Carbon Sequestration Costs in Global Forests

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INTRODUCTION

Numerous studies have estimated the cost of carbon sequestration in forests and land-use. Globally, the costs are estimated to range \$10 - \$200 per ton stored (Richards and Stokes, 2004). While these estimates suggest substantial potential to sequester carbon in ecosystems, how sequestration fits into a global program to reduce net emissions of greenhouse gases remains an open question. For instance, should incentives be developed to adopt forest sequestration immediately by promoting land use change or increasing the management of forests, or should incentives instead focus on reducing energy emissions or other greenhouse gases in the near term, leaving carbon sequestration to later periods. Because forestry has the potential to sequester substantial carbon at prices consistent with current estimates of potential greenhouse gas abatement polices (i.e. Sedjo et al., 1995; Watson et al., 2000; Sohngen and Mendelsohn, 2003), it is useful to ask how forestry fits within the set of available policy tools.

Understanding how forest sequestration integrates with other climate change options is challenging. For the most part, climate policy is assessed with national or global economic models that capture important economic linkages in the world economy (i.e. Manne and Richels, 2001; Nordhaus and Boyer, 2000; Intergovernmental Panel on Climate Change, 2000). Most of these global energy models do not currently allow forest carbon sequestration to be determined endogenously with prices for other greenhouse gases, although a recent effort did integrate the DICE model with a global forestry model

(Sohngen and Mendelsohn, 2003). It is a useful task, therefore, to integrate forestry models with additional energy or global economy models to assess whether sequester influences greenhouse gas abatement prices for different types of policies.

Developing such an integrated approach is complicated. This paper focuses on the forestry issues, although it recognizes that there are likely to be additional issues on the energy side that will complicate integration of different types of models. While numerous studies have investigated the costs of carbon sequestration in specific places or regions, it is difficult to integrate these many individual studies with large models of the global economy. As shown in Murray et al. (2004) and Sohngen and Brown (2004), leakage in local projects can potentially reduce the efficiency of sequestration, and consequently raise costs. Most carbon sequestration studies to date have failed to incorporate these potential leakage effects when estimating costs, and thus may over-estimate the carbon potential at different prices. To address the potential for leakage, appropriate global models must be developed to account for the effects changes in timber supply will have on global markets.

There are also important dynamic issues related to carbon sequestration in forests. One dynamic issue relates to timber management itself. Foresters have large potential to alter the future supply of timber by changing harvesting regimes, regenerating, thinning, or fertilizing. If incentives are provided to increase the stock of carbon, land owners may shift their management regimes from providing timber outputs to providing carbon sequestration. Some of the adjustments can occur relatively quickly, for example, by holding trees longer than the economically optimal rotation age, or stopping deforestation. Other adjustments, however, may occur over longer time periods, such as replanting agricultural land to trees. The choice of these options at different points in time will depend heavily both on timber market prices, and the price of greenhouse gas abatement. Capturing the adjustment of markets to changes in the management of trees requires not only global models, but also dynamic models that balance the demands of forest stocks for carbon sequestration and for timber products.

Another dynamic issue relates to overall greenhouse gas abatement policies, including policy stringency, and incorporation of different options. If policies are adopted to meet long-term targets for concentration of carbon in the atmosphere, the marginal cost of greenhouse gas abatement may start out low, but rise to very high levels as the target becomes imminent. Alternatively, policies may be adopted to meet more stringent short term targets, such as emissions reductions in particular commitment periods, or restrictions on decadal changes in temperature. With more stringent near term targets, prices should rise to higher levels initially and persist (as long as the policy persists). In addition, there are options for reducing greenhouse gases across multiple sectors, and policies that include more greenhouse gases as abatement sources will have different prices than policies that focus strictly on carbon. Because forest sequestration entails managing a capital stock of trees, the particular policy the world chooses, and corresponding greenhouse gas price path, could heavily influence how sequestration fits into overall greenhouse mitigation programs.

Methods for integrating energy models and forestry models are only now underway. A recent example by Sohngen and Mendelsohn (2003) linked a dynamic timber model to the DICE model (Nordhaus and Boyer, 2000), and showed that forests could account for approximately a third of total abatement over the next century. That study, however, looked at only two potential policy responses. More stringent policy targets, or policies that include additional abatement options, such as methane abatement, could lead to different greenhouse gas price paths, and different implications for the "where" and "when" of accomplishing carbon sequestration in forests. The earlier study by Sohngen and Mendelsohn (2003) also suggests less initial deforestation in tropical regions in the baseline than the Intergovernmental Panel on Climate Change suggests in their Special Report on Energy Emissions (SRES; Intergovernmental Panel on Climate Change, 2000). Developing a baseline that is more consistent with the SRES scenarios could lead to different projections about the potential global costs of carbon sequestration.

This paper takes a closer look at forest sequestration under different assumptions about the price path for energy and other gas abatement. While it would be useful to integrate directly with energy models, we do not undertake that step in this paper. Rather, we use a set of price paths that are consistent with potential prices from large-scale energy models as part of the Energy Modeling Forum, EMF-21 study. Forest sequestration is then analyzed with the dynamic global forestry model described in Sohngen et al. (1999). The scenarios are carefully analyzed to provide information on (1) where carbon sequestration occurs in the world regionally; (2) how much is derived from different actions in forestry (reducing deforestation, increasing afforestation, enhancing management, or changing rotation ages); and (3) what are the implications of alternative carbon price paths? In addition, the model develops an alternative baseline that is consistent with the SRES scenarios and presents the results of that alternative baseline.

FOREST MODEL DESCRIPTION

The model used in this analysis is built upon the earlier Timber Supply Model originally developed by Sedjo and Lyon (1990). The model was updated and expanded in Sohngen et al. (1999) to incorporate additional regions as responsive to timber market prices, and Sohngen and Sedjo (2000) detail the methods used for carbon accounting within the model. Most recently, the model has been integrated with the DICE model (Nordhaus and Boyer, 2000), and used to assess optimal carbon sequestration policy (Sohngen and Mendelsohn, 2003).

In the model presented by Sohngen and Mendelsohn (2003), incentives for carbon sequestration were incorporated into the forestry model by renting carbon. The price of energy abatement is the value of sequestering and holding a ton of carbon permanently. The rental value for holding a ton of carbon for a year is determined as the path of current and future rental values on that tons that is consistent with the price of energy abatement currently. One of the benefits of using the rental concept for carbon sequestration is that carbon temporarily stored can be paid while it is stored, with no payments accruing when it is no longer stored (i.e. if forest land is converted to agriculture, or if timber is harvested, leaving the forest in a temporarily low carbon state). Furthermore, renting carbon does not penalize current forestland owners by charging them for emissions.

