A Sensitivity Analysis of Carbon Sequestration

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Abstract

This paper projects how land supply, timber demand, and technical change in the forest sector affect both projections of the amount of carbon that forests will sequester on their own and the effectiveness of efficient carbon sequestration programs. The model projects that although deforestation will slow over time, forests will lose 76 Pg C globally over the next hundred years through timber harvests and land conversion. If the demand for land from agriculture is higher, forests could lose another 7.1 Pg C, if timber demand growth is higher, they could lose another 7.8 Pg C and, if harvest costs decline, they could lose another 10.6 Pg C. Technical change centered on plantations is not expected to have any major impact on carbon sequestration. The model also predicts that carbon sequestration programs could sequester between 55 and 116 Pg C if carbon prices rise by $61 and $188 per ton respectively by the end of the century. Higher agricultural demand for land would reduce these amounts somewhat but sequestration program results are largely insensitive to both demand and technical change in the forestry sector.

1. Introduction

Between 2.0 – 2.2 Pg/yr (1 Pg = 1 trillion Kg) of carbon (C) have been emitted from forests due to land use change in the last few decades (Houghton, 2003), and the Intergovernmental Panel on Climate Change (2000) suggests that land use change could continue to lead to large C emissions over the next few decades (1 – 2 Pg/yr). While most models agree that there are likely to be large potential shifts in land use in the future, the direction, size, regional scope, time path, and influence of these changes on C emission paths are still debated. Specifically, little is known about what affect the demand for agricultural land, timber demand, or technological change in the forestry sector might have on sequestration. Using a welfare-maximizing framework, this paper further develops a dynamic timber model that incorporates carbon sequestration (see Sohngen and Mendelsohn 2003). The paper uses a sensitivity analysis to quantify how the above factors potentially affect the amount of carbon stored in terrestrial ecosystems over the next century. The paper also explores whether these same factors would affect the amount of carbon stored by an efficient carbon sequestration program tied to optimal carbon prices.

Forestry studies have considered how changes in the supply of land, timber demand and technological change could influence returns to forestry and global production patterns (Sedjo, 2004a;b; Siry, 2002) but these studies have not explored how these factors could affect carbon sequestration. As agriculture demands more land, forestland declines, reducing baseline amounts of carbon sequestration, and increasing the cost of carbon sequestration programs. Increases in the demand for timber would increase prices, draw more land into forestry, and increase management intensity. However, the higher prices would also increase harvesting in inaccessible regions so that the net effects of changes in timber demand on sequestration are ambiguous. Increases in the productivity of managed forests will cause land to be converted from farmland into fast growing plantations but the resulting lower timber prices could also reduce the area of natural forests. All of these factors could potentially affect carbon sequestration in forests and the costs of a sequestration program.

This paper explores how the supply of land, timber demand, and technological change in forestry may influence global carbon sequestration over the next century. Using the global forestry model described in Sohngen and Mendelsohn (2003), we quantify how these factors affect both carbon storage in forests and the effectiveness of carbon sequestration programs. A set of baseline scenarios project what the ecosystem and market would do in the absence of a terrestrial carbon sequestration program. The carbon sequestration program pays forest owners to store carbon given the price of carbon determined by optimal mitigation plans for greenhouse gases (Nordhaus and Boyer 2000).

The next section describes the global forestry model in detail. First, the model optimizes forest management over time in the absence of a carbon sequestration program to see what would happen to forestland and carbon storage. Second, we introduce into the model a carbon sequestration program targeted at a low and high carbon price trajectory. Section 3 displays the results of a sensitivity analysis that explores how changing model parameters affect the results. Section 4 reviews the conclusions and discusses policy implications.

2. Global Forestry Model

The forestry model utilized for this analysis is built upon the model described in Sohngen et al. (1999), and used by Sohngen and Mendelsohn (2003) to analyze global sequestration potential. The forestry model has been expanded, however, and now contains 146 distinct timber types in 13 different regions. The timber types represent different species, although similar species can occur in different regions. The timber types will have different merchantable quality characteristics, harvesting costs, establishment or regeneration costs, and rental costs. For the purposes of describing the model, each timber type can be allocated into one of three general types of forest stocks. Stocks S^i are moderately valued forests, managed in optimal rotations, and located primarily in temperate regions. Stocks S^j are high value timber plantations that are managed intensively. Subtropical plantations are grown in the southern United States (loblolly pine plantations), South America, southern Africa, the Iberian Peninsula, Indonesia, and Oceania (Australia and New Zealand). Stocks S^k are relatively low valued forests, managed lightly if at all, and located primarily in inaccessible regions of the boreal and tropical forests. The inaccessible forests are harvested only when timber prices exceed marginal access costs[1].

