006; Plantinga, Mauldin and Miller 1999; Stavins 1999). The revealed-preference approach analyzes how landowners historically have allocated land use between agriculture and forest in response to different timber and agricultural product prices, and statistically estimates a response function. Usually such studies estimate the probability of switching from an agricultural practice to an alternative use as a function of prices, land quality, land location, etc. Including a carbon credit in the model allows one to simulate the amount of land conversion that is likely to occur at various levels of the credit. Drawbacks of the econometric approach include the large data requirements and the assumption that future choices will behave in a similar fashion to past changes.

Methodology and model

In our study, we use the bottom-up approach mainly due to data availability. Econometric models usually require panel data with parcel level land-use information, which is hard to get. Some other studies used county-level data, including proportion of land engaged in agricultural and forestry activities and the change of land use over time. However, county-level aggregate data do not capture land quality differentiation within the county and thus are not very reliable. Besides model selection, there are a number of other issues that require attention when doing an economic analysis of carbon sequestration.

Carbon-stock equilibrium and saturation

Carbon-stock equilibrium refers to the finite period of time that terrestrial systems can accumulate additional carbon under a new management system. Over time, assuming relatively constant environmental and management conditions, rates of carbon additions and emissions tend to equilibrate and the amount of organic carbon in soils stabilizes at a constant, or steady-state level, which is also referred to as saturation. This problem is addressed in the paper by recognizing the time span of carbon accumulation of different practices. For afforestation (all species), carbon accumulates at a decreasing rate before it saturates at around 100-120 years. On the other hand, wetlands can sequester carbon at a constant rate over a very long period of time (for example, peatlands in Minnesota have been continuously sequestering carbon since the last ice age).

Co-benefits/costs

Carbon sequestration is not separable from other environmental effects of a given land-use practice. For example, the introduction of cover crops also reduces soil erosion. The list of potential co-benefits is large, including wildlife habitat provision, water quality improvement, and landscape aesthetics. A few existing studies have addressed the issue of co-benefit. Matthews, O'Connor, and Plantinga (2002) found that carbon sequestration through afforestation has significant positive impacts on biodiversity. McCarl and Schneider (2001) found reduced levels of erosion, phosphorous, and nitrogen pollution from traditional cropland as carbon price increase. Greenhalgh and Sauer (2003) showed that the water quality co-benefit of carbon sequestration is significant. These studies have not attempted to quantify the monetary benefits of these co-benefits. Since payments are based on carbon sequestration amount, co-benefits will be mentioned in a qualitative manner, but are not included in the quantitative economic analysis.

Uncertainty of carbon sequestration

A practical issue hindering the development of a market for carbon credits is the uncertainty associated with sequestration. A market for carbon credits is one way to generate payments to landowners for practices for carbon sequestration. In a carbon-credit market, industrial firms, electric utilities, and other large emitters of greenhouse gases, could purchase carbon credits to cover their emissions of greenhouse gases from landowners who could guarantee a certain amount of carbon sequestration. However, future carbon credits for landowners are uncertain because carbon sequestration in agricultural soil is affected by various factors, such as weather and solar radiation, which are inherently stochastic. It is also difficult to measure and monitor carbon sequestration in soils, making it difficult to certify the required level of carbon sequestration. There is also the question of permanence of carbon sequestration. For example, a forest fire may release carbon stored in forests.

In addition to natural variation, currently there is much we do not know about the biophysical and economic aspects of carbon sequestration. We plan to address the issue of lack of knowledge and uncertainty by using Monte Carlo simulation over both economic and biophysical factors to generate a confidence interval for the carbon supply function. This analysis will be included in the next step of the analysis (but is not included in this white paper).

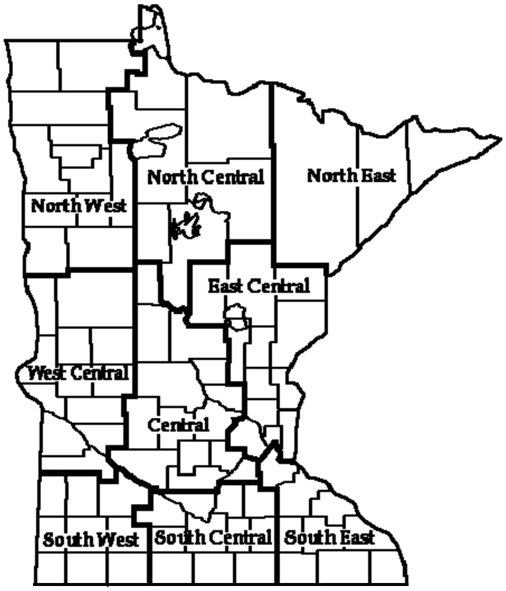

Figure 1. USDA National Agricultural Statistics Service reporting district boundaries (Minnesota Land Economics)

In this study, the state of Minnesota is grouped into nine NASS (National Agricultural Statistical Service) Districts (see Figure 1). We are mostly concerned with converting agricultural land to alternative uses or adopting new cultivation practices, therefore north east and north central districts are excluded from the analysis. The east central district is also excluded because it includes the seven-county metro area and sales prices are no longer an accurate reflection of agricultural land values. We believe that soils with the same productivity within each NASS district generate similar agricultural returns but that these returns may vary across districts. Analysis is done separately for each of the six districts. At the end, a state-level aggregate carbon supply will be generated by summing up the six individual district supply curves.

We analyze a profit-maximizing landowner's problem to determine examine the conditions under which an individual landowner would decide to switch from current agricultural production to an alternative land use. Let the discounted present value of the owner's current practice from agricultural land i be $\pi_i^0(q_i)$, where q_i is a continuous variable that indicates the quality (or productivity) of the land. To measure land productivity, we use the Crop Equivalent Ratings (CER). This measure was developed by University of Minnesota soil scientists for hundreds of soils in over 40 counties. The ratings range from 0 to 100, with 100 being the value assigned to the most productive soil in the entire state (Minnesota Land Economics). Let the present value of the alternative practices be $\pi_i^{a_j}(q_i)$, for j = 1, 2, 3, 4, 5, where these represent the five alternative land-use/land-management practices that are suitable for carbon sequestration in Minnesota: a_1=land retirement (CRP); a_2=wetland restoration; a_3=cover crop adoption; a_4= afforestation with pine; and a_5=agroforestation with poplar. We compare $\pi_i^0(q_i)$ with the five alternatives, $\pi_i^{a_1}(q_i),\cdots,\pi_i^{a_5}(q_i)$. If for a given q_i, $\pi_i^0(q_i) \geq \pi_i^{a_j}(q_i) - C^{a_j}$, for all j, land should remain in the current use (agriculture), where C^{a_j} is the sum of conversion costs from agriculture land to alternative practice j, and the maintenance costs thereafter. We assume that conversion costs do not vary by land quality (q_i) but are only a function of the alternative land use or practice. If $\pi_i^0(q_i) < \pi_i^{a_j}(q_i) - C^{a_j}$ for some j, agricultural land should be converted to the alternative practice.