For this analysis, the model is altered to pay for sequestration when it occurs and to tax emissions from forests when and if emission occur. The price of a ton of carbon sequestered or the tax on carbon emitted in any given year is the marginal cost of energy abatement The price for a ton of abatement is paid in the year in which it occurs and the tax is paid in the year in which the emission occurs. The difference between this payment/tax policy and the rental policy is that the payment/tax policy alters the property right associated with forest carbon in that owners of current forests will be taxed if those forests emit carbon through harvesting or land use changes. Under the rental payments, landowners with current forests are not penalized for harvesting or converting those lands from forests. With proper discounting methods, the rental method or the tax and subsidy method result in the same marginal value for sequestration, but they do affect the flow of money to and from forestry.

Sequestration is measured as a reduction of net annual baseline emissions. If baseline emissions are E^b_t , emissions in the sequestration scenario are E^s_t, and carbon prices are P^C_t, then the model credits sequestration according to:

(1) Carbon credit in time t = $CC_t = P^C(t)\left[E^b(t) - E^s(t)\right]$

Emissions are treated as positive numbers indicating that emissions enter the atmosphere (the most common method of handling carbon emissions in energy models), and sequestration is treated as a negative number. In equation 1, note that if carbon prices induce sequestration for a period, but carbon is emitted in the future, carbon emissions will be "taxed" at whatever the current carbon price is. E^s_t in this case is determined endogenously, and will depend on the price of carbon sequestration.

Within the foresty model, there are three types of forest stocks. Stocks in i represent general stocks that are managed in optimal rotations. These include most temperate forests, as well as some stocks in other regions of the world. Stocks in j represent high value timber plantations that occur mainly in subtropical regions. These stocks have additional establishment costs relative to stocks in i, although they too are managed in optimal rotations. Stocks in k represent currently inaccessible timber types. Large areas of boreal and tropical forests are classified in this region. They can be converted to accessible forests through harvesting if timber prices exceed the marginal access costs.

The forestry model maximizes the net present value of net welfare in the forestry sector. Formally, this is:

$$(2)\ Max\sum_{0}^{\infty}\rho^{t}\left\{\begin{array}{l}\int_{0}^{Q^{*}(t)}\left\{\begin{array}{l}D(Q(H_{a,t}^{1}...H_{a,t}^{I},H_{a,t}^{1}...H_{a,t}^{J},H_{a,t}^{1}...H_{a,t}^{K}),Z_{t})\\-C_{H^{i}}(\cdot)-C_{H^{j}}(\cdot)-C_{H^{k}}(\cdot)\end{array}\right\}dQ(t)-\\\sum_{i,k}C_{G}^{i,k}(G_{t}^{i,k},m_{t}^{i.k})-\sum_{j}C_{N}^{j}(N_{t}^{j},m_{t}^{j})-\sum_{i,j,k}R^{i,j,k}(X_{t}^{i,j,k})+CC(t)\end{array}\right\}$$

In equation (2), D(Q(▪)) is a global demand function for industrial wood products, $H^{i,j,k}$ is the area of land harvested in the timber types in i, j, or k, and C_H(▪) is the cost function for harvesting and transporting logs to mills from each of those types. Marginal harvest costs for temperate and subtropical plantation forests (i and j) are constant, while marginal harvest costs for inaccessible forests rise as additional land is accessed.

$C^{i,k}_G$(▪) is the cost function for planting land in temperate and previously inaccessible forests, and C^j_N(▪) is the cost function for planting forests in subtropical plantation regions. $G^{i,k}_t$ is the area of land planted in types i and k, and N^j_t is the area of land planted in highly valuable plantation forests. The planting cost functions are given as:

(3) $$C_G^{i,k}(\cdot) = p_m^{i,k} m_t^{i,k} G_t^{i,k}$$

$$C_N^j(\cdot) = p_m^j m_t^j N_t^j + f(N_t^j, X_t^j)$$

where $m^{i,j,k}_t$ is the management intensity of those plantings purchased at price p^i_m, p^j_m, or p^k_m. $f(N^j_t, X^j_t)$ is a function that representing establishment costs for new plantations. The cost function for establishing new plantations rises as the total area of plantations expands.

To see how management intensity influences the stock of trees, note that each hectare of land is assigned a yield function of the form, $V^{i,j,k}(a_t, m^{i,j,k}(t_0))$, where a_t is the age of the hectare at time t, and $m^{i,j,k}(t_0)$ is the management intensity applied to the stand at the time of regeneration, t_0. The yield function is assumed to be typical for ecological species in that region, and $V_a>0$ and $V_{aa}<0$. Management intensity determined at the time of regeneration influences the stock of merchantable products at the time of harvest. The following two conditions hold for trees planted at time t_0 and harvested at time $a = t_{ai}$:

(4) $$\frac{dV^i(t_{a_i} - t_0)}{dm^i(t_0)} \geq 0 \text{ and } \frac{d^2V^i(t_{a_i} - t_0)}{dm^i(t_0)^2} \leq 0$$

The total area of land in each forest type is given as $X^{i,j,k}_t$. $R^{i,j,k}(\blacksquare)$ is a rental function for the opportunity costs of maintaining lands in forests. The form of the rental function is:

(5) $R(X) = \alpha X + \beta X^2$.

This function is applied to all species, and α and β are parameters. The parameters of the rental function for each region are set using current elasticity estimates, as described in Sohngen and Mendelsohn (2003), and current stocks of forests. The stock of land in each forest type adjusts over time according to:

(6) $$X^i_{a,t} = X^i_{a-1,t-1} - H^i_{a-1,t-1} + G^i_{a=0,t-1} \qquad i = 1 - I$$

$$X^j_{a,t} = X^j_{a-1,t-1} - H^j_{a-1,t-1} + N^j_{a=0,t-1} \qquad j = 1 - J$$

$$X^k_{a,t} = X^k_{a-1,t-1} - H^k_{a-1,t-1} + G^k_{a=0,t-1} \qquad k = 1 - K$$

Stocks of inaccessible forests will regenerate naturally, unless they are converted to agriculture. In tropical regions in particular, forests are converted to agriculture when harvested, that is $G^k_{a=0}$ is often 0 for tropical forests in initial periods when the opportunity costs of holding land in forests are high.

The model is programmed into GAMS and solved. The model is solved in 10 year time increments, and terminal conditions are imposed on the system after 180 years. For the baseline case, $P^C_t = 0$, so the term CC_t has no effect on the model. Baseline carbon emissions are then estimated, and used for E^b_t in the carbon scenarios. The scenarios assume an exogenous path for P^C_t, and solve for optimal management. E^s_t under the scenarios is determined endogenously.

For the version of the model considered in this paper, there are 53 timber types distributed across 9 regions. The regions and a brief description of the timber types is shown in table 1. The underlying data and a full description of its development will be available online through the Global Trade and Analysis Project at Purdue University in summer, 2004.

