The Cost and Quantity of Carbon Sequestration by Extending the Forest Rotation Age.

Brent Sohngen
AED Economics
Ohio State University
2120 Fyffe Rd.
Columbus, OH 43210-1067
614-688-4640
sohngen.1@osu.edu

Sandra Brown
Winrock International
Ecosystem Services Unit
1621 N. Kent Street, Suite 1200
Arlington, VA 22207
sbrown@winrock.org

The Cost and Quantity of Carbon Sequestration by Extending the Forest Rotation Age.

ABSTRACT

Increasing forest management and extending the timber rotation age beyond the economically optimal age have been proposed as options for increasing carbon sequestration. In this paper we examine the potential costs and quantity of sequestered carbon from such activities for forests in the southern and western regions of the U.S. A model of optimal rotations when carbon is a valued asset is presented to show how optimal rotations will adjust when carbon is priced. Data on a range of softwood forest types and site classes in 12 southern and western states that dominate softwood timber production in the U.S. are then used to examine the costs of extending rotations. The results indicate that carbon sequestration is relatively expensive from extending rotations. In these 12 states, about 4.1 million t C could be sequestered for less than $25 per t C (1 t C = 1000 Kg Carbon), although for high carbon prices of $200 per t C., up to 57 million t C could be sequestered. Timber prices are found to have important influences on the marginal costs of carbon sequestration, with site quality being of secondary importance. The results also show the carbon prices that would be necessary to set-aside timberland. Very little land would likely be set aside at $50 per ton C, however, at $200 per t C, the results indicate that nearly 1 million hectares of land could be set-aside in the U.S., with 83% of this land occurring in the Western U.S.

INTRODUCTION

A number of studies have suggested that incentives for carbon sequestration could lead to longer rotation periods (Van Kooten et al., 1995; Englin and Callaway, 1993; Adams et al., 1999; Sohngen and Mendelsohn, 2003). Anything that shifts rotation periods away from the economically optimal rotation age could be costly however. While some national or international modeling efforts have suggested that rotation age management can be an important component of overall forest carbon sequestration opportunities, there have been few attempts to assess what the potential extent is for increasing carbon sequestered on forestlands by increasing the timber rotation age and at what cost. Further, no studies have examined which locations in the U.S. would be economically suited for increasing rotation ages.

It may also be possible to sequester carbon by setting timberland aside from all harvesting. Setting aside timberland occurs when it is held permanently from future harvesting (i.e., forests are aged "permanently"). In addition to providing benefits to the atmosphere by storing carbon, permanently setting aside timberland may also promote other environmental benefits, such as improving bio-diversity or reducing negative externalities from run-off. The economic efficiency of setting aside timberland permanently for carbon sequestration has been analyzed by several authors to assess leakage (Murray et al., 2004; Sohngen and Brown, 2004), but no studies have assessed where and at what price, set-asides might be efficient.

When considering which timberland is optimal to shift towards longer rotations or into set-asides, it is important to account for the growing conditions of specific timber types and site classes, and economic conditions like price. The optimal rotation age, for instance, depends both on ecological factors (i.e., the curvature of the biological growth function), and economic factors (i.e., prices and costs). The productivity and growth characteristics of different types of timber vary widely across the landscape due to growing and climatic conditions. Stumpage prices for timber products also vary across the landscape as a result of mill density, road quality, and the costs of harvesting different types of sites. While the studies described above have examined the influence of carbon prices on rotation ages, no studies have looked at how timber productivity, timber prices, and species choice influence the costs of sequestering carbon through extending rotations.

This study examines the potential for extending rotations and setting aside timberland for carbon sequestration in two important timber producing regions of the United States, southern states and the west coast states. The timber types in these two regions differ substantially, and allow us to show how holding timberland beyond the currently optimal rotation period, and potentially setting it aside, could enter into a sequestration program. The analysis is conducted for each softwood timber type and up to three productivity classes in each county in the states. Although we do not present them in this analysis, county-level maps for the two regions have been generated to assist policy makers in determining where to focus efforts on carbon sequestration programs (Brown et al. 2004, Brown and Kadyszewski, 2005). The next section of the paper presents the methods used to analyze and estimate carbon sequestration costs and benefits. The third section presents the underlying data used in the analysis. The fourth section presents empirical results, and the final section is our conclusion.

THE MARGINAL COSTS OF CARBON SEQUESTRATION BY EXTENDING ROTATIONS.

The potential to sequester carbon by extending rotation ages arises because many species are still growing when they achieve their economically optimal rotation age. The rate of growth of timber and the addition of carbon depends on the timber type, site quality, and the rotation period. For most timber species, it is typically not efficient to reduce the rotation period to more quickly cycle carbon into wood products because the mix of products associated with shorter rotations tend to be emitted into the atmosphere more quickly (i.e. pulpwood), and the period of maximum sustained yield (when annual average wood production is maximized) occurs later than the economically optimal rotation period. There may be opportunities to convert stands to biomass energy production, but we do not consider those possibilities in this analysis.

Opportunity costs associated with increasing the rotation age result from holding off harvests several years, and delaying the next rotation. Hartmann (1976) notes that when there are non-market benefits associated with older timber, it may be economically efficient to extend rotation ages. Englin and Callaway (1993) and Van Kooten et al. (1995) showed how rotation ages would likely increase in the case of carbon sequestration payments tied to the annual accumulation of timber and storage in marketed products.

For this analysis, we build upon the results in Van Kooten et al. (1995), however, rather than paying for increments and taxing emissions, we rent carbon in the forest and we pay for carbon stored in marketed products. Renting carbon in forests assumes that landowners have the property right for the carbon stored on their land and that they are able to sell the annual rental equivalent of holding the carbon out of the atmosphere for each year they store it. When landowners harvest their forests some dead wood remains on the site and is assumed to decompose immediately. The remaining wood is assumed to move into either sawtimber or pulpwood. Sawtimber product is assumed to be retired and to turnover at 0.5% per year, and pulpwood at 1.0% per year (Winjum et al., 1998). Using these numbers and a discount rate of 6%, we determine the amount of "present value" carbon stored permanently in harvested products. We assume that landowners are credited for this "permanent" storage at the time the forest is harvested. They are paid the carbon price at the time of harvest for this permanent storage.