Next we consider the policy-maker's problem. The policy-maker has a fixed budget that can be used to pay landowners to switch to alternative land-uses or land-management practices. Let $p_i^{a_j}$ be the price needed for a profit-maximizing landowner to switch from current agricultural management to alternative a_j: $\pi_i^0(q_i) = \pi_i^{a_j}(q_i) - C^{a_j} + p_i^{a_j}$. The policy-maker wants to get the most carbon sequestered per dollar invested, i.e., pay the lowest possible price per unit of carbon, in order to maximize the amount of carbon sequestered given the budget. Given the five alternative choices and a fixed budget, land will be switched out of current agricultural management into alternative land-uses or land-management practices in order from highest carbon sequestered per dollar invested to lowest carbon sequestered per dollar invested until the budget is fully allocated. Within one NASS district, we aggregate all land with the same CER. Let $\bar{x}_i$ be the area of land with CER i, i=1, 2, ….100; and let $c_i^{a_j}$ be the amount of additional carbon sequestered per unit area using practice a_j for land with CER i. However, the data from the biophysical side do not differentiate carbon sequestration ability according to land quality. Therefore, $c_i^{a_j} = c_k^{a_j} = c^{a_j}$. x_i is the acreage from CER i that will be enrolled in practice j. Mathematically, for any given a_j, the policy-makers' problem is

$$\text{Max } \sum_i x_i c^{a_j}$$

$$s.t. \quad \sum_i x_i p_i^{a_j} = \bar{B},\ 0 \leq x_i \leq \bar{x}_i. \quad (1)$$

Solving this simple maximization problem, we get the following results. λ^* is the shadow price of carbon sequestration and $\frac{c^{a_j^*}}{p_i^{a_j^*}}$ is the marginal benefit (carbon sequestered) per dollar from land with CER i when practice a_j is chosen. Land with CER i will be converted to practice a_j as long as marginal benefit exceeds marginal costs, that is $\frac{c^{a_j^*}}{p_i^{a_j^*}} > \lambda^*$. By varying the budget, the value of λ* will vary and we can solve for different levels of carbon sequestration and different overall cost.

Procedures and Data

Opportunity costs of agricultural land

$\pi_i^0(q_j)$ is the opportunity costs of agricultural land with current management practices. It is the value the landowner will forgo if she chooses an alternative land-use or management practice. We use the market value of land, which in theory summarizes the present value of profits generated by the land when it is allocated to its most profitable use, to represent opportunity cost of switching from agricultural land under current land-management practices. The market value of agricultural land is obtained from the farmland sales data in Minnesota. Minnesota Land Economics provides data for every farm real estate sale in the state since 1990, but this includes only "agricultural" sales of land that buyers indicate no intention to change the use of, as reported to the Minnesota Department of Revenue by county assessors. This π_i^0 is the present value of all future returns generated by the land and is not an annual rental payment.

The available data from 1990 to 2004 showed a strong positive linear relationship between sales price and CER. A simple linear regression was fitted with land sales price as the dependent variable, CER and year (treated as categorical) as explanatory variables:

$$\pi^0 = \beta_0 + \beta_1 CER + \beta_2 Year + \varepsilon \qquad (2)$$

We used the results of estimating equation (2) to generate predicted values of land prices for each CER in each district. We excluded certain sales that were significant outliers in the analysis. Most outliers had extremely high sales values corresponding to low CERs, indicating that the land is engaged in uses other than agriculture production, such as land for environmental and recreational uses, particularly lakefront properties.

Costs and benefits of alternative practices

The costs of alternative practices C^{a_j} can be divided in two main categories: establishment costs and maintenance costs. Establishment cost refers to a one-time cost incurred when cropland is converted to an alternative use, for example, forest or grassland. Maintenance costs are annual recurring costs. Total costs of conversion equal establishment costs plus the discounted present value of the total maintenance costs over the program time span. We assume a 120-year time frame for our analysis.

The benefits of the new practice refer to the profit the landowner can derive from the practice, $\pi_i^{a_j}(q_j)$. Besides monetary costs and benefits, there are environmental co-benefits/costs related to each practice, which will be mentioned later, but will not be quantified in the economic analysis.

In the biophysical review, afforestation is not limited to one particular practice. For the convenience of economic analysis, we estimate the costs of conversion based on pine. The establishment cost for pine is $150/acre, and the present value of maintenance costs are around $80/acre for a 100-year rotation (Goychuk 2005). Landowners will get a profit ranging from $300 to $2600 per acre from selling the timber products. For poplar, establishment costs are from $206 to $285 per acre and the present value of maintenance costs are $80-104 for a 12-year harvesting rotation. The total profit will be $977/acre for each 12-year rotation (Demchik et al. 2002).

For cover crop adoption, the establishment costs are not a one-time investment. Farmers have to plant the cover crop every year and remove it before the next season. The planting costs are $12-15/acre/year and the removal costs are $8-10/acre/year for winter rye (Baker 2006). The total costs of conversion are therefore the discounted present value of the sum of planting costs and removing costs over the program length. Cover crop adoption may result in increased yield and reduction of fertilizer costs in the long run. Some data from field experiments showed an increase in yield after cover crop adoption with the resulting increase in profits outweighing the costs in southern Minnesota. However, other experiments showed no significant change in yield. Since cover crop in Minnesota is not widely applied and we don't have reliable data sources, we assumed that yield (as well as profit) did not vary with cover crop adoption.

The cost of retiring agricultural land and placing it into CRP is $110/acre. The maintenance cost is $20/acre each year (USDA, 2005). Land is assumed to be left idle, and options such as haying or grazing are not considered. This means that the monetary income landowners derived from this new practice is zero.

The establishment costs of wetland restoration have a wide range, depending on the scale and local hydric conditions. Larson (2005) estimates that average costs of wetland restoration are $1060/acre. Kuester (2001) estimates the costs of restoring drained wetland to be $200-300/acre. The present value of maintenance cost is approximately $100/acre for the entire program time span. We also assume that once the conversion is done, the wetland is left alone and will not generate any profits. Table 1 summarizes the costs and benefits of alternative land uses.

Carbon sequestration rates

We base our carbon sequestration rates for all the five practices from work by Dr. Ed Nater and Megan Lennon (refer to the white paper on the biophysical aspects of carbon sequestration). For land retirement, cover crop and wetland, we use a weighted average carbon sequestration rate over all land types. The average carbon sequestration rate for land retirement, cover crop and wetland is 0.41 metric ton (MT)/acre/year, 1.01 MT/acre/year and 1.23 MT/acre/year, respectively. Compared to other practices, the advantage of wetlands is that they will not saturate for a very long time (thousands of years). For afforestation, we get a carbon sequestration curve over 120 years. The curves are strictly increasing and concave for all species in our analysis, and they all flatten out after 100-120 years. Table 2 provides the annual sequestration rates of alternative practices. They will be used in the baseline analysis. Later, the present value of carbon sequestration will be calculated and presented in the sensitivity analysis.

Payment required to change land use

Landowners will switch to alternative land use or land-management practice if they receive payments exceeding the sum of agricultural opportunity costs and conversion costs. In this analysis, a one-time asset payment is used instead of an annual rental payment. Both the opportunity costs of the land, the value of the land in our case, and the conversion costs are upfront costs that do not need to be discounted. For recurring costs, such as maintenance and management costs, we calculate the discounted present value over the term of the project. These calculations generate the payment per acre for land-use changes, divided by additional carbon flow in tons per acre, from which we can get the costs of carbon sequestration, a dollar-per-metric-ton figure.

Table 1. Summary of annual costs and benefits for alternative practices

Practices		**Forestry**		**Cover Crop (Winter Rye)**	**CRP**	**Wetland Restoration**
		Afforestation	Agroforestry			
Costs ($/acre)	Land value	Yes	Yes	No	Yes	Yes
	Conversion costs on an annual basis	10.98	35.53	22	24.78	14.33
Benefits	Monetary ($/acre)	0 (assuming no harvesting)	55.21	0	CRP rental payment	0
	Environmental co-benefits (costs)	Improve water quality; habitat for wildlife; recreation values; etc. (Paper production from poplar will emit toxic chemicals into the air and water.)		More efficient utilization of water resources; reduction in water runoff and soil erosion; reduction in nutrient pollution of groundwater and surface water sources.	Prevent loss of topsoil; improve water quality	Improve water quality; Protect stream banks and shore lines from erosion; Reduce severity of floods downstream; Recharge groundwater; Provide habitat for fish and wildlife; recreational values

Table 2. Summary of annual carbon yield of alternative land uses (MT/acre/year).

Practices	**Afforestation**	**Agroforestry**	**Cover Crop**	**CRP**	**Wetland**
	no harvesting	harvesting			
Carbon Value	1.09	0.48	1.01	0.41	1.23
CO_2 Value	4.00	1.76	3.71	1.50	4.51

Results

We begin by presenting baseline results for the supply curve for carbon sequestration in Minnesota using available data in Minnesota. Carbon sequestration supply curves are constructed for each NASS region for all the possible practices. The supply curve shows how much it costs to sequester various levels of carbon. We can also use the analysis to show the practices that are the least cost method to supply carbon sequestration. We generate a state-wide supply curve of carbon sequestration by aggregated all of the regional curves. The state supply curve shows how much carbon would likely be sequestered for a range of possible carbon-credit prices in Minnesota.