CARBON SEQUESTRATION COST ESTIMATES

Baseline case

The baseline for the timber model assumes that demand for timber products rises at 1% per year initially, falling to 0% per year demand growth in 2100 and beyond. Global harvests rise from approximately 1.6 billion m^3 pear year initially to 2.2 billion m^3 per year by 2100 (Figure 1). Prices rise at an average of 0.4% per year during the century, although they are stable for the last few decades. Most timber harvests are derived from temperate regions initially, with over 70% of timber harvests coming from North America, Europe, and the Former Soviet Union. Harvests in these regions, however, are relatively constant over the century, with most growth in harvests in the long-term occurring in regions with substantial subtropical plantation forestry (South America and Oceania in particular).

The total area of forestland in the model falls from 3.4 million to 3.1 million hectares of land in forests over the century. The regional changes follow general trends of the recent years, where temperate regions are experiencing afforestation and tropical regions are experiencing deforestation (Figure 2). The initial estimates of land use change for particular regions, however, do differ from historical estimates in the literature. For the most part, the differences arise in tropical regions. The UN Food and Agricultural Organization (FAO, 2003) suggests that in the 1990's, net forest loss in Africa, South and Central America, and Asia was 12.2 million hectares per year. With the parameters for the rental functions used in these regions in the timber model, however, the projected rate of net forest loss in those regions is 7.4 million hectares lost per year for the period 2000 – 2010.

While our estimates are lower than recent historical estimates by FAO, we note that there are substantial uncertainties associated with the estimates of land use change made by FAO (Houghton, 2003). Consequently, the baseline scenario for this analysis utilizes conservative estimates of land use change. We address this point more thoroughly in the sensitivity analysis at the end of the paper, where we provide an alternative baseline case that follows more closely historical estimates from FAO in the initial periods.

Initial carbon stocks in the model are estimated to be 811 billion tons of carbon, which is close to that estimated by Dixon et al. (1994) if peatlands are removed from the forest inventory (Brown, 1998). Approximately 53% of the carbon is stored in temperate and boreal regions, with the remaining 47% stored in tropical regions. In addition, 35%

of total carbon is maintained in vegetation, and 65% in soil. Both these numbers are consistent with estimates provided by Dixon et al. (1994).

As a result of deforestation, the world forests are projected to be a net carbon emitter over the coming century. During period 2000 - 2010, annual emissions from the world's forests are estimated to be 368 million tons per year. These are substantially lower than other estimates of annual emission from deforestation for recent periods, such as Dixon et al (1994). However, as noted in Houghton (2003) and Plattner et al. (2002), net global terrestrial fluxes have been revised downward substantially in recent years. The most recent estimates from Houghton (2003) suggest net fluxes of 700 million tons per year rather than 1400 million tons per year as previously believed.

One reason why the estimates in this model remain lower is that the model focuses on adjustments in management and age class distributions. That is, the model predicts the forest stock by age class, and forests are harvested by age class. In our initial inventories, there are numerous forests in young age classes. Over the coming decades, these forests are expected to grow and store additional carbon. The carbon storage in the growth of these existing forests is included in our estimates of sequestration, and thus offsets some of the losses predicted from deforestation.

The regional distribution of carbon emissions from forests for the baseline is shown in figure 3. Most of the emission, as predicted elsewhere, occurs in the tropical regions of South America, Africa, and Southeast Asia. Alternatively, most sequestration occurs in North America, Europe, and the Former Soviet Union. The trends over time are generally towards lower emissions from the tropics and towards 0 emissions and sequestration in the temperate and boreal zones. One interesting consequence of the optimization approach used to solve the model is that the emission pathways adjust over time as the stock of forests adjusts. That is, emissions will be higher when there are large areas of older forests being removed, and emissions will be lower when these older forests have been regenerated and they are re-growing.

Scenario Analysis

For the analysis of alternative policies, 6 scenarios with different carbon price paths were developed in conjunction with the EMF-21 process. The price paths were developed to attempt to simulate a wide range of potential energy model responses to carbon policy. The scenarios used in this analysis are as follows:

- Scenario 1: P^C_{2010} = $5 per ton C; rising at 5% per year
- Scenario 2: P^C_{2010} = $10 per ton C; rising at 5% per year
- Scenario 3: P^C_{2010} = $10 per ton C; rising at 3% per year
- Scenario 4: P^C_{2010} = $20 per ton C; rising at 3% per year
- Scenario 5: P^C_{2010} = $100 per ton C; remaining constant over time.
- Scenario 6: P^C_{2010} = $75 per ton C; rising by $5 per year through 2050.

Scenarios 1 – 4 simulate sequestration policies that attempt to meet long term stabilization goals using carbon only measures, and using measures to reduce other greenhouse gases, such as methane. In particular, EMF-21 examines the potential for stabilizing the radiative forcing from greenhouse gases at 4.5 Watts per square meter. Different initial prices are used to address differential assumptions about abatement costs, and inclusiveness of different greenhouse gases. Models that allow more greenhouse gases to enter into the optimal solution are likely to have lower initial carbon prices. The rate of growth in carbon prices is incorporated to simulate potential differences in the rate of social discounting assumed by energy models. In general, the price of greenhouse gas abatement will rise at the rate of discounting assumed by the modelers when policy-makers are attempting to meet a stabilization target. Thus, the rate of price increase provides sensitivity over different potential rates of social discounting used by different energy modelers.

Scenarios 5 and 6 are incorporated to show the potential effects of policies that try to meet potentially more stringent near term objectives. For instance, EMF 21 energy modelers address the possibility of trying to meet targets that limit the rate of warming over the century. Such targets would like raise near term greenhouse gas abatement prices substantially relative to the price paths above for longer term targets. We thus consider a constant price path of $100 per ton, and a price path that is initially $75, rising at $5 per year through 2050. For results from a wider range of potential carbon price paths, readers are referred to Sedjo et al. (2001).

The path of carbon projected to be sequestered by the global timber model for these six scenarios, and the prices in 2100 (denoted "PC") are shown in figure 4. Prices rise to levels ranging from \$100 to \$807 per Mg (1Mg = 1000 Kilograms = 1 metric ton) carbon in 2100, and cumulative sequestration by 2100 ranges from 59 to 146 Pg carbon (1 Pg = 1 x 10^9 Mg). Sequestration is measured as the increase in carbon above the baseline case. The results clearly show the influence of expectations within the global forestry model with quickly growing prices. Scenarios 1 and 2 have the fastest increases in prices and the highest long term prices, but sequester little carbon initially. In fact, these two scenarios sequester little carbon at all before 2040. Scenarios 3 and 4 have slower price increases, and sequester more carbon initially. Over the long-term, scenario 4 sequesters more carbon than scenario 1, even though 2100 prices in scenario 1 are \$404 and in scenario 4 they are \$286 per Mg. This result is partly explained by the higher prices in scenario 4 for the period 2000 – 2060, but the main difference is the slower growth in prices over the century.