To estimate the marginal costs of carbon sequestration in forests through aging, we calculate the optimal rotation period with and without terms for the valuation of carbon storage. For the purposes of this analysis, we assume that the prices of all products and carbon are constant over time. Assuming that the price of sawtimber products is P_S, the price of pulpwood products is P_p, the price of sequestering a ton of carbon forever is P_C, and that the interest rate is r, the value of bare land with carbon payments described above is:

(1) Bare Land Value =

$$W(a) = \frac{(P_S\phi_t^S + P_P\phi_t^P)V_t(1+r)^{-t} + P_C\alpha V_t(1+r)^{-t} + rP_C\sum_{n=1}^{t}\beta_n V_n(1+r)^{-n} - C}{(1-(1+r)^{-t})}$$

Where:

V_t = biomass yield, or growing stock volume (m^3 per hectare) at age t.

ϕ_t^S = proportion of biomass used for sawtimber at age t.

ϕ_t^P = proportion of biomass used for pulpwood at age t.

α = factor for converting harvested biomass into "permanently" stored carbon.

β_t = conversion factor converting biomass yield into carbon.

C = planting costs

r = interest rate (6%)

The first part of equation (1) —$(P_S\varphi_S + P_P\varphi_P)*V_t(1+r)^{-t}$ — represents the value of harvesting the stand and selling products in markets. The second part of equation (1) — $[P_C\alpha V_t(1+r)^{-t}]$ — is the value of storing carbon permanently in markets. The term α is calculated as the present value of initial storage in market products less the present value of turnover in product markets (i.e., decomposition):

(2) $$\alpha = \gamma\phi_1^S - \sum_n \delta_S \gamma\phi_n^S (1+r)^{-n} + \gamma\phi_1^P - \sum_n \delta_P \gamma\phi_n^P (1+r)^{-n}$$

The term γ accounts for wood density and converts wood biomass into carbon. The terms δ_S and δ_P are the rates of turnover of wood products in solidwood (S) or pulpwood (P) marketed products. The term α therefore accounts for the proportion of the harvested volume that is carbon as well as the proportion stored permanently in marketed products. Permanent storage is valued at the market price for carbon sequestration, P_C.

The term [$rP_C \sum_{n=1}^{t} \beta_n V_n (1+r)^{-n}$] accounts for the value of carbon sequestered on the stump. Carbon on the stump is rented annually at the rate of rP_C. Because the volume of carbon on the stump grows over time, the annual value of rental payments for carbon sequestration will increase over time. Consequently, within each rotation, the present value of rental payments must be calculated with the sum shown above. The term β_n converts timber volume into carbon. As noted in Brown et al. (1999) and Smith et al. (2003), carbon per unit of timber volume changes over time, so the carbon conversion factor for timber on the stump is a function of time.

For the analysis, equation (1) is solved numerically over a range of carbon prices for a given yield function and forest product price to determine the optimal rotation age. The carbon price is the marginal cost of carbon storage in forests. As a result of assuming that all prices remain constant, we do not account for potential leakage associated with carbon sequestration projects. If carbon sequestration projects lead to widespread extending of timber rotations, it is likely that prices could rise initially if landowners with-hold substantial timber from markets. Over the long term, prices could fall if rotations are extended (causing timber supplies to expand as forests move towards maximum sustainable yield), or they could rise if carbon prices are high enough to cause forestland to be set-aside permanently. These considerations are important, but would need to be addressed with a market model. Market modeling such as this, while plausible with more aggregated data, is not feasible with the county level data on multiple species that is employed in this analysis.

The numerical solution to equation (1), given values for the parameters, defines a change in rotation age when evaluated across different carbon prices. To assess the marginal costs of carbon sequestration, we need to estimate the increase in carbon when rotations are extended. Consider, for example, a medium site loblolly (*Pinus taeda*) stand in Mississippi with an economically optimal rotation age of 30 years with $P^C = 0$. Figure 1 shows the annual stock of carbon on this site for the initial 30 year rotation period, and for a 45 year rotation period (assuming the stand is initially 30 years old). There are approximately 47 t C per hectare (1 t C = 1000 Kg Carbon) in forests at age 30 with this site quality land. At 30 years, forests are growing 1.4 t C per hectare per year, although the rate of growth declines to 0.6 t C per hectare per year by the time the forests reach 45 years of age.

If the stand is harvested at 30 years, 20.5 t C are stored in forest products immediately, and the forest begins growing again. Alternatively if the stand remains standing and continues to grow, 47 t C are stored initially on the landscape, rising to 61 t C by year 45. Even though the stand that is aging past the original optimal rotation age accumulates carbon more slowly than a newly planted stand, throughout the period from age 30 to 45, more carbon is stored on the landscape (and in products, as shown in Figure 1) for a stand that is held past its optimal rotation period than in forest products plus new growth in a newly established stand.

To calculate the carbon gain, the difference in carbon stocks between the scenario with a positive carbon price and the baseline is calculated as CSD_t:

(3a) $$CSD_t = CS_t^{ER} - CS_t^{B}$$

This is the difference in the stock of carbon on the land and in products at time t. It represents the net gain in carbon (reduction in atmospheric carbon) at each time period. As can be seen from Figure 1, the net gain may be positive or negative at any given time. To assess the marginal costs of entering new land into a carbon program today, one needs to consider the entire time path of net gains. Specifically, we calculate the carbon sequestered in such an activity as the net present value of the annual change in CSD_t. The annual change, S_t, is defined as

(3b) $S_t = CSD_t - CSD_{t-1}$

and the net gain in carbon is:

(3c) Net C Gain = $NPV(Carbon) = \sum_{0}^{300} S_t (1+r)^{-t}$

Other alternatives have been suggested to estimate the carbon gains. Richards and Stokes (2004) for instance, describe two other alternatives, average storage and flow summation as alternatives to the discounting techniques. In the case of the average storage method, one would determine the average carbon in forests and products far in the future (once decomposition from products equals periodic inputs from harvesting). Average storage ignores any intertemporal carbon sequestration benefits (or costs) of extending rotations. Flow summation would involve summing S_t over a given number of years. Flow summation is problematic in this case because two different rotation periods are compared. As a consequence, the choice of ending dates has substantial influence on the estimated carbon. For example, if 240 years (a year in which the two rotations coincide) is chosen 23 t C would be estimated as stored, but if 290 years are chosen, then -6 t C would be estimated as stored. It is arbitrary to decide which date to use as the cut-off date. If project managers decide to use the date when the two rotations coincide, then they are essentially choosing to compare the steady-state difference in carbon stored in forest products. Thus, yet another alternative would be to compare carbon stored in forest products at some far distant point in the future when the periodic harvest inputs equal decomposition over the harvest cycle.