Since our analysis is based on different estimation methods and model parameters, we also analyze how changes in assumptions or data impact the results. We perform this sensitivity analysis in a region with average land values as a representative case. The sensitivity analysis shows how the costs of carbon sequestration change if some of the parameters change, such as cropland rental rate and carbon sequestration values.

Cost supply curves are constructed using a discounted present value for a 120-year time horizon. The discounted monetary value beyond 120 years, for any discount rate significantly different from zero, becomes negligible. In addition to reporting figures for the 120-year time horizon, we also report figures on an annual sequestration basis. Doing so facilitates comparison with other studies that typically report on an annual sequestration basis.

Baseline Result

Given c^{a_j} and $p_i^{a_j}$, a carbon supply curve can be constructed by sorting all land by cost per ton for each region. Since our costs per ton are linearly related to CER, this is equivalent to sorting CER from lowest to highest. For each CER, the marginal cost of carbon sequestration is calculated for all practices. The practice with the lowest costs per unit of carbon sequestered is selected. Figures 2 through 7 show the cost curves of each practice within the six regions. In general, cover crop adoption is the cheapest alternative practice. However, this result relies on a high estimate of the carbon sequestration rate for cover crop. This estimate is based on a single study and may not be accurate or valid for all soil types, regions or conditions. Because further study and better data might reveal that cover crops are less beneficial than assumed here, and may not necessarily be the dominant carbon sequestration alternative, we also report the second best solutions for alternatives besides cover crops.

In the **Northwest** region, agroforestry is the least cost carbon sequestration alternative on the lowest quality land. On very low quality land, planting poplar yields higher returns than the current agricultural use so that carbon sequestration costs are actually negative, i.e., planting poplar for these soil classes is actually a “win-win” solution. Except for extremely low-quality lands, cover-crop adoption is the lowest cost carbon sequestration practice. The cost of carbon sequestration for each alternative land use or land-management practice is shown in figure 2a. From figure 2a, we can see that afforestation has a slightly higher carbon sequestration potential than cover-crop adoption (also refer to Table 2, the carbon value of afforestation being 1.09MT/acre/year compared to cover crop being 1.01MT/acre). If more carbon needs to be sequestered than can be achieved by cover crop, we must take land out of cover crop and allocate it to afforestation. The cost per ton additional carbon sequestered in moving from cover crop to afforestation is equal to the difference in costs per acre divided by the difference in sequestration rates per acre. Figure 2b illustrates the regional supply curve of carbon. If we ignore cover crop, agroforestry and afforestation become the most cost-efficient choices. Figure 2c shows the regional supply curve without cover crop.

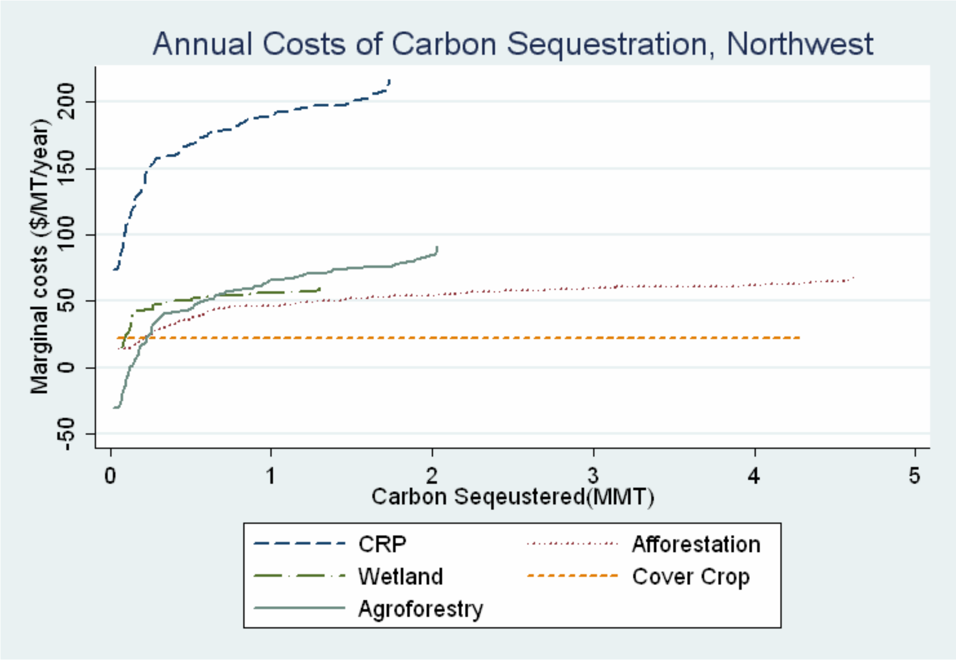

Figure 2a. Costs of carbon sequestration with all five alternative practices in the Northwest