The effects of price levels and price expectations can be further illustrated by comparing scenario 5 to scenario 4. Prices in scenario 5 are constant at \$100 per Mg, whereas prices in scenario 4 start at \$20 per Mg and rise to \$286 per Mg by 2100. Not surprisingly, scenario 5 sequesters substantially more carbon in early periods due to higher prices then. However, even though there is a substantial price difference in 2100, the two scenarios sequester similar amounts of carbon. Scenario 6 sequesters the most carbon of all the scenarios because prices are initially quite high, and they rise at a relatively slow rate of change.

The rate of increase in carbon prices thus has substantial implications for carbon sequestration. Whether prices rise rapidly or slowly, higher long-term prices tend to increase sequestration in the long-term. Policies that induce sustained, rapid price increases (>3%), however, will cause landowners to hold off on sequestration projects until later periods when these projects become more valuable. Alternatively, policies that cause prices to rise to higher sustained levels in early periods and then stabilize suggest a larger initial role for sequestration. The results also confirm the finding in Sohngen and Mendelsohn (2003) that it takes some time to sequester carbon, and that attempts to obtain carbon more quickly could be expensive.

In addition to considering global sequestration levels, it is useful to consider which activities and regions provide the most sequestration. To show this, the results of the scenarios are averaged and presented for 2020 and 2100. Scenarios 1 and 2 are averaged because they have the same, 5% annual increase in prices; scenarios 3 and 4 are averaged likewise because they have the same 3% annual increase in prices. Scenarios 5 and 6 are averaged because they have slow or no increase in prices, and the highest initial prices. While an imperfect method of aggregating, this method will at least provide some indication about the direction of change for policies with different types of price behavior.

The first result when considering where carbon is stored globally is that regions with the most land area and the most existing forest and cropland are able to sequester the most carbon (Table 2). For instance, North America, South America, Southeast Asia, and Africa are projected to sequester the most carbon in these scenarios. The Former Soviet Union has substantial forest area, but already stores significant quantities of carbon in forests, and it has less productive land to shift into forests. The second result is that the rapid price increase suggested by scenarios 1 and 2 imply additional emissions from South America and Southeast Asia between 2000 and 2020. When aggregated to the global level, these emissions are large enough to induce net additional global emissions initially. This occurs because land conversions actually increase in these regions in response to future higher prices for sequestration. Landowners can get the benefits of agriculture now, and the benefits of carbon sequestration in the future by reforesting at high carbon prices.

The third result is that the temperate regions are a larger proportion of global storage initially (i.e. by 2020) than in the long-run (i.e. 2100). Of the temperate regions North America and the Former Soviet Union have the most short-term and long-term potential, followed by Europe, China, and Oceania. Temperate regions take advantage of the current heavy use of forests for industrial forestry activities, and choose to extend rotations initially. Fourth, as noted above, higher initial prices enhance the potential for long-term sequestration in temperate forests. The long-term prices in scenarios 3 and 5 are similar, and the long term prices in 4 and 6 are similar. Temperate regions sequester a larger proportion of the world's total carbon, however, under scenarios 5 and 6. The reason for this is that early initially high prices (that are sustained) attract substantial afforestation in early periods, and these forests have long term benefits for sequestration purposes.

These results generally suggest that policies attempting to achieve lower long term carbon abatement targets (and consequently have less rapid price increases), or that try to moderate the rate of change in temperature over time with large initial targets, should place more emphasis initially on tropical regions like South America, SE Asia, and Africa. Over the longer run, carbon sequestration is heavily influenced by the availability of land that can be converted to forests. As a result, North America, South America, Southeast Asia, and Africa sequester the largest shares of carbon. While Europe has substantial land available for forests, it is fairly costly to convert large areas of land there from agriculture to forests.

It's useful to also consider what type of actions are undertaken to increase sequestration. The global forestry model allows foresters to change the area of land in forests, enhance management in order to increase growing stock (i.e. by fertilizing forests or controlling pests), and increasing timber rotation ages. Overall, in temperate regions, 35 – 44% of the carbon is stored as a result of land use change, and 56 – 65% of the carbon is stored as a result of changes in management (table 3). The balance between management and land use change depends heavily on the price path. Scenarios 1 – 4 imply similar long term storage components for temperate regions, with relatively more emphasis placed on land use change (mainly afforestation in temperate regions). Scenarios 5 and 6 place more emphasis on adjustments in management, and in particular on extending rotation ages. The tropical regions behave differently, with only 27 – 34% of carbon resulting from management changes, and 65 – 72% of the carbon resulting from land use change. This makes sense given the large amount of current deforestation occurring in those regions.

Sensitivity Analysis with Alternative Baseline

The results above relay the importance of deforestation the tropics as an option for mitigating climate change. Central and South America, Africa, and Southeast Asia account for more than 65% of the global estimate. Further, more than 65% of this results from changes in land use. Early on, these changes entail reducing deforestation, while later in the century they entail increasing afforestation. As noted earlier in this paper, however, there is uncertainty about the level of deforestation that will occur in the tropics over the next century. This section takes a closer look at the baseline estimates of deforestation and the influence of those estimates on the potential costs of carbon sequestration.

The baseline used in the analysis above is the same as presented in Sohngen and Mendelsohn (2003). The land use change estimates for tropical regions in that baseline differ from the projections used in the IPCC Special Report on Emission Scenarios (SRES; IPCC, 2000). In particular, the SRES scenarios suggest substantial initial deforestation in tropical regions, but that deforestation declines nearly to 0 by the end of the century. In contrast, Sohngen and Mendelsohn (2003) suggest less initial deforestation, but that it is persistent over the century. To address baseline uncertainty, an alternative baseline scenario is estimated and the alternative price scenarios described above are run under the alternative baseline and compared to the original baseline.

An alternative baseline case is generated by adjusting the parameters of the rental function in equation (5) above for forests in Central and South America, Africa, and Southeast Asia. Note that net annual forest change estimates are endogenous projections of the timber model, based on these underlying rental functions. The parameters for the alternative baseline are chosen to obtain more deforestation initially, less future deforestation, and more cumulative deforestation than the original baseline. Statistics for the net annual change in forestland area in 2000 – 2010, 2090 – 2100, and the cumulative change over the century are given for the original scenario in Sohngen and Mendelsohn (2003), and for the alternative baseline scenario developed for this analysis. As can be seen in the table, deforestation rates are initially much higher for the alternative baseline, but lower in the long run. For comparison, deforestation rates in tropical regions, including South and Central America, Africa, and Southeast Asia, have been estimated at around 12.2 million hectares of net forest loss per year for the period 1991 - 2000 (Houghton, 2003), so our two baselines bracket the most recent estimates.