We have chosen to use the net present value (discounting) techniques to estimate carbon gains for several reasons. First, as Richards and Stokes (2004) argue, discounting carbon allows project managers to compare forestry projects with other carbon mitigation options, both within the land-use sector and outside the land-use sector. Second, the present value techniques account for the benefits that accrue initially when forests are held rather than harvested. Early storage of carbon should gain some benefit because when carbon is priced, it is a valued commodity. Third, if flow summation techniques are used, there is little rationale for choosing a time period over which to sum the carbon. Although discount rates are also arbitrarily chosen for analysis purposes, markets clearly incorporate the time value of money into project-level decisions for other capital expenditures, and there is no reason to believe that carbon markets, if they evolve, will behave differently.

The carbon analysis uses the same discount rate as assumed for markets, 6%, to calculate the benefits of carbon storage. Only 300 years are counted in this analysis. Beyond 300 years, the present value of additional carbon gains are very small and are ignored. For the medium site loblolly pine stand shown in Figure 1, the net present value of additional carbon stored for a 15 year lengthened rotation on the site is estimated to be 17.2 t C.

Using equations (1) - (3), we determine the marginal costs of increasing the rotation age for a stand that is close to the optimal rotation period. The price of carbon sequestration, P_C, is equated with the marginal cost of sequestration. Different prices will lead to different optimal rotation periods. Equations (3a) - (3c) provide an estimate of the increase in carbon associated with each increase in rotation ages. Combining the two pieces of information allows us to generate marginal cost curves for different forest types and site classes (which will have different yield functions, V_t), and for different regions, which will have different stumpage prices and costs of regeneration. The next section presents empirical estimates from a number of southern and western states.

COMPARISON OF COSTS IN SOUTHERN AND WESTERN STATES

This study focuses on softwood forests in nine states of the southern U.S. (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee) and the three states on the west coast of the continental U.S. (California, Oregon, and Washington).[1] Softwood forests are often managed in rotations in these regions, and therefore provide opportunities for managers to increase rotation ages in order to enhance carbon sequestration. All of the data on forest resources in the

[1] These states were selected in part because the analyses presented here are based on a larger body of work designed to quantify the carbon supply from terrestrial carbon sequestration in two regional partnerships funded by the U.S.Department of Energy: the Southeast Regional Partnership and the West Coast Regional Partnership.

United States used in this section are obtained from the US Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA; USDA FIA, 2003), unless otherwise noted. In the nine southern states examined here, there are approximately 64 million hectares of timberland, of which 44% is softwood (loblolly pine and shortleaf/slash—*pinus taeda and pinus elliottii*) . Softwood forests in the region are heavily managed, and about 11 million ha of the softwood forests are classified as plantation forests in these nine states.

In the three western states a larger share of the land is in softwood forests. In California, Oregon, and Washington, there are 24 million hectares of forestland, with 89% of that being softwood, and around 1.3 million hectares classified as plantation forests. As a result of the relatively intensive management in these southern and western states, combined they account for around 85% of the total annual US softwood timber harvest (Haynes, 2003).

Marginal cost curves for carbon sequestration were calculated for all softwood forest cover types in each of the states. For the southern states these are loblolly/longleaf and shortleaf/slash forest types. For the western states, the forest types included are Douglas fir (*Pseudotsuga menziesii*), hemlock (*Tsuga sp.*), ponderosa pine (*Pinus ponderosa)*, fir/spruce (*Abies sp.* and *Picea sp.*), lodgepole pine (*Pinus contorta*), and redwood (*Sequoia sp.*).

Data

The first step in the analysis involves calculating yield functions for the growing stock volume of timber in forest stands. The FIA database classifies timberland into six different site classes, where each of the site classes has a different productivity. For this analysis, the six original site classes were aggregated into three classes for each forest type. Low site classes are those sites capable of producing up to 5.9 m^3 per hectare per year, medium site classes are those capable of producing 5.9 – 8.3 m^3 per hectare per year, and high site classes are those capable of producing more than 8.3 m^3 per hectare per year. Yield functions for growing stock volume were first estimated for each of the species and site classes using data from the FIA data base. Different yield functions were estimated for southern and western species, as shown below:

Western states:

Yield (m^3/hectare) = $\exp(a - b/Age)$	If age <120 years
Yield (m^3/hectare) = $\exp(a - b/120)$	If Age >=120 years

Southern states:

Yield (m^3/hectare) = $a + b*Age + c*Age^2 + d*Age^3$	If Yield < Vmax
Yield (m^3/hectare) = Vmax	If Yield >=Vmax

Growing stock volume is then converted to above-ground carbon biomass using parameters from Smith et al. (2003).[2]

[2] There are parameters for 53 separate yield functions used in the analysis. The specific parameters are available from the authors upon request.

In addition to differences in site quality and growing stock, marginal costs of sequestration will depend on regional differences in timber prices, costs of management, taxes and other factors. Many of these differences are captured in this analysis using region specific data. For example, in Arkansas, we obtain timber price data for two regions, and in California we obtain timber price data for 11 regions (Table 1). Costs are also likely to differ across states and counties, but it is difficult to find specific information on costs of managing and regenerating forests. Several surveys of costs associated with forest management in the South have been conducted (Dubois et al., 1997; Siry, 2002; and Rogers and Munn, 2003;). We used a value of $625 per hectare for site preparation and regeneration costs for each of the southern states. For California, $395 per hectare was used, per the California Forestland Improvement Program (2003), and for Oregon and Washington, these costs were assumed to be $735 per hectare on average, based on data from state agencies in the two states.[3]

Marginal Cost Functions by Type, Site Class, and Pricing Region

Across the 12 states, 324 marginal cost curves were calculated, one for each distinct species and site class in each pricing region. These marginal cost curves were developed by calculating optimal rotation periods under a range of potential carbon prices ($1 per T C to $600 per T C) using equation (1) above. The additional carbon sequestered for a stand currently at the baseline (no carbon price) optimal rotation age, but held for the additional time period suggested by the carbon price, was then calculated using equations (3a) - (3c).

[3] This information was obtained via personal communication with Jim Cathcart, Oregon Department of Forestry and Tony Ifie, Washington Department of Natural Resources.

As an example, marginal cost curves for extending the rotation age for several species and sites are shown in figures 2a and 2b. The marginal costs in the medium and high productivity loblolly stands in northern Georgia are similar to the marginal costs for the higher productivity loblolly of northern Mississippi forest (Figure 2a); marginal costs for the medium productivity loblolly stand in Mississippi are relatively low in contrast. In northern Mississippi and northern Georgia, high site loblolly stands have higher costs than do the medium site classes (Figure 2a). The main difference between high or medium site loblolly stands in northern Georgia and Mississippi is the timber price. Prices are higher in Georgia, so marginal costs are higher. The results also show that higher site classes have higher marginal costs. While higher site classes produce more biomass (and carbon) on each hectare, they also have higher opportunity costs associated with extending rotations.