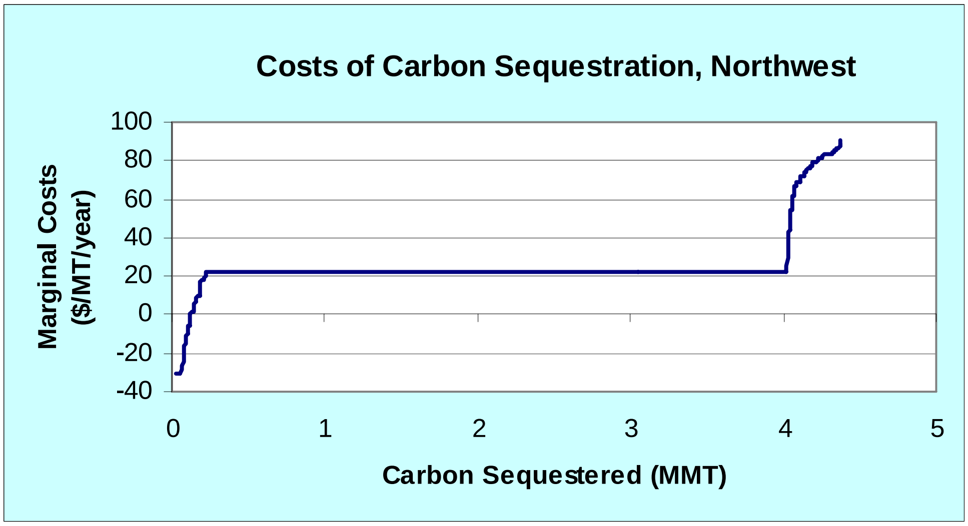

Figure 2b. Region-wide costs curve in Northwest, with cover crop

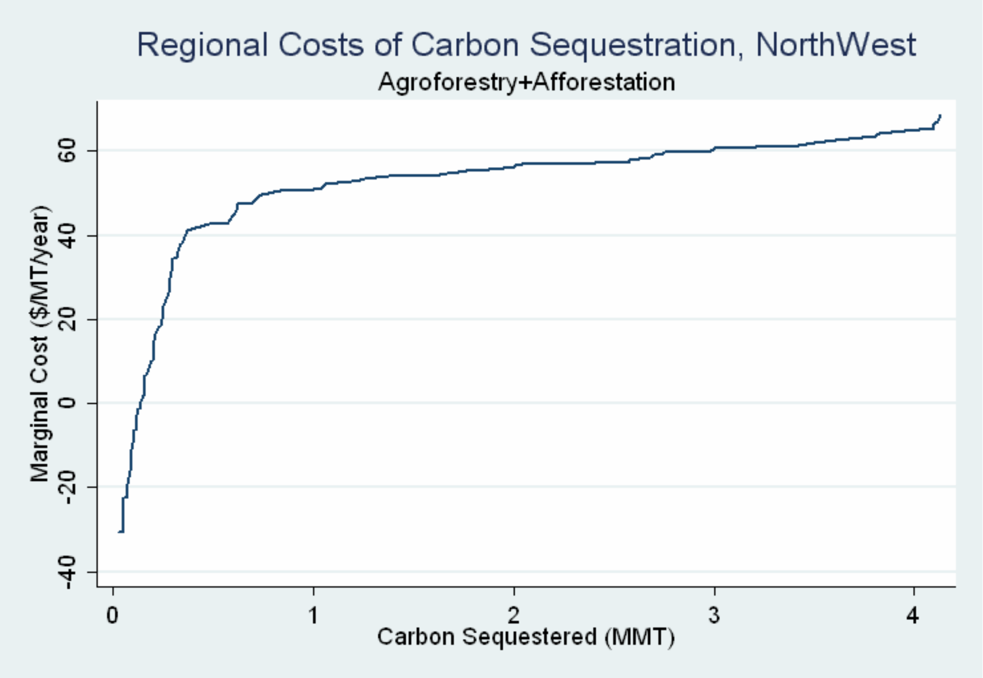

Figure 2c. Region-wide costs curve in Northwest, without cover crop

From this point on, we will discuss only the case without cover crop. In the **West Central** region, wetland restoration and afforestation are the next best choices. The cost curves of wetland and afforestation almost overlap, but wetland restoration has much lower sequestration potential. Actually, the carbon sequestration rate per acre for wetland is a little higher than that of the pre acre rate for afforestation (Table 2). However, wetland restoration can only be implemented on wet soils, which constitutes fewer than half of the total land. Comparing the marginal costs of the two practices, wetland restoration always has lower costs than afforestation on wet soils. Therefore, we should restore wetland on wet soils and grow trees on dry soils. The regional supply curve is shown in Figure 3b. As land quality increases, we switch back and forth between wetland restoration and afforestation depending on soil types. The situation for the rest of the regions is very similar to the West Central region and will not be described in detail. Results for these regions is summarized in figures 4–7.

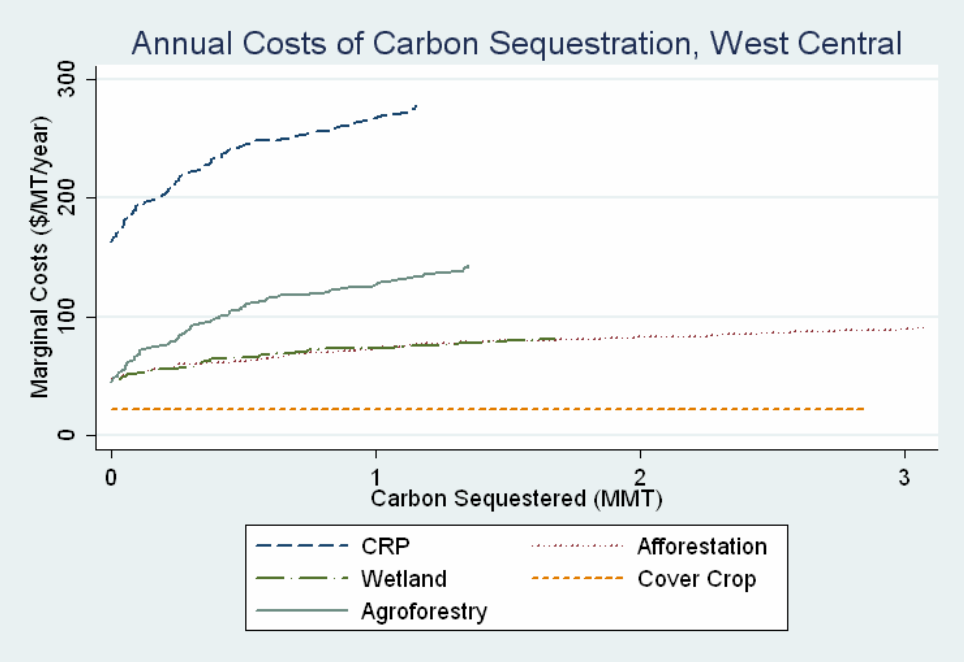

Figure 3a. Costs of carbon sequestration with all five alternative practices, West Central

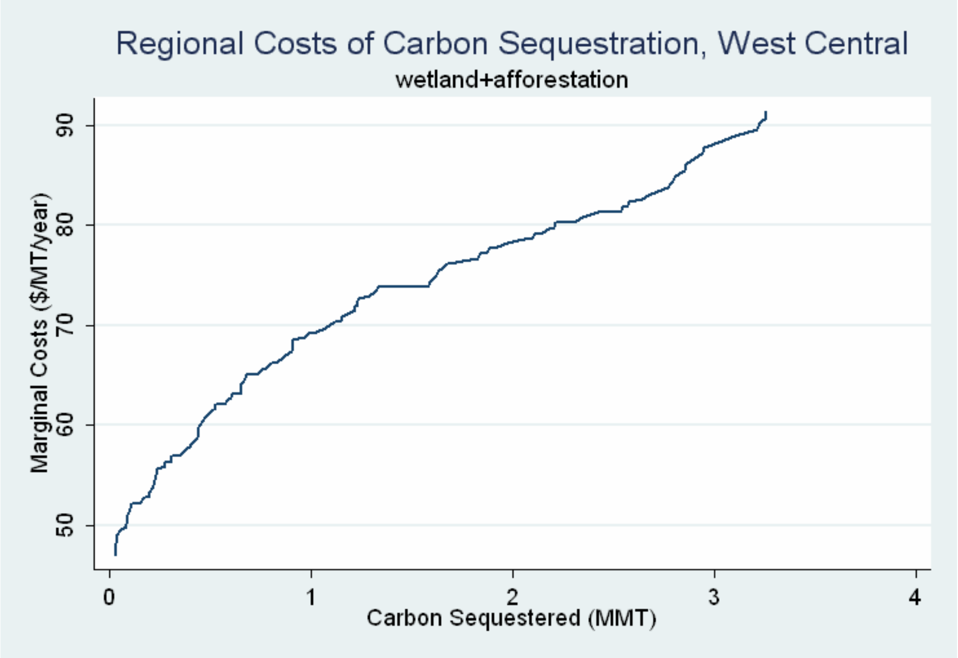

Figure 3b. Region-wide costs curve in West Central

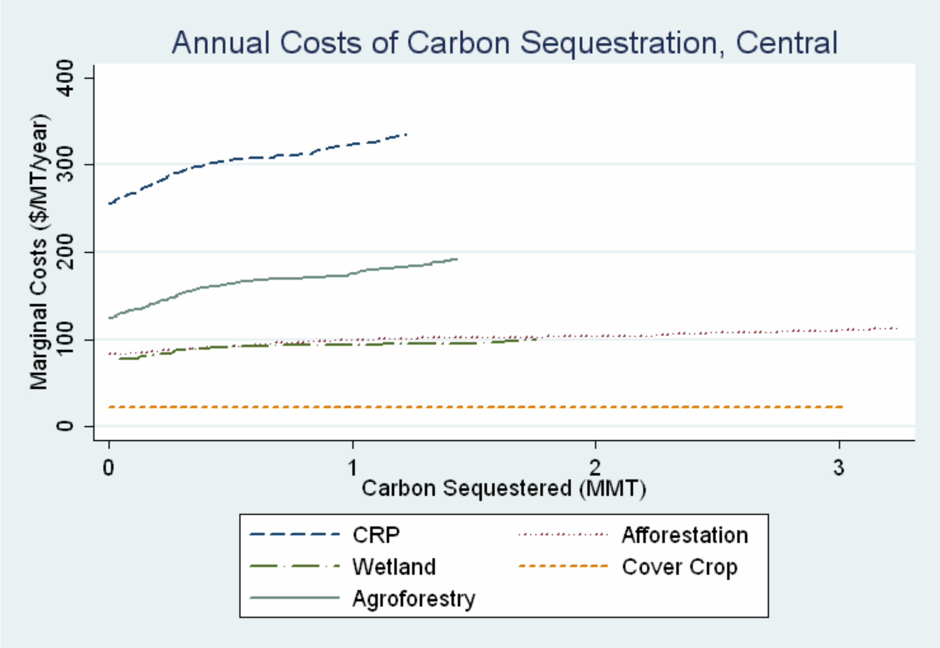

Figure 4a. Costs of carbon sequestration with all five alternative practices, Central.