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

[1] In this study, forests in inaccessible regions are harvested when MAC are less than the value of the standing stock plus the present value of maintaining and managing that land as an accessible forest in the future.

$$(2)\ Max\sum_{0}^{\infty}\rho^{t}\left\{\begin{array}{l}\int_{0}^{Q^*(t)}\left\{D(Q_t,Z_t)-C_{H^i}(\cdot)-C_{H^j}(\cdot)-C_{H^k}(\cdot)\right\}dQ(t)- \\ \sum_{i,k}C_{G}^{i,k}(G_t^{i,k},m_t^{i,k})-\sum_{j}C_{N}^{j}(N_t^{j},m_t^{j})-\sum_{i,j,k}R^{i,j,k}(X_t^{i,j,k})+CC(t)\end{array}\right\}$$

where $Q_t = \sum_{i,j,k}\left(\sum_{a}H_{a,t}^{i,j,k}V_{a,t}^{i,j,k}(m_{t0})\right)$

In equation (2), $D(Q_t,Z_t)$ is a global demand function for industrial wood products given the quantity of wood, Q_t, and income, Z_t. The quantity of wood depends upon $H^{i,j,k}$, the area of land harvested in the timber types in i, j, or k, and $V_a^{i,j,k}(m_{t0})$, the yield function of each plot. The yield per hectare depends upon the species, the age of the tree (a), and the management intensity at the time of planting (m_{t0}).

The net annual welfare in timber markets also depends upon the costs. $C_H(\blacksquare)$ is the cost function for harvesting and transporting logs to mills from each of timber type. 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. $C^{i,k}{}_G(\blacksquare)$ is the cost function for planting land in temperate and previously inaccessible forests, and $C^j{}_N(\blacksquare)$ 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 plantation forests. The planting cost functions are given as:

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

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

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 representing establishment costs for new plantations. The cost function for establishing new plantations rises as the total area of plantations expands.

The yield function has the following properties typical of ecological species: $V_a>0$ and $V_{aa}<0$. We assume that management intensity is determined at planting. The following two conditions hold for trees planted at time t_0 and harvested "a" years later $(a+t_0) = t_{ai}$:

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

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

$$(5) \qquad R(X) = \alpha X + \beta X^2 \qquad \text{for temperate and boreal regions}$$

$$R(X) = \alpha X^2 + \beta X^3 \qquad \text{for tropical regions}$$

The marginal cost of additional forestland in tropical forests is assumed to be non-linear to account with relatively high opportunity costs associated with shifting large areas of land out of agriculture and into forests. The rental functions represent a weakness of the current model because it is likely that the land supply function will vary a great deal across ecosystems and regions, and we have only considered two potential functional forms. The parameters of the rental function are chosen so that the elasticity of land supply is 0.25 initially, the reported relationship between forests and agriculture in the US (Hardie and Parks, 1997; Plantinga et al., 1999). This elasticity implies that the area of forests could increase by 0.25% if forests can pay an additional 1% rental payment per year. Unfortunately, similar estimates for other regions of the world are not available, so the same elasticity estimate is applied globally.

The stock of land in each forest type adjusts over time according to:

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

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

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

Stocks of inaccessible forests in S^k are treated differently depending on whether they are in tropical or temperate/boreal regions. First, all inaccessible forests are assumed to regenerate naturally unless they are converted to agriculture. Second, in tropical regions, forests often are converted to agriculture when harvested, so that $G^k_{a=0}$ is often 0 for tropical forests in initial periods when the opportunity costs of holding land in forests are high. As land is converted to agriculture in tropical regions, rental values for remaining forestland declines, and land eventually begins regenerating in forests in those regions. This regeneration is dependent on comparing the value of land in forests versus the rental value of holding those forests. In this study, we do not track the type of agriculture to which forests are converted, i.e. crops or grazing. Third, temperate/boreal forests that are harvested are converted to accessible timber types so that $G^{k}_{a=0}$ is set to 0. The stock of inaccessible forests in S^{k} is therefore declining over time if these stocks are being harvested. Each inaccessible boreal timber type has a corresponding accessible timber type in S^{i}, and forests that are harvested in inaccessible forested areas in temperate/boreal regions are converted to these accessible types. Thus, for the corresponding timber type, we set $G^{i}_{a=0} \geq H^{k}_{a-1}$. Note that the area regenerated, $G^{i}_{a=0}$, can be greater than the area of the inaccessible timber type harvested because over time, harvests and regeneration occurs in forests of the accessible type.

The term CC(t) represents carbon sequestration rental payments. Rental payments are made on the total stock of carbon in forests, thus, the form for CC(t) is given as:

(7)
$$CC(t) = CR(t)\sum_{i,j,k}\gamma_{i,j,k}\sum_{a}\left\{V^{i,j,k}_{a,t}(m^{i,j,k}(t_0))\right\}X^{i,j,k}_{a,t} + P$$

$$C(t)\sum_{i,j,k}\theta_{i,j,k}\sum_{a}\left\{V^{i,j,k}_{a,t}(m^{i,j,k}(t_0))\right\}H^{i,j,k}_{a,t} - E^{b}_{t},$$

where CR(t) is the annual rental value on a ton of carbon, PC(t) is the price of a ton of carbon, $\gamma_{i,j,k}$ is a conversion factor to convert forest biomass into carbon, $\theta_{i,j,k}$ is a conversion factor to convert harvested biomass into carbon stored in products, and E^{t}_{b} is baseline carbon sequestration. For this model, we assume that product storage in long-lived wood products is 30% of total carbon harvested (Winjum et al., 1998).

The model is programmed into GAMS and solved in 10 year time increments. Terminal conditions are imposed on the system after 150 years. These conditions were imposed far enough into the future not to affect the study results over the period of interest. For the baseline case, $P^C_t = 0$, there is no sequestration program, and the term CC_t has no effect on the model. Baseline carbon sequestration is then estimated, and