Marginal costs in the western states are flat in contrast to those in the south, and more carbon can be sequestered overall on sites in western forests—up to four times more for similar cost ranges (Figure 2b). For the marginal cost functions shown in Figure 2b, marginal costs are higher in Oregon because timber values are higher. This result is consistent with the results for the South shown above. However, in western states, marginal costs of extending rotations for medium site classes tend be higher than those for higher site classes. Figures (2a) and (2b) highlight differences in site quality, carbon accumulation, prices, and costs. There is substantial variation in costs across the entire 12 state region analyzed. Across the 324 distinct softwood types and pricing regions, the marginal costs of sequestering 10 t C per hectare range from \$2.50 to \$620 per t C, with the lowest cost estimates occurring in spruce/fir forests in the Western U.S., and the highest costs in loblolly stands of the Southern U.S.

It is useful for managers to know which species, pricing regions, and site classes to target for carbon sequestration. Managers likely cannot develop full carbon analysis for every site, at least initially, and therefore could use some indicators to better focus their efforts in making contracts with landowners. To demonstrate the relationship between these important variables we developed a simple marginal cost function for each region. The marginal cost of sequestering carbon is assumed to be a function of tons sequestered, timber prices, wood production, and species type (Table 2). Data for the analysis includes all the simulated carbon prices and quantities for all 324 timber types, pricing regions, and site classes.

The results show that, as expected, increasing the carbon stored on a hectare raises the marginal cost. For the South, increasing rotations by 5 years leads to about 6 t C per hectare on average, and the marginal cost of this increase is $210 per t C. For a 10 and 15 year rotation extension (sequestering 9.6 and 11.6 t C per hectare), marginal costs are $276 and $309 per t C, respectively. Marginal costs increase by $2.89 per t C for every $1/m^3$ increase in timber prices, and they increase by $12.88 per t C for every additional 1 m^3/ha/year in annual wood production. Loblolly pine stands are $100 per hectare lower in costs on average than slash pine stands.

In the West, the marginal cost function is more nearly linear, following Figure 2a above (i.e., the squared term on carbon gain per hectare is 0). For 5, 10, and 15 year rotation extensions respectively (13.7, 22.2, and 28.9 t C per hectare), marginal costs of sequestration are $102, $116, and $127 per t C. Similarly to the South, a $1/m^3$ increase in timber price raises the marginal costs by \$2.49/t C. Unlike the South, however, an increase in annual wood production (site index) reduces the marginal cost on average. Specifically, an additional 1 m^3/ha/year in annual wood production reduces marginal costs by \$1.52 per t C on average. Douglas fir, hemlock, spruce, fir, and pine stands are all lower cost than the redwood stands, which represent the base type in the regression.

AGGREGATED MARGINAL COST CURVES

Marginal cost curves for each timber type, site class, and pricing region, were constructed as described above, and used to develop aggregate marginal cost curves for all 12 states. To accomplish this, the area of timberland in each forest type and site class was downloaded by age class from the FIA database (USDA FIA, 2003). For the South, forests within the range of 25 – 35 years of age were selected for potential carbon projects, while for the West Coast, forests in the range of 40 – 60 years of age were selected. These age classes encompass the range of economically optimal rotation ages calculated for the baseline (no carbon price) case. Only forests within these age ranges were used to construct aggregate marginal cost curves because we assumed that only forests close to the optimal rotation age could be put under contract in the near-term. Further, our calculation of the amount of carbon that could be sequestered with an increase in rotation ages is only consistent with contracts made for land that is currently (when contracted) at the optimal rotation period.

We have further only considered private timberland in this analysis. Government ownership is not included in the analysis because many of these ownerships (i.e. federal, state, and local) have multiple objectives when managing their land and they could have different issues related to entering into private contracts for carbon sequestration. It would be helpful to consider the two primary types of private forestland ownership, industrial and non-industrial private, but the FIA data currently do not lend themselves to an analysis that separates forest industry from other private land at the county level, so we analyze these two ownership classes together.

At a given C price, the total amount of carbon that can be sequestered in each county is the sum of carbon sequestered on each site at that price. Thus, we summed the total carbon sequestered for a given C price across the area in suitable age classes, forest types, and site classes for each county in the 12 state region. This allowed us to develop marginal cost curves for different levels of aggregation. Marginal cost curves were produced for three regions by dividing the southern states into two sub-regions (Southeast—Alabama, Georgia, Florida, South Carolina, North Carolina, Tennessee; South Central—Arkansas, Louisiana, Mississippi) to reflect differences in the key variables used in the model (Figure 3).

The South Central region has the highest overall costs and potentially the smallest amount of carbon sequestration (give value in million t C). One reason for this is that states in that region have the smallest area of softwood forests at ages nearing economic maturity. The South Central region is also smaller than the other two regions, so costs should be higher. Costs and quantities in the Southeast and along the West Coast are relatively similar for prices up to $50 per t C (about 5 million t C in each region), but more carbon can be sequestered for higher prices on the West Coast. Overall carbon sequestration potential through aging in the West Coast appears to be greater, mainly due to the large potential carbon storage on sites in that region (cf. Figure 2b). In total, the results indicate that around 10 million t C could be stored for prices below $50 per t C, and around 30 million t C could be stored for prices up to about $100 per t C. Above $150 per t C, very little additional carbon can be sequestered in forests that are currently near their optimal rotation age.

Table 3 presents information on the area that could be potentially included in a program to extend the rotation age, the tons sequestered, the age increase, and the area potentially set-aside for three different carbon prices, $25, $50, and $200 per t C. Note that for the analysis in table 3, the actual increase in the rotation age differs depending on the species type and the carbon price analyzed. In addition to considering aging of forests, one can also use the results to assess land that may potentially be set aside from timber harvesting. For the purposes of our analysis, we define a set-aside as occurring whenever the rotation age is effectively doubled.

The first two prices are within the range of potential carbon prices at the Chicago Climate Exchange— for a voluntary market (CCX: http://www.chicagoclimatex.com/)— and within the European Union Emissions Trading Scheme— for a regulated market (ETS: http://europa.eu.int/comm/environment/climat/emission.htm). In Europe, trading began in January, 2005, but no terrestrial sequestration projects are allowed at present to trade. The maximum price in Europe (i.e., the fine for non-compliance) is approximately $225 per t C (€49 per t CO_2 Eq.). The higher price thus captures the maximum potential price in Europe.