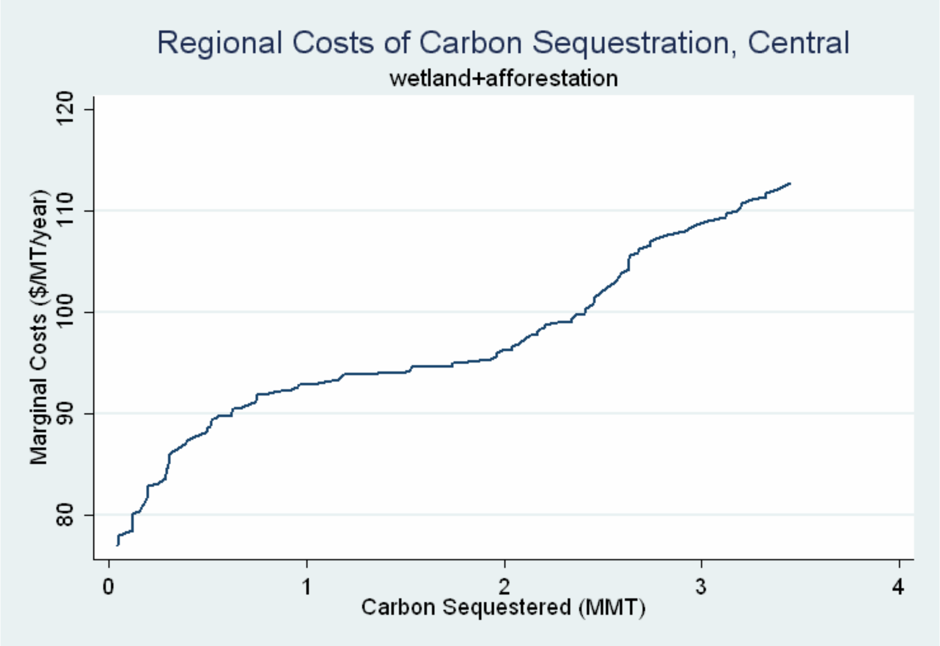

Figure 4b. Region-wide Costs Curve in Central

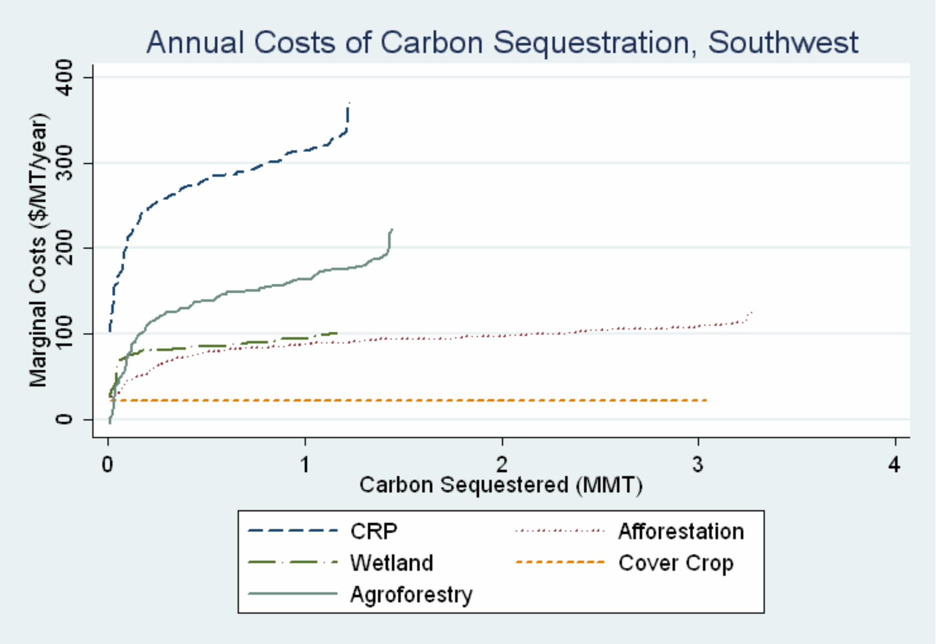

Figure 5a. Costs of carbon sequestration with all five alternative practices, Southwest

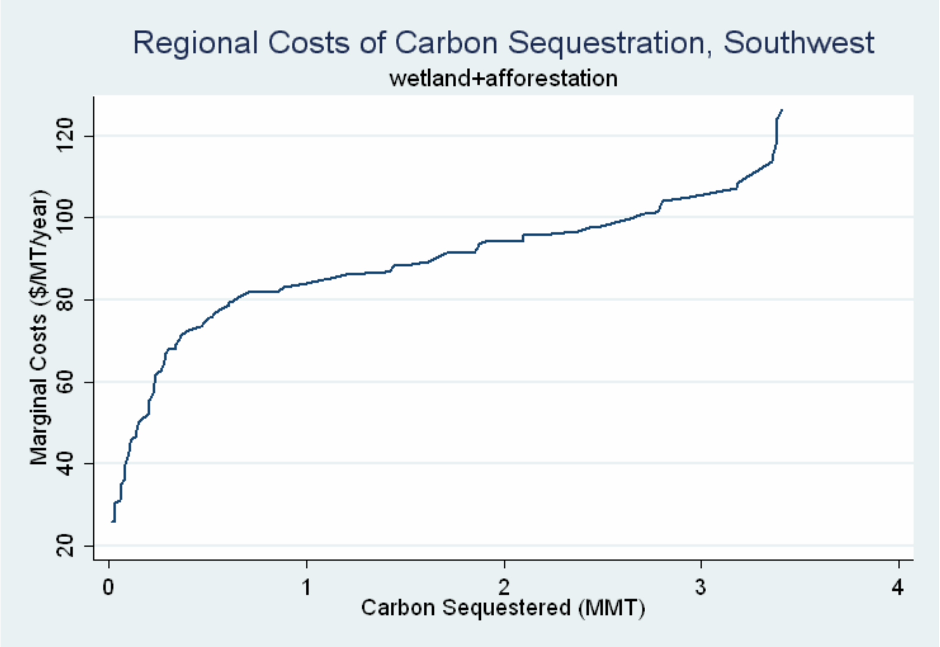

Figure 5b. Region-wide costs curve in Southwest

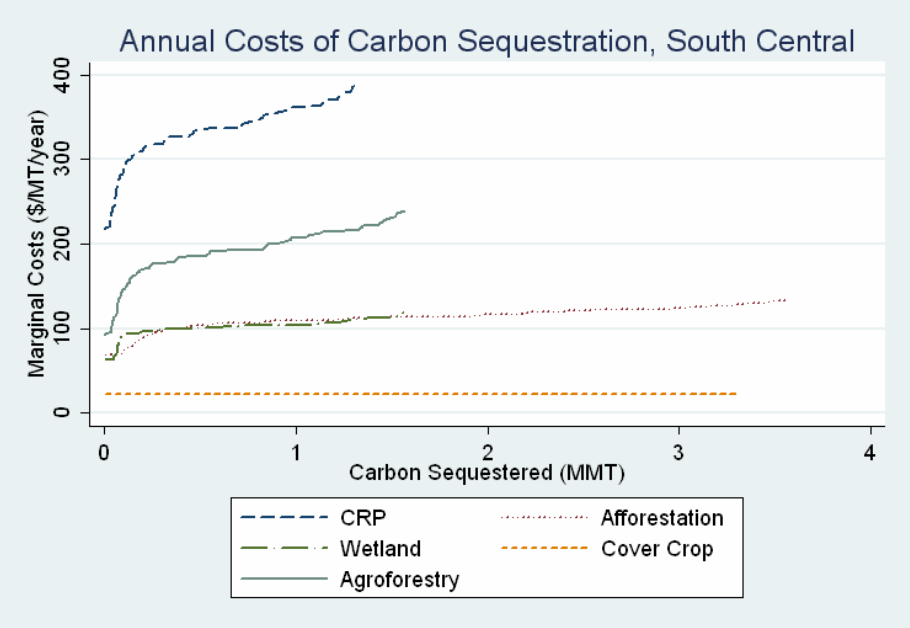

Figure 6a. Costs of carbon sequestration with all five alternative practices, South Central