The baseline carbon generated by the alternative baseline is shown in figure 5, which can be compared directly to figure 3. As expected, total emissions from deforestation are initially greater in the alternative baseline scenario, although they decline over time. By 2100, all regions in the model are sequestering net carbon.

Cumulative carbon sequestration for global forests, and for three aggregated regions are shown in table 5 for all six scenarios for the periods 2020, 2050, and 2100. The accelerated deforestation baseline projects less overall cumulative sequestration for all the scenarios in all periods, although the regional distribution varies. Recall that carbon prices are the same in each case, so these differences suggest that under the alternative baseline scenario, sequestration is projected to be more expensive on average.

The differences are largest in the tropical regions because the alternative rental functions were only changed in these regions. Timber prices do not change substantially, and the temperate regions sequester nearly as much carbon as in the baseline case. The largest differences occur initially. In fact, under the alternative baseline, sequestration in initial period is greater than in the original baseline scenario, mainly because baseline deforestation is larger.

Surprisingly, although the cumulative deforestation is greater in the alternative scenario, the costs of carbon sequestration increase under this alternative baseline (i.e. for the same carbon price, there is less carbon sequestered relative to the baseline). The reason for this is simple. The economic forces that would lead to more deforestation than projected in the original baseline are higher demand for agricultural land. This higher demand for agricultural land raises rental rates, and increases the costs of keeping land in forests. This in turn raises the costs of carbon sequestration in regions where land use is particularly important, such as the tropics. The alternative baseline shows that assumptions about the productivity of forestland in agriculture in the tropics can have large influences on total potential sequestration, and it illustrates the importance tropical forests have for the overall sequestration picture.

CONCLUSION

This paper presents the results of a scenario analysis exploring how alternative greenhouse gas abatement prices and price paths could potentially affect the timing and quantity of carbon sequestration in forests. The paper builds upon the global timber model described in Sohngen et al. (1999), by integrating values for carbon sequestration into the forestry model. The carbon price scenarios are developed as part of the EMF-21 process to be consistent with other models exploring carbon sequestration, and to be consistent with prices generally observed in large-scale global energy models exploring the economics of alternative climate change policies. In addition to addressing the sensitivity of carbon sequestration across different assumptions about the price path of greenhouse gas abatement, the paper also explores the sensitivity of the forest sequestration results to an alternative deforestation baseline.

The results highlight several key issues that will arise when attempting to integrate forestry models into energy models in order to assess forest carbon sequestration in relationship to other options for mitigation greenhouse gases. One issue is the importance of the assumed rate of growth of greenhouse gas abatement prices. The results show that under slower growth in greenhouse gas prices, more carbon sequestration is possible in earlier periods, and forests will generally be a larger component of overall greenhouse gas abatement strategies. Higher rates of growth in prices give landowners an incentive to hold-off on investing in forest carbon sequestration until later periods when carbon sequestration is most valuable. Since the rate of growth of greenhouse gas prices in stabilization policies is closely related to the assumed rate of social discounting used by energy models, this suggests, not surprisingly, that forestry can have a larger impact in models that assume lower social discount rates. This confirms the finding in earlier research by Sedjo et al. (2001).

The role of forestry also depends on assumptions about what other options are available for abating greenhouse gases (i.e. methane mitigation). If including these other options reduces the costs of greenhouse gas abatement over the long run, then forestry too, will become a smaller part of the puzzle. That is, consider comparing two pairs of scenarios with the same rate of price growth: scenario 1 to scenario 2, or scenario 3 to scenario 4. The only difference is the initial price level, which declines by 50% when comparing the largest initial price to the smallest for the individual pairs. The effect of this 50% reduction in initial prices on cumulative sequestration over the century is a 32% reduction from scenario 2 compared to scenario 1, and a 42% reduction for scenario 4 compared to scenario 3. It is not clear whether these relationships would hold for larger or smaller reductions in initial prices, however, the results imply that if including other options for greenhouse gas mitigation reduces initial greenhouse gas prices by 50%, the role of forestry would be reduced by 32 – 42%. Of course, to fully understand the effects of alternative options for greenhouse gas mitigation on prices and forest sequestration, one would need to integrate forestry directly into energy models that include a full range of options for greenhouse gas abatement.

The results in this study show that more rapid carbon sequestration is possible, although more costly. The two scenarios that had high initial carbon prices, scenarios 5 and 6, sequester substantial carbon initially and in the long run. These scenarios are consistent with policies that set strict emissions targets in particular commitment periods, or that attempt to limit the rate of change of temperatures over time, suggesting that more stringent earlier targets for carbon sequestration would likely involve substantial use of forestry options for meeting the target.

Overall, forestry seems to be not so much a stop gap measure for a long-term policy as argued elsewhere, but instead, a valuable near-term option if policy targets focus on near term targets that are relatively stringent. Price paths consistent with long term warming targets suggest low initial prices, but relatively rapid price increases.

Under these price paths, forests show little sequestration initially, with most sequestration occurring in later periods. Although forestry can potentially play an important long-term role, it has little influence initially. Price paths consistent with more stringent near term targets suggest higher initial prices, which, while more costly for society, would generate substantial investments in forest carbon sequestration.

Regionally, around 65% of the sequestration projected by this model occurs in tropical regions, with over 65% of that resulting from changes in land use (either reducing deforestation or inducing afforestation). The temperate zones sequester less carbon overall, but sequester more of it, potentially more than 50%, by changing management of forests to increase growing stock. The rate of growth of carbon prices appears to influence storage options slightly. In particular, with the fastest growing prices observed in this study, most carbon sequestration occurs in the temperate forests in early periods. This occurs in part because the faster price increases can potentially induce additional emissions of carbon (above the baseline) from tropical forests by increasing rates of deforestation.

The paper shows the influence of the baseline estimates of rates of deforestation. A sensitivity analysis on an alternative baseline case with more extensive deforestation in tropical regions was conducted to test the results. Higher initial deforestation rates are found to reduce long-term global carbon storage potential at the given prices. Higher deforestation rates are generated in the model by changing parameters in the land rental functions for tropical regions. Higher rental rates induce more deforestation. While the area of land deforested increases when comparing the alternative baseline case to the original baseline case, the cost of reforesting land or maintaining it in forests, is higher as well. Thus, higher land prices reduce the potential role for tropical regions for the same prices. The rental rates were changed only for the tropical regions, so while there are some slight adjustments in potential carbon sequestration in the temperate zone, the results are fairly consistent for the temperate forests under both sets of baseline assumptions.