At $25 per t C, about 4.1 million t C could be stored on 1.4 million hectares of land. The largest carbon gains occur in Washington (about 44% of the total), although the largest area could be enrolled in a program in Georgia. According to the definition of set-asides described above, no land would be set-aside when carbon prices are $25 per t C. Similarly, no land would be set-aside at $50 per t C, although 8.4 million tons carbon could be sequestered on 1.9 million hectares enrolled in rotation extension programs. Average rotation extensions are only about 2-4 years for $25 per t C, and 3 - 14 years for $50 per t C. At the much higher price of $200 per t C, about 1 million hectares in these states would be set-aside. This is approximately 40% of the total 2.6 million hectares that could be enrolled in a rotation extension program. Most of this set-aside area, 83%, is in the West Coast region. Around 70% of the carbon could be also stored in the west, although only 35% of the total area is in that region. The opportunity costs of extending rotation, and setting aside land, are higher in the south, and carbon potential is substantially higher in the western states.

CONCLUSION

This paper develops methods to estimate the marginal costs of carbon sequestration through aging timberland. Increasing rotation ages can increase carbon sequestration by holding more carbon on the land and avoiding the emissions that occur with harvesting. The landowner's maximization problem is presented where carbon is assumed to be a joint product with traditional timber outputs. Landowners are assumed to obtain rental payments for the carbon they hold on the stump and payments for carbon stored in timber products. Methods for counting the carbon gains associated with holding timber beyond the optimal rotation age are presented as well. The methods are used with economic and ecological data from 12 southern and western U.S. states to assess the marginal costs of sequestering carbon through aging timberland in these regions.

Timber prices influence carbon sequestration costs by influencing the opportunity costs of sequestering carbon--higher prices generally mean higher opportunity costs associated with aging timberland beyond the optimal rotation period. A comparison of a number of these region, species, and site class specific marginal cost curves indicate that for lower levels of sequestration, costs are lower in the South, however, for larger amounts of sequestration costs rise rapidly in the South. In contrast, marginal costs for many species in the western U.S. are higher at low levels of sequestration, but lower for high levels (i.e. the marginal cost functions are flatter). Although not shown, there are some low cost opportunities in the western U.S. with spruce/fir forests in particular, but there are relatively few of these lands available. The results indicate that forest landowners in the South would be more likely to participate in carbon sequestration programs at lower prices. As prices rise, western landowners would likely participate in higher numbers. At the highest price levels, western landowners would potentially set their land aside from timber production entirely. Overall, the lowest cost opportunities occur in low and medium site loblolly pine stands in the south central states, and spruce/fir stands in California. Costs tend to be lower in these forest types due to lower opportunity costs of delaying harvest and future rotations rather than higher levels of productivity and carbon sequestration.

The marginal costs of carbon sequestration through aging timber on highly productive timberland are driven by timber prices, wood production (i.e., site class), and species. Higher prices raise the opportunity costs of holding timber longer than the optimal rotation period. In the South, better wood production increases the marginal cost of C sequestration, while in the West, better wood production reduces the marginal costs of C sequestration. Thus, carbon managers can reduce costs by seeking out lower quality sites in the South, and higher quality sites in the West. Loblolly pine is the lowest cost softwood in the South, while pine and Douglas fir are the lowest cost softwoods in the West.

Marginal costs are highest in the south central U.S., mainly because there are relatively fewer areas of merchantable timber in that region, but also because timber prices tend to be higher there. The western and southeastern U.S. could sequester similar amounts of carbon for prices lower than $50 per t C. However, for prices higher than this, the western states could sequester the most carbon. Overall, for $25, $50, and $200 per t C, we find that 4.1, 8.4, and 57.2 million t C could be sequestered through aging of timberland.

There is little evidence that at carbon prices lower than $150/t C that it would be efficient to set-aside land from timber harvesting entirely. However, as prices rise above $150/t C, set-asides become feasible, particularly in the western U.S. In particular, at $200/t C, nearly 1 million hectares could be set-aside, with 83% of this occurring in the western U.S.

While the analysis in this study provides information that can assist policy makers in deciding how much carbon can potentially be sequestered by lengthening timber rotations, there are several caveats in the analysis. First, we have not attempted to account for price changes that may occur as rotation ages are adjusted. These price changes, as shown in Sohngen and Mendelsohn (2003) and Lee et al., (2005), could be fairly substantial, and could influence the efficiency of extending timber rotations. For the most part, sequestering additional carbon is expected to lower future timber prices, suggesting that our results may over-estimate marginal costs (i.e., more carbon may be available by extending rotations in these states than we show here). Second, we have not considered leakage as in Murray et al. (2004) and Sohngen and Brown (2004). Leakage would be expected to raise the marginal costs of sequestration by accounting for net adjustments in carbon sequestration across a larger area than considered here. Finally, we have assumed that carbon and timber prices are constant over time. Carbon prices, as suggested in Nordhaus and Boyer (2000) are likely to rise over time if climate damages increase. Rising prices could alter the decisions that landowners make about the timing of their harvests. Although accounting for these other factors could be important, the results of this study do provide a first step towards developing more comprehensive assessments of carbon sequestration potential through aging and setting aside timberland for carbon sequestration purposes.

ACKNOWLEDGEMENTS

The work on the southern states was funded by subcontract from the Electric Power Research Institute, Agreement No. EP-P14591/C7157 (S. Brown and J. Kadyszewski project coordinators) and for the West Coast states by a subcontract from the Regents of the University of California on behalf of the California Institute of Energy Efficiency, Subcontract No. Mr-03-28D (S. Brown and J. Kadyszewski, project coordinators). We also thank Jim Cathcart, Tony Ifie, Jonathan Winsten, and Aaron Dushku.

REFERENCES

Adams, D.M., R.J. Alig, B.A. McCarl, J.M. Callaway, and S.M. Winnett. 1999. Minimum Cost Strategies for Sequestering Carbon in Forests. *Land Economics*. 75: 360 – 74.

Brown, S., A. Dushku, T. Pearson, D. Shoch, J. Winsten, S. Sweet, and J. Kadyszewski. 2004. Carbon Supply from Changes in Management of Forest, Range, and Agricultural Lands of California. Winrock International, for the California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-04-068F. (http://www.energy.ca.gov/pier/final_project_reports/500-04-068.html)

Brown, S. and J Kadyszewski (Project Coordinators). 2005. Carbon Supply from Sequestration Activities on Agriculture and Forest lands for the SECARB Partnership. Report to Electric Power Research Institute (available from Winrock International, 1621 N Kent St., Suite 1200, Arlington, VA, 122 pp.