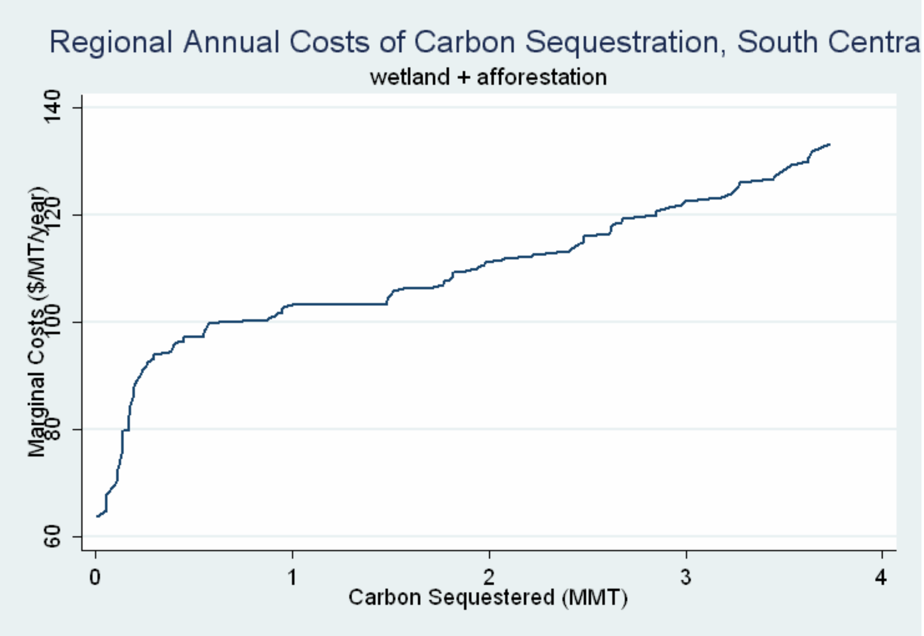

Figure 6b. Region-wide costs curve in South Central

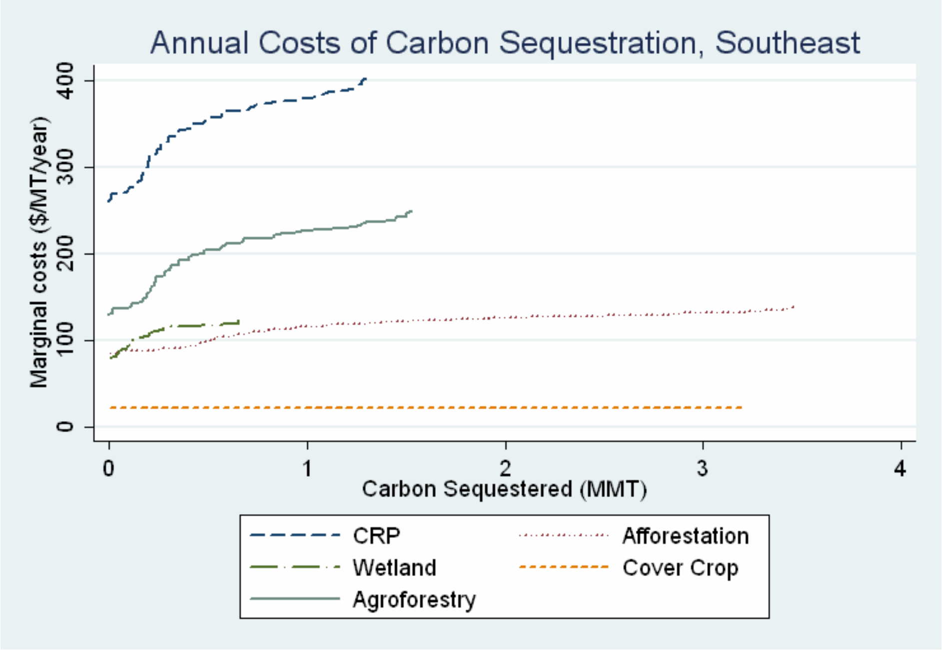

Figure 7a. Costs of carbon sequestration with all five alternative practices, Southeast