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Table 1: Timber region descriptions[1]

Regions	Description
North America	14 total timber types: 11 in type i, 0 in type j, and 3 in type k.
South America	5 total timber types: 2 in type i, 2 in type j, and 1 in type k.
Europe	8 total timber types: 6 in type i, 1 in type j, and 1 in type k.
Former Soviet Union (includes Central Asia)	5 total timber types: 4 in type i, 0 in type j, and 1 in type k.
China	7 total timber types: 4 in type i, 1 in type j, and 2 in type k.
India	2 total timber types: 0 in type i, 2 in type j, 0 in type k.
Oceania (Australia and New Zealand only)	4 total timber types: 1 in type i, 2 in type j, and 1 in type k.
Southeast Asia	4 total timber types: 1 in type i, 2 in type j, and 1 in type k.
Africa	4 total timber types: 1 in type i, 2 in type j, and 1 in type k.

[1] Type i is optimally managed forests, type j is subtropical plantation forests, and type k is inaccessible forests.

Table 2: Proportion of global carbon sequestration by region under alternative scenarios for the years 2020 and 2100.

	2020			2100		
	Average S1 & S2	Average S3 & S4	Average S5 & S6	Average S1 & S2	Average S3 & S4	Average S5 & S6
North America	44%	19%	16%	14%	13%	15%
South America	-12%	16%	23%	24%	27%	24%
Europe	5%	7%	4%	5%	4%	5%
FSU	30%	14%	15%	8%	8%	9%
China	13%	5%	5%	6%	4%	5%
India	0%	0%	1%	1%	1%	1%
Oceania	3%	1%	1%	3%	1%	1%
SE Asia	-105%	19%	20%	21%	22%	21%
Africa	5%	18%	16%	18%	20%	19%

Table 3: Percent of Carbon Storage in each region accomplished by Changes in Land Use or Management (increasing inputs or changing rotation ages) in 2100. Market storage is not included in this table, so the numbers for a particular region do not sum to 100%.

	2100					
	1&2		3&4		5&6	
	LUC	MGMT	LUC	MGMT	LUC	MGMT
North America	41	61	39	60	26	65
Europe	40	62	34	63	40	54
FSU	50	54	53	47	51	44
China	47	58	49	52	32	61
Oceania	49	49	45	47	24	50
Temperate	44	58	43	56	35	57
South America	80	20	88	12	86	12
India	65	31	53	36	49	7
SE Asia	72	30	78	23	61	38
Africa	83	18	93	8	89	12
Tropical	78	22	86	14	79	20
Global	68	34	72	27	65	32

Table 4: Net forest area change for two baseline scenarios

	Sohngen and Mendelsohn (2003)			Alternative Baseline		
	Annual Change 2000 – 2010	Annual Change 2090 -2100	Cumulative 2000 – 2100	Annual Change 2000 – 2010	Annual Change 2090 -2100	Cumulative 2000 - 2100
	Million ha					
Africa	1.6	1.1	129.2	5.3	0.7	230.5
Americas	3.7	1.5	199.7	4.2	0.9	218.5
SE Asia	1.8	0.5	101.6	3.2	-0.2	76.4
Total	7.2	3.1	430.5	12.7	1.4	525.3

Table 5: Comparison of total carbon sequestration under the original baseline scenario and accelerated deforestation base scenario.

	2020			2050			2100		
	Total	Temperate	Tropical	Total	Temperate	Tropical	Total	Temperate	Tropical
	Billion Metric Tons (Pg) Cumulative Sequestration (Above Baseline)								
Accelerated Deforestation Baseline									
Scen. 1	0.4	0.4	0.0	2.0	1.7	0.3	81.8	30.9	50.9
Scen. 2	0.4	0.3	0.2	4.1	3.3	0.8	132.9	58.0	75.0
Scen. 3	2.4	0.9	1.4	6.8	3.8	3.0	48.2	16.2	32.1
Scen. 4	4.4	1.9	2.5	14.4	6.1	8.4	88.3	33.6	54.8
Scen. 5	23.1	9.3	13.8	43.8	15.5	28.3	60.2	23.2	37.0
Scen. 6	17.4	8.1	9.4	67.1	26.0	41.1	112.9	47.5	65.4
Original Baseline									
Scen. 1	-0.2	0.4	-0.6	2.9	1.1	1.8	98.6	32.6	66.0
Scen. 2	0.0	0.9	-0.9	6.2	2.2	4.0	146.6	56.7	89.9
Scen. 3	2.1	1.0	1.1	8.3	3.2	5.1	59.1	15.5	43.6
Scen. 4	4.5	2.1	2.4	17.0	5.9	11.1	103.6	32.6	70.9
Scen. 5	23.1	9.4	13.7	48.1	15.6	32.6	73.9	23.3	50.6
Scen. 6	18.2	7.7	10.4	81.2	27.6	53.6	139.8	51.5	88.3

Figure 1: Baseline global timber harvests by region.