Brown, S. L., P. Schroeder, and J. S. Kern. 1999. Spatial distribution of biomass in forests of the eastern USA. *Forest Ecology and Management*. 123:81-90.

California Forest Improvement Program (CFIP). 2003. California Department of Forestry And Fire Protection USER'S GUIDE 2003 EDITION, Vol. 1

California State Board of Equalization Harvest Schedule. 2002. Effective Janaury 1, 2003 through June 30, 2003. (Adopted by the California State Board of Equalization December 18, 2002). www.boe.ca.gov

Dubois, M.R., K. McNabb, and T.J. Straka. 1997. Costs and Cost Trends for Forestry Practices in the South. *The Forest Landowner Manual 31st edition.* 56(2): 7 – 13.

Englin, J. and J.M. Callaway. 1993. Global Climate Change and Optimal Forest Management. *Natural Resource Modeling* 7(3): 191- 202.

Hartman, R. 1976. The Harvesting Decision when the Standing Forest has Value. *Economic Inquiry*. 14(1): 52-58.

Haynes, R. W. 2003. An analysis of the timber situation in the United States: 1952 to 2050. Gen. Tech. Rep. PNW-GTR-560. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 254 p.

Lee, H-C, B.A. McCarl, D. Gillig, & B. Murray. 2005. U.S. agriculture and forestry greenhouse mitigation over time. In F. Brouwer & B.A. McCarl (Eds.), *Rural lands, agriculture and climate beyond 2015: Usage and management responses.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Louisiana Department of Agriculture:
http://www.ldaf.state.la.us/divisions/forestry/reports/quarterreport/original-report.asp

Mississippi State University Extension: http://msucares.com/forestry/prices/

Murray, B.C., McCarl, B.A., and Lee, H. 2004. Estimating leakage from forest carbon sequestration programs. *Land Economics*. 80(1):109–124.

Nordhaus, W., and J. Boyer. 2000. Warming the World: Economic Models of Global Warming. Cambridge, MA: MIT Press.

Oregon Department of Forestry:
http://oregon.gov/ODF/STATE_FORESTS/TIMBER_SALES/logpage.shtml

Richards, K.R., and C. Stokes. 2004. A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research. *Climatic Change.* 63: 1–48.

Rogers, W.R. and I.A. Munn. 2003. Forest Management Intensity: A comparison of timber investment management organizations and industrial landowners in Mississippi. *Southern Journal of Applied Forestry.* 27(2): 83-91.

Siry, J. 2002. Intensive Timber Management Practices. Chapter 14 in Southern Forest Resource Assessment. US Department of Agriculture, Forest Service, Southern Forest Research Station. (See: www.srs.fs.fed.us)

Smith, J.E., L.S. Heath, and J.C. Jenkins. 2003. Forest Volume-to-Biomass Models and Estimates of Mass for Live and Standing Dead Trees of U.S. Forests. US Department of Agriculture, Forest Service, Northeastern Research Station, General Technical Report NE-298.

Sohngen, B. and R. Mendelsohn. 2003. An Optimal Control Model of Forest Carbon Sequestration. *American Journal of Agricultural Economics*. 85(2): 448-457.

Sohngen, B. and S. Brown. 2004. Measuring leakage from carbon projects in open economies: a stop timber harvesting project in Bolivia as a case study. *Canadian Journal of Forest Research*. 34: 829–839.

Timber Mart South: http://www.tmart-south.com/tmart/

Van Kooten, G.C., C.S. Binkley, and G. Delcourt. 1995. Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services. *American Journal of Agricultural Economics*. 77: 365 – 74.

Washington Department of Natural Resources: Personal Communication with Tony Ifie.

Winjum, J. K., Brown, S., and Schlamadinger, B. 1998. Forest Harvests and Wood Products: Sources and Sinks of Atmospheric Carbon Dioxide. *Forest Science*, 44:272-284.

USDA FIA. 2003. US Department of Agriculture, Forest Service, Forest Inventory and Analysis. Website: http://www.fia.fs.fed.us/

Table 1: Stumpage price ($\$/m^3$) ranges and sources. Prices are 2000 real US $.

	Sawtimber Prices	Pulpwood Prices	Source (Price Regions in State)
Southern States			
Alabama	$61.45 - $66.74	$20.39 - $22.56	Timber Mart South (2)
Arkansas	$49.52 - $58.49	$7.38 - $7.72	Timber Mart South (2)
Florida	$48.03 - $54.03	$22.60 - $26.84	Timber Mart South (2)
Georgia	$50.33 - $65.51	$8.65 - $11.42	Timber Mart South (2)
Louisiana	$67.46 - $70.91	$7.47 - $10.76	LA Dept. of Agriculture (5)
Mississippi	$80.15 - $83.52	$7.86 - $9.60	MSU Extension (4)
North Carolina	$42.38 - $55.8	$14.48 - $19.07	Timber Mart South (2)
South Carolina	$52.27 - $56.15	$17.30 - $18.72	Timber Mart South (2)
Tennessee	$32.89 - $42.28	417.88 - $21.66	Timber Mart South (2)
Western States			
California	$31.53 - $69.91	$12.54 - $12.54	California Board of Equalization (11)
Oregon	$38.15 - $51.6	$7.50 - $7.50	Oregon Dept. of Forestry (4)
Washington	$38.06 - $42.75	$7.50 - $7.50	Washington Dept. of Natural Resources (4)

Table 2: Regression Analysis: Marginal Cost Functions for Carbon Sequestration. Dependent Variable is Marginal Cost (\$/t C per hectare).

	South	West
Intercept	-102.10**	42.63**
C Gain (t C/ha)	14.25**	1.64**
C Gain^2	0.19**	0.00**
Timber Price (\$/m^3)	2.89**	2.49**
Wood Production (m^3/ha/yr)	12.88**	-1.52**
Loblolly Pine (1,0)	-99.95**	--
Douglas Fir (1,0)	--	-93.99**
Hemlock, Fir, Spruce (1,0)	--	-69.20**
Pine (1,0)	--	-96.92**
# observations	5175	8228
Adj-R^2	0.35	0.86

** indicates that the parameter estimate is significant at $\alpha = 0.01$.

Table 3: Comparison of area and carbon sequestration totals for all 12 states at three prices —$25, $50, and $200 per t C.