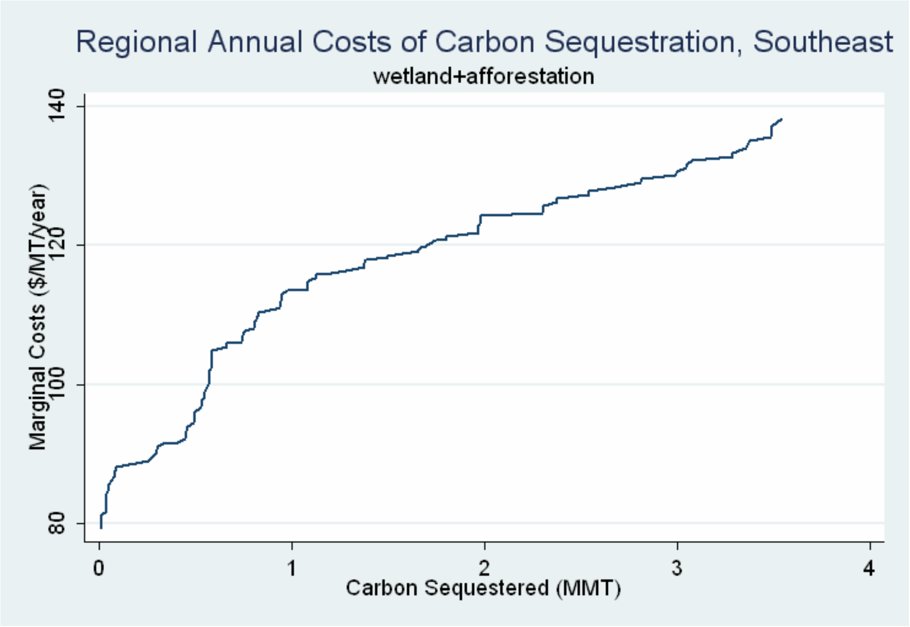

Figure 7b. Region-wide costs curve in Southeast

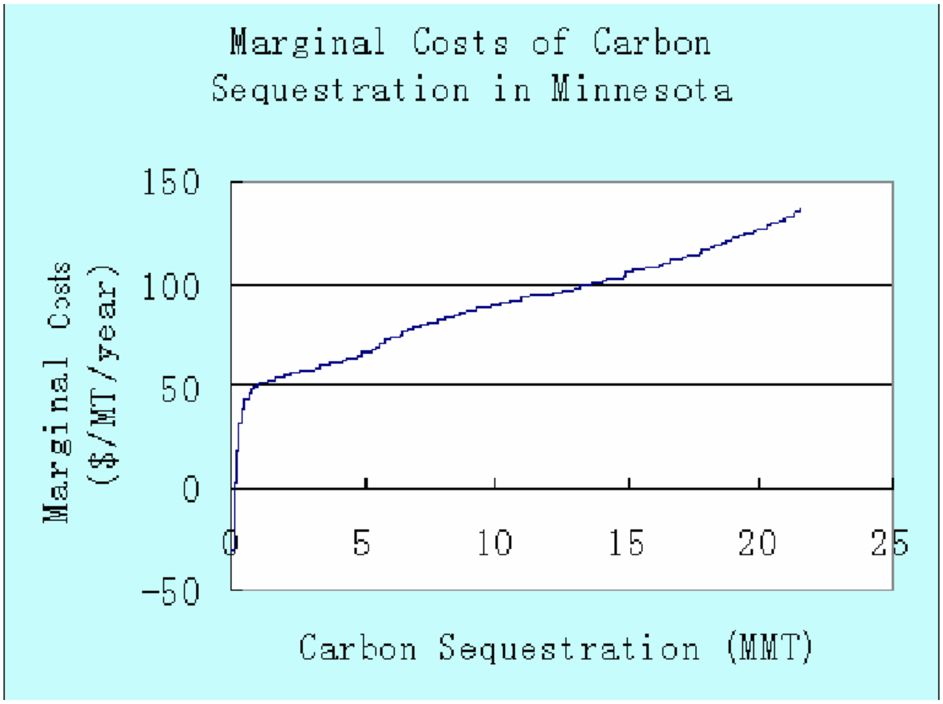

Figure 8. State wide carbon supply curve

We aggregate the supply curves from the six regions to generate a state wide carbon sequestration supply curve. This aggregation is accomplished by adding the amount of carbon sequestered at each price across the six regions. Figure 8 shows the state wide carbon sequestration supply curve that results from this aggregation. This supply curve does not incorporate cover crop adoption. The supply curve with cover crop adoption is a flat line at roughly $20/MT/year. As shown in figure 8, there as a small amount of carbon that can be sequestered at a negative price (i.e., win-win solutions). However, most carbon sequestration has reasonably high cost. Profit-maximizing private landowners will only agree to this carbon sequestration is carbon credit payments are on the order of $50 to $100/MT.

Sensitivity Analysis

We chose the West Central region as one representative region on which to conduct sensitivity analyses.

Increase rental rate of land

One of the most important components in this cost analysis is the opportunity costs of agricultural land. In this study, we used the sales price of cropland as a proxy for the land value. Since we do not have actual sales data on all the agricultural land, predicted land values are obtained using regression analysis. Comparing our estimated land value with the average rental rate per acre provided by University of Minnesota Extension Service, our estimates are reasonable (Table 3).

Table 3. Average rental rate of agricultural land in Minnesota

County	Predicted rental rate ($/acre, 2004)			Reported rental rate by U of M Extension Service ($/acre, 2005)		
	10th pctile	average	90th pctile	10th pctile	average	90th pctile
Northwest	9.7	33.1	54.7	36.8	55.4	68
West Central	47.2	66.2	83.8	50.1	72. 7	87
Central	83.9	96.7	107.9	53.7	86.9	106.9
Southwest	29.9	72.1	105.9	73.5	95.75	114.5
South Central	74.6	104.1	126.4	80.7	113.5	133.1
Southeast	88.2	112.1	132.6	69.8	113.	135

Figure 9 shows the results with a 25% increase in rental rate, using the West Central region as an example. The marginal costs of sequestration also increase by 25% for all practices except cover crop adoption, since it does not involve changing land uses.

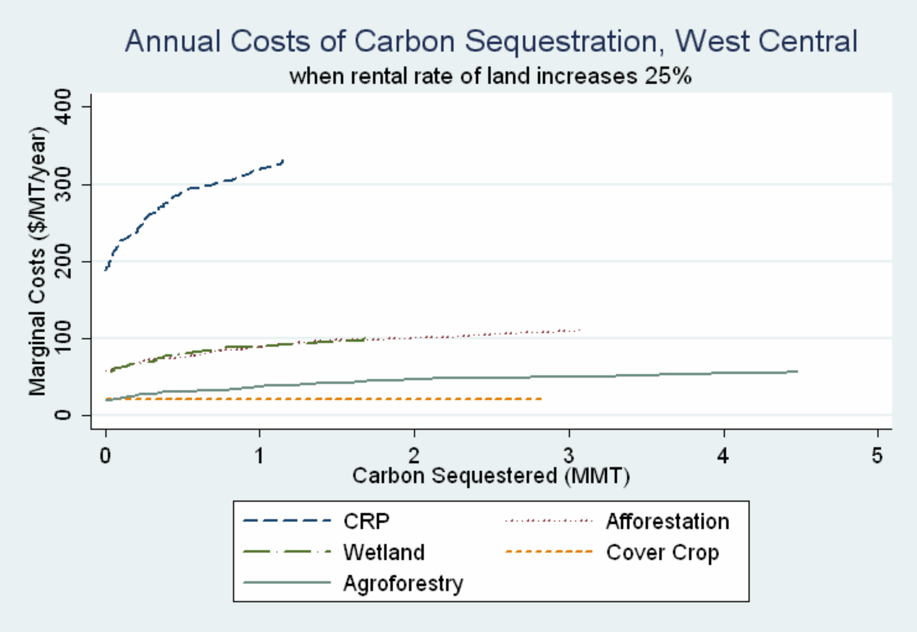

Figure 9. Annual costs of carbon sequestration when rental rate of land increases by 25%

Different discounting rates

We also explored how the choice of different discounting rates would affect our result. Figure 12 shows the regional supply curve of the West Central region with 3% and 7% discounting rates, respectively. Compared with 5% discounting rate used in our analysis, we can see that as the discounting rate increases, the marginal costs of carbon sequestration also increase.

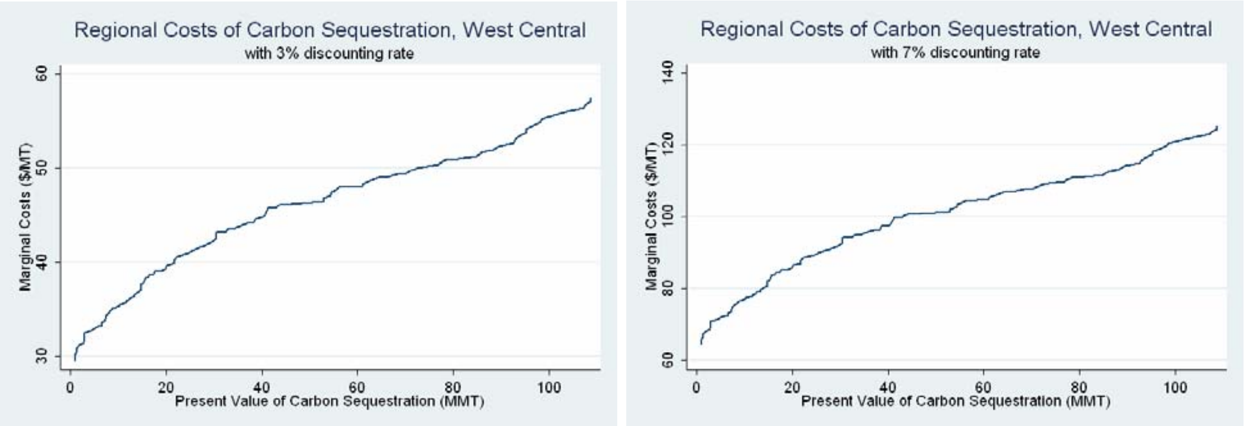

Figure 10. Costs of carbon sequestration in West Central with different discounting rates

Comparison of results to prior studies

In our study, cover crop adoption, wetland restoration and afforestation are the three least cost methods to sequester carbon in Minnesota. Most prior studies of the cost of carbon sequestration have focused on afforestation. These studies have not considered wetland restoration or cover crop adoption. Table 5 lists carbon sequestration rates through afforestation used in prior economic studies. The carbon sequestration rate we used in our study is somewhat lower than the rate used in other studies. Trees in Minnesota tend to grow at a slower rate than trees in other parts of the country (e.g., Douglas fir forests in the Pacific Northwest or Pine forests in the Southeast). Assuming a higher rate of sequestration lowers the cost per unit of sequestration and increases the total amount of sequestration that can be achieved. The carbon sequestration rate after accounting for decay of carbon post-harvest is lower in our study than the value in Plantinga et al. (1999). Plantinga et al. (1999) assumed assume that timber products are made into furniture or used in construction, which have much lower decay rates than for paper, which is what we assumed was the product made from poplar. An alternative use for poplar is to burn it for energy production. In this use, carbon is immediately returned to the atmosphere. However, a full accounting of carbon would also subtract the carbon emissions due to fuel substitution. We did not analyze use of poplar for energy or fuel substitution.