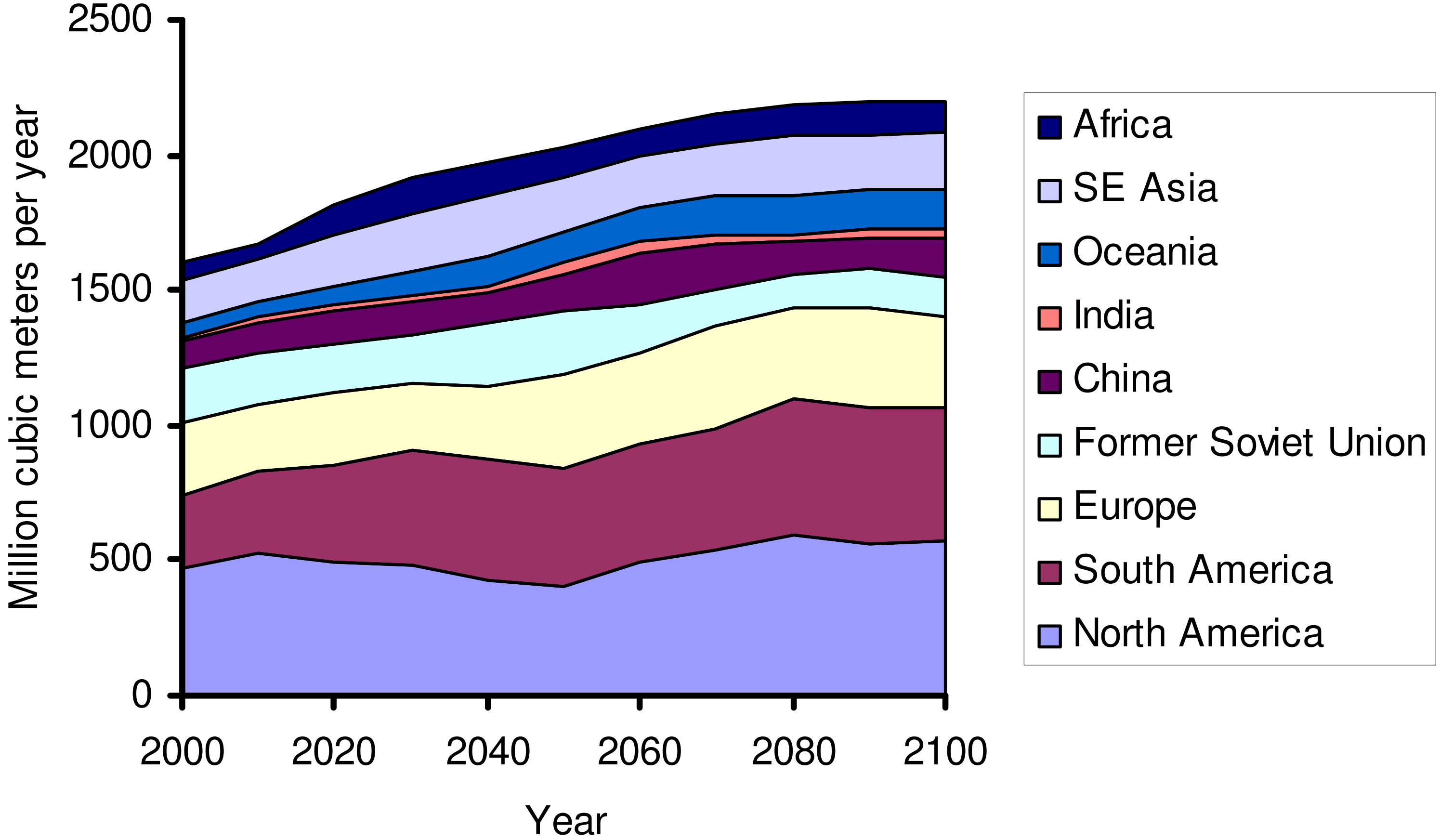

Figure 2: Baseline area of forestland in each region in 2000, 2050, and 2100.

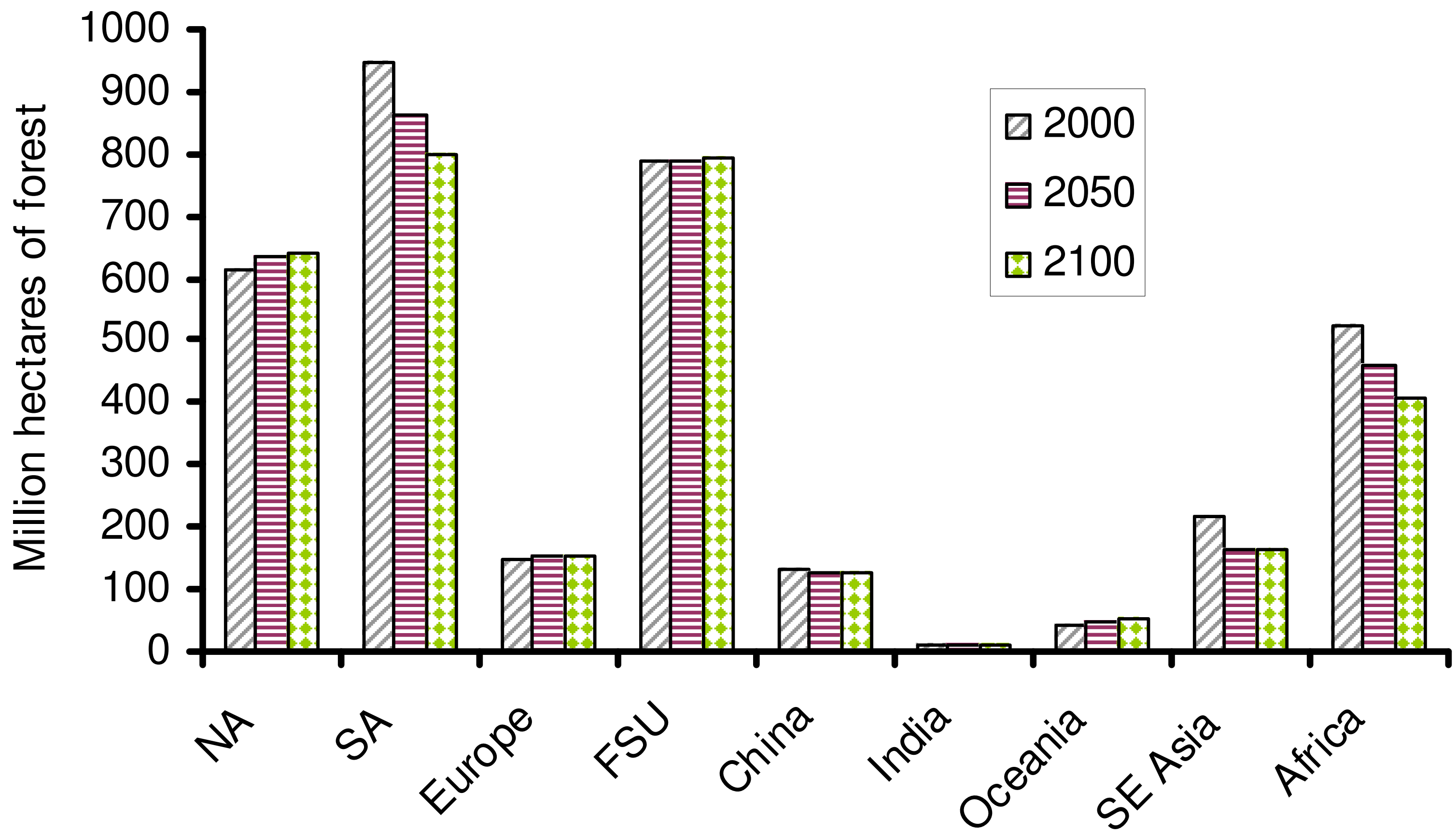

Figure 3: Trends in carbon emissions (+) or sequestration in aggregated regions (-) of the world.

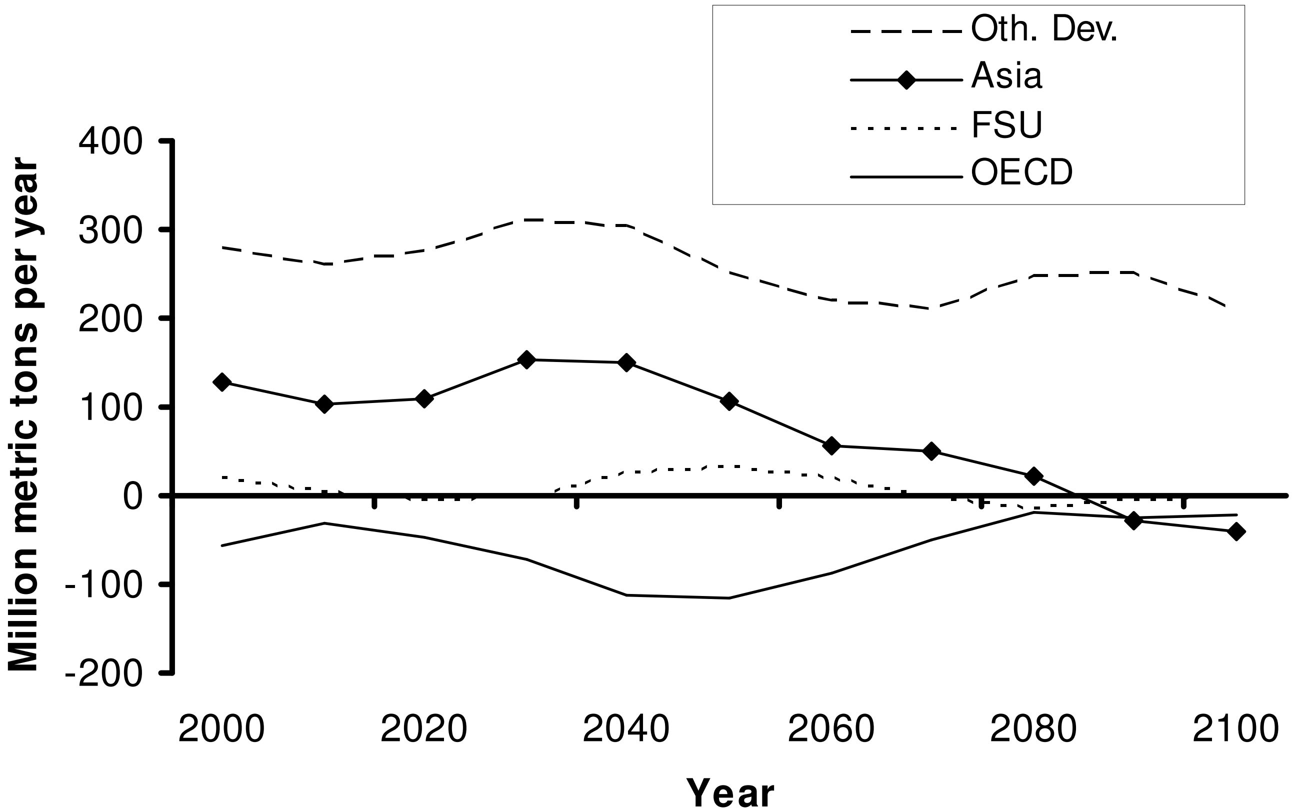

Figure 4: Path of Carbon Sequestration above the baseline for the scenarios.

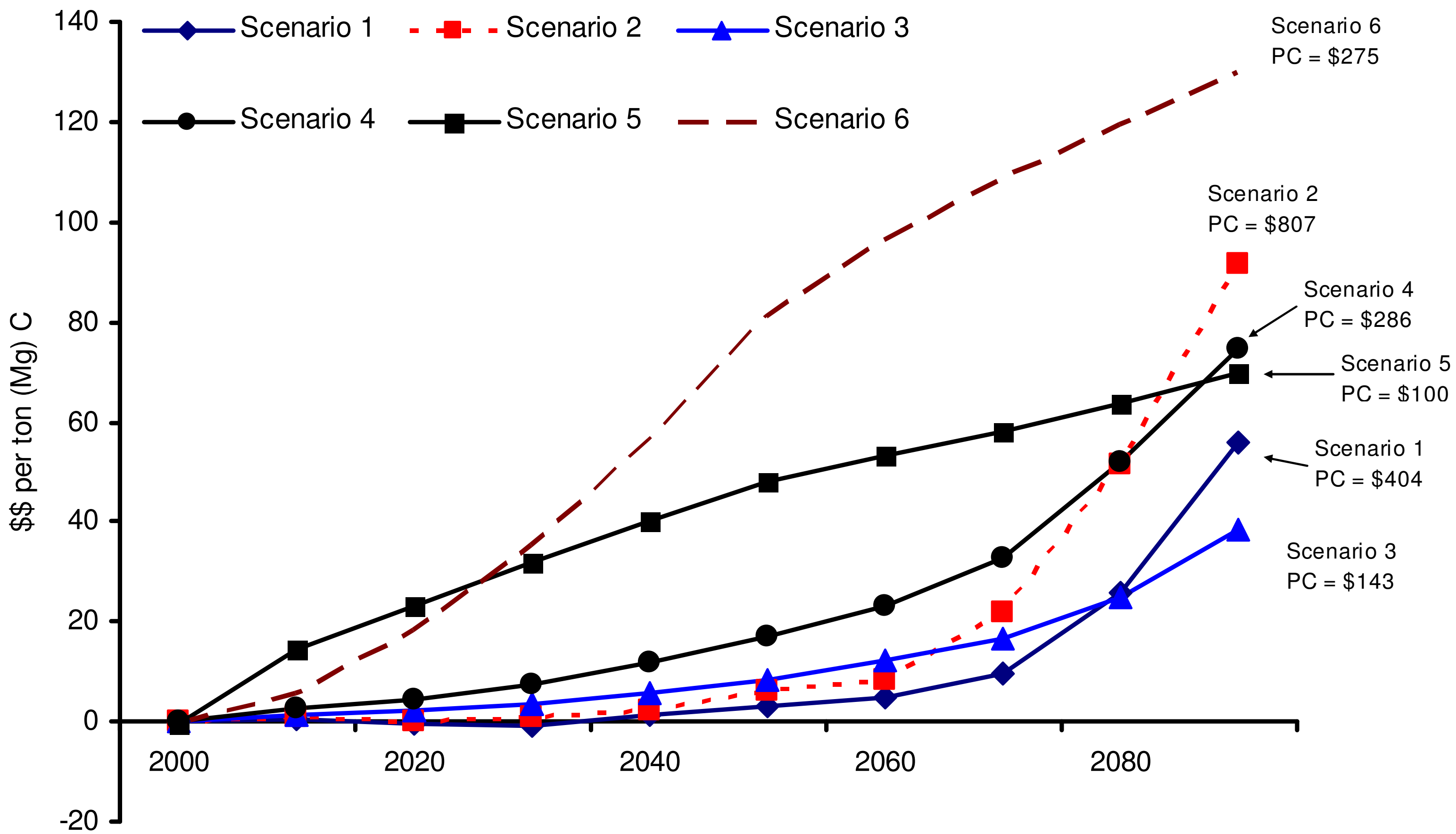

Figure 5: Alternative baseline scenario carbon emission path.