	State	Price			State	Price		
$/ t C		$25.00	$50.00	$200.00		$25.00	$50.00	$200.00
$/ t CO2		$6.81	$13.62	$54.50		$6.81	$13.62	$54.50
		South Eastern States				South Central States		
Million t C	Georgia	0.4	0.7	4.6	Arkansas	0.0	0.0	0.1
1000 ha's		267.1	290.5	480.7		0.0	16.0	16.4
Perm Set-a-side (1000 ha's)		0.0	0.0	0.0		0.0	0.0	0.0
Million t C	Alabama	0.1	0.9	2.2	Louisiana	0.0	0.0	0.5
1000 ha's		50.8	325.8	325.8		0.0	3.4	104.3
Perm Set-aside (1000 ha's)		0.0	0.0	0.0		0.0	0.0	0.0
Million t C	Florida	0.3	0.7	2.4	Mississippi	0.1	0.2	0.5
1000 ha's		194.9	253.4	253.4		28.2	29.4	29.4
Perm Set-aside (1000 ha's)		0.0	0.0	14.7		0.0	0.0	0.7
						Western States		
Million t C	N. Carolina	0.7	1.3	3.8	Oregon	0.3	0.3	11.3
1000 ha's		247.1	247.1	247.1		84.0	84.0	232.2
Perm Set-aside (1000 ha's)		0.0	0.0	84.5		0.0	0.0	171.2
Million t C	S. Carolina	0.2	0.7	2.8	Washington	1.8	2.6	21.9
1000 ha's		178.8	220.5	220.5		233.6	331.6	474.7
Perm Set-aside (1000 ha's)		0.0	0.0	24.6		0.0	0.0	473.9
Million t C	Tennessee	0.2	0.5	1.1	California	0.1	0.5	6.5
1000 ha's		65.5	65.5	65.5		12.6	16.6	181.7
Perm Set-aside (1000 ha's)		0.0	0.0	39.5		0.0	0.0	159.1
Million t C	**All States**	**4.1**	**8.4**	**57.2**				
1000 ha's		**1362.7**	**1880.4**	**2527.5**				
Perm Set-aside (1000 ha's)		**0.0**	**0.0**	**968.3**				

Figure 1: Pattern of carbon stocks in product storage and in the forest stand (stumpage) in the optimal rotation period versus a 15 year extension on the rotation period, starting from the initial optimal rotation age.

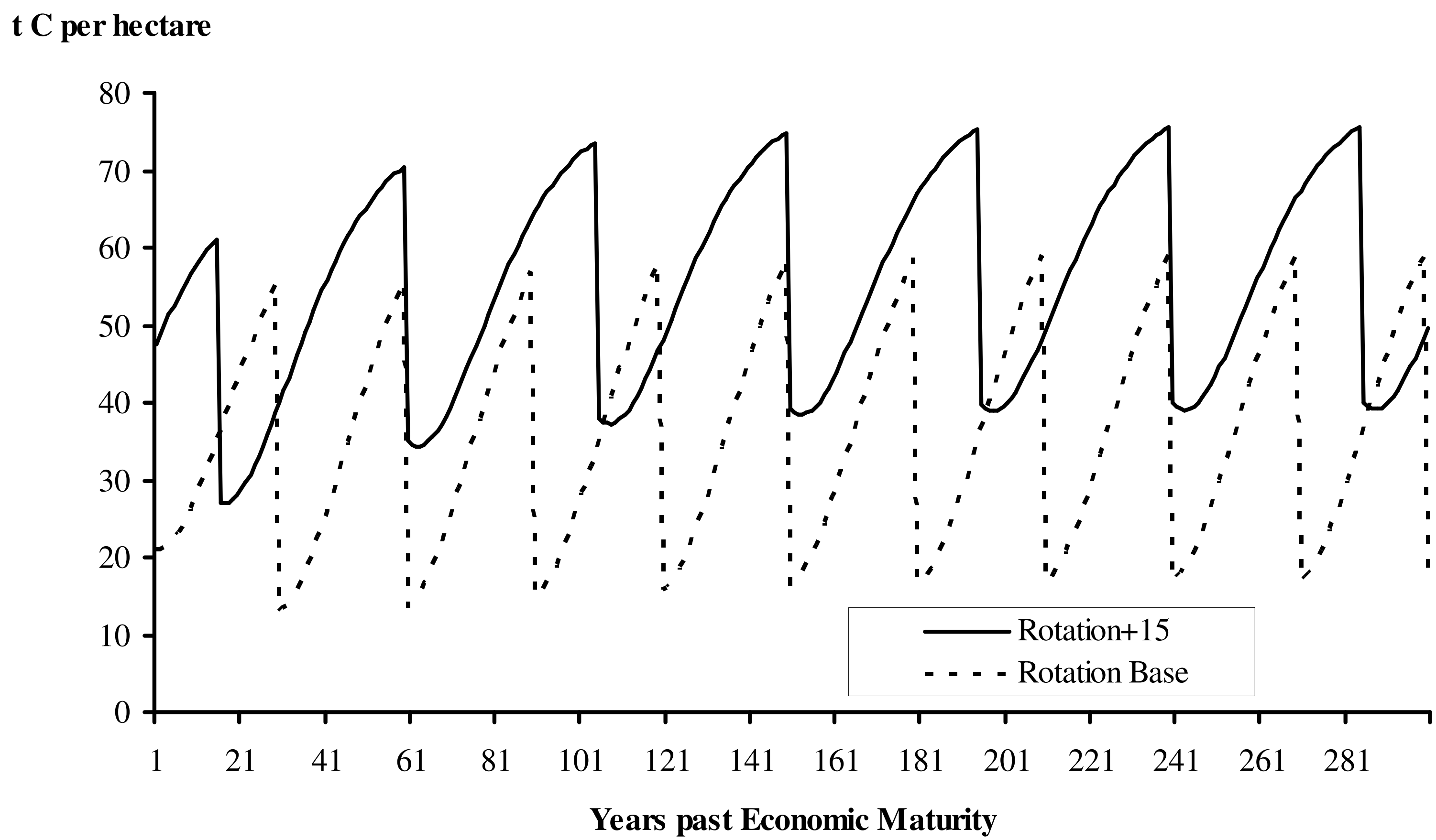

Figure 2a: Costs of carbon sequestration by aging forests in northern Mississippi (MSN) and northern Georgia (GAN) (high and medium site loblolly pine stands)

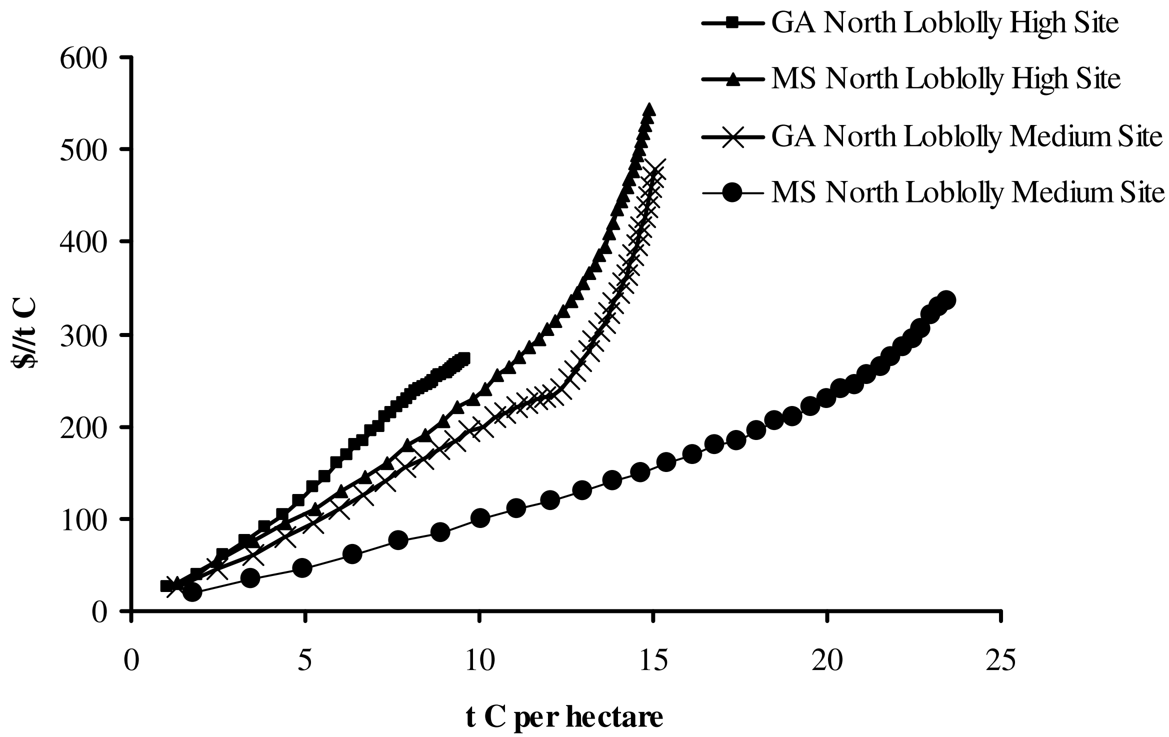

Figure 2b: Costs of carbon sequestration by aging forests in Oregon price region 1 and California price region 7 (high and medium site Douglas fir stands)

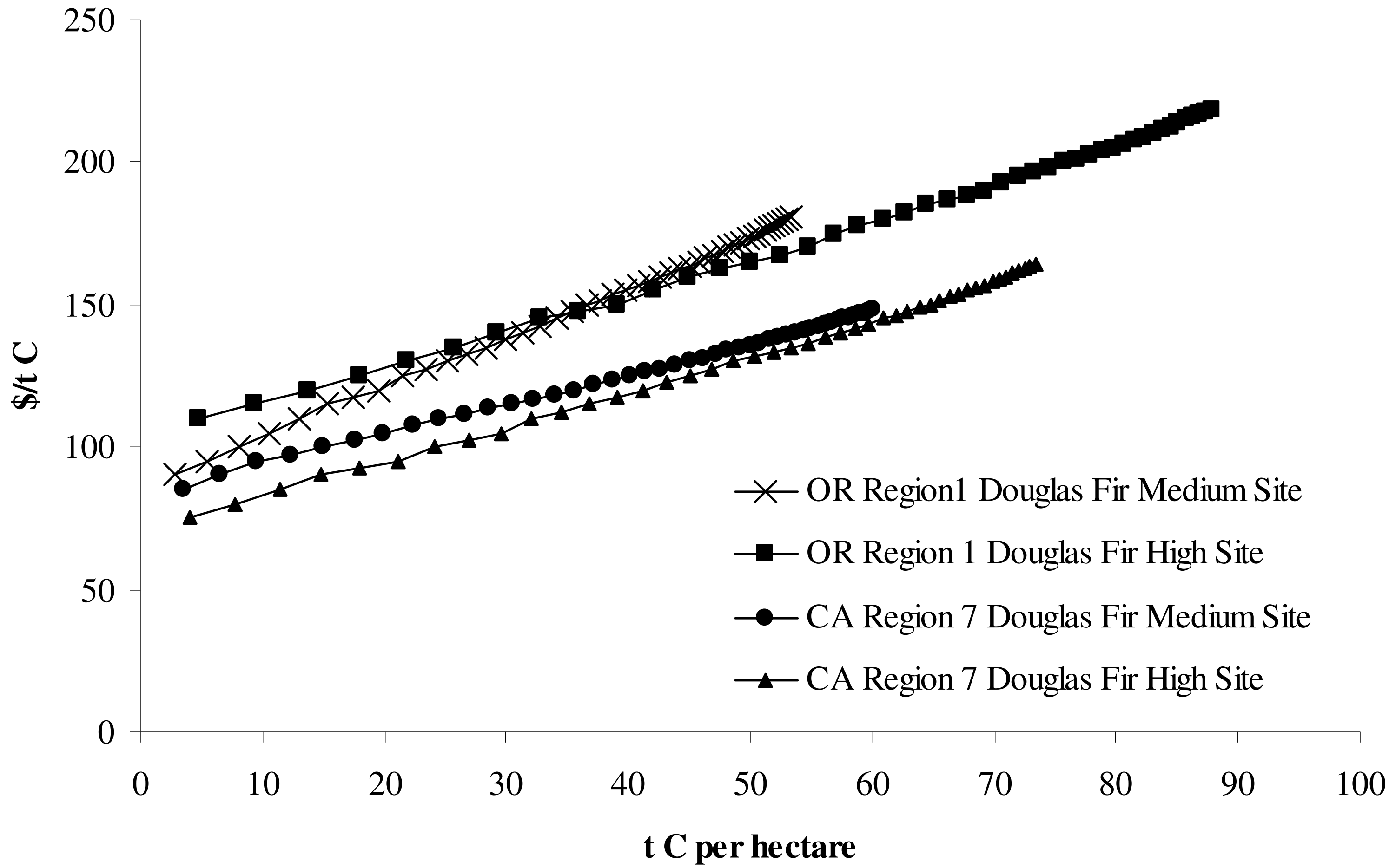

Figure 3: Aggregate marginal cost curves for carbon sequestration by aging in three regions and in aggregate (Southeast = Alabama, Georgia, Florida, North Carolina, South Carolina, Tennessee; South Central = Arkansas, Louisiana, Mississippi; West Coast = California, Oregon, Washington).