Table 6 summarizes results from several previous economic studies, for comparison with our results. Generally, the carbon sequestration potential we estimated is greater than that in most of the previous studies. The main reason for this is that previous studies either limit enrollment to 25% of the agricultural land or imposed a fixed budget for enrollment. We present the sequestration potential for the entire state without imposing any restrictions. Were we to impose caps of 25% as in Plantinga et al. (1999) we would arrive at similar conclusions regarding sequestration potential. The marginal cost in this study is higher than in Plantinga et al. (1999)

and Parks and Hardie (1995) since we assume no monetary benefits from most of the alternative practices, except for afforestation with poplar. Both of these other studies assume return from afforestation. The marginal cost curve in Feng *et al* (2004) is higher than our cost curve. In their study, based in Iowa, carbon sequestration from land retirement has higher costs than in our study because land in Iowa tends to have a higher rental rate. The average rental rate is their study was $120/acre, which is higher than the 90-percentile estimated rental rate in all NASS regions for our study.

Table 5. Comparison of Afforestation Carbon Sequestration rate of different studies

Author	**Region**	**Yield Format**	**Potential carbon yield with afforestation (MT/acre/year)**	
			no harvesting	**decay after harvesting**
Parks and Hardie(1995)	National	Average carbon flow	1.34~2.06	not specified
Stavins(1999)	Delta States	Carbon flow curve	1.85	---
Richards,et. al (1993)	Delta States	Carbon flow curve	2.64	---
Plantinga, et. al (1999)	Wisconsin	Carbon flow curve	1.22	1.07
This study	Minnesota	Average carbon flow	1.09	0.48

Table 6. Results from previous studies on the costs of carbon sequestration

Authors	Scope	Practice	Potential sequestration	Costs Range	Typical costs	Economic Method	Other information
Plantinga, Mauldin and Miller, 1999	Wisconsin	Afforestation from cropland, with and without harvesting	60 MT(short ton)	\$20~\$80/short ton;	\$40/short ton of carbon for 30 MT	Econometric approach using county level data	limited to 25% of the cropland area 1995\$, present value of 60 years 5% discount
	Maine		3.5 MT	\$20~120/short ton	\$40 for 1.5 MT and \$80 for 2.5MT		
	South Carolina		potential 16 MT	\$10~65/short ton	\$40 for 10 MT		
Park and Hardie, 1995	National	CRP, converting from cropland	120MT/year	\$4~82/year/short ton	\$500 for 50MT/year	Bottom-up	8-12% of the eligible land
Feng, et al, 2004	Iowa	CRP	6MT/year	\$100~800/Mt/year	\$300/Mt for 5 MT, \$200/Mt for 3.5 MT	Econometric approach using NRI points	
		Conservation tillage	3 MT/year	\$10~150 Mt/year	\$50 for 1.8MT		

Important Caveats in Interpreting the Results

There are several issues that need to be kept in mind when using the numbers reported for carbon sequestration costs and supply in Minnesota, as reported in this study. First, the report uses the best available information about carbon sequestration rates. But, in some cases, the “best” available data is not very good. In general, there is a need to improve the biophysical data on carbon sequestration rates and to improve our understanding of how sequestration rates are affected by soil conditions, climate, land use, and land-management practices. For afforestation, agroforestry and CRP, our understanding of carbon sequestration rates is fairly good and these data can be used with greater confidence. But for wetland restoration and cover-crop adoption, not enough prior research has been done and we have much less confidence in these results. Our results indicate that planting cover crop is a very promising approach for obtaining low cost carbon sequestration in Minnesota. However, this result is based on carbon values estimated from a single study at one location in Minnesota. We need many more studies, under different conditions, to have much confidence that cover crop adoption is really such a low-cost alternative in Minnesota.

Second, the bottom-up methodology we used in this study will under-estimate costs by overlooking factors influencing farmers’ land-use choices other than those that directly impact a farmer’ bottom-line. We assume that farmers will switch practices when the alternative land use has a higher monetary return than the current agricultural production. In this approach, as soon as the return is $1 higher, farmers are assumed to switch. Reality, of course, is far more complicated. There are many factors other than profit maximization that influence people’s choice of land use in the real world, especially when the land-use change is irreversible. There may also be a high level of inertia that prevents switching even when alternatives are demonstrably better. As discussed in the literature review section, the advantage of econometric methods is that they use data based on actual behavior, rather than assumed profit-maximizing behavior. Econometric methods tend to show that there are higher costs and lower sequestration potential than do bottom-up studies. If a voluntary carbon sequestration program is to be implemented with private landowners, we may expect payments higher than our estimates to induce land-use or land-management changes.

Third, we will tend to over-estimate the carbon sequestration potential and under-estimate the costs in the long run by ignoring market effects. For example, when more land is converted to poplar plantation, the supply of poplar will increase. Assuming the demand for poplar stays the same, price of poplar will drop when the supply is increased. The profit margin in growing poplar will shrink, thus making agricultural production more attractive. Observing the relative price changes of poplar to agricultural products, farmers would need a higher carbon payment to keep them from switching back to cropland. This type of problem is known as the “leakage” problem. We know that including market feedback effects will tend to increase the costs of carbon sequestration. But without including supply and demand equations that allow endogenous determination of prices in to our model, we cannot estimate how large the leakage problem will be.

Literature Cited

Alig, R., D. Adams, B. McCarl, J. M. Callaway and S. Winnet. 1997. "Assessing effects of mitigation strategies for global climate change with an intertemporal model of the US forest and agricultural sectors." *Environmental and Resource Economics* 9:259-274.

Antle, J., S. M. Capalbo, S. Mooney, E. T. Elliott and K. H. Paustian. 2001. "Economic Analysis of Agricultural Soil Carbon Sequestration: An Integrated Assessment Approach." *Journal of Agricultural and Resource Economics* 26(2):344-367.

Baker, J. 2006. Personal Communication.

Demchik, M., D. Current, W. Johnson, D. Riemenschneider, S. Vongroven and E. Wene. 2002. *Natural Resource Special Report: Hybrid Poplar as an Alternative Crop.* St. Paul, Minnesota: College of Natural Resource, U of M Extension Service.

Feng, H., L. A. Kurkalova, C. L. Kling and P. W. Gassman. 2004. "Environmental Conservation in Agriculture: Land Retirement versus Changing Practices on Working Land."

Goychuk, D. A. 2005. "Increasing Forest Productivity in Northern Minnesota through Investment in Red Pine Management: A Financial Evaluation." Department of Forest Resource, University of Minnesota, St. Paul, Minnesota.

Greenhalgh, S. and A. Sauer. 2003. Awakening the dead zone: An investment for agriculture, water quality, and climate change. Washington DC: World Resources Institute.

Kuester, L. 2001. “Partners for Fish and Wildlife: Minnesota.” U.S. Fish and Wildlife Service, Minnesota Private Lands Office.

Larson, G. 2005. “Sales of Wetland Credits to Public Transportation Authorities Revised Policy.” Personal Communication.

Lubowski, R. N., A. J. Plantinga and R. N. Stavins. 2006. "Land-Use Change and Carbon Sinks: Econometric Estimation of the Carbon Sequestration Supply Function." *Journal of Environmental Economics and Management* 51(2):135-152.

Matthews, S., R. O'Connor and A. J. Plantinga. 2002. "Quantifying the impacts on biodiversity of policies for carbon sequestration in forests. " *Ecological Economics* 40(1):71-87.

McCarl, B. A. and U. A. Schneider. 2001. The cost of greenhouse gas mitigation in US agriculture and forestry. St. Paul, Minnesota: USDA.

Park, P. J. and I. W. Hardie. 1995. "Least cost forest carbon reserves: cost-effective subsidies to convert marginal agricultural land to forests." *Land Economics* 71(1):122-136.

Plantinga, A., T. Mauldin and D. Miller. 1999. "An Econometric Analysis of the Costs of Sequestering Carbon in Forests." *American Journal of Agricultural Economics* 81(4):812-824.

Stavins, R. N. 1999. "The Costs of Carbon Sequestration: A Revealed-Preference Approach." *American Economic Review* 89:994-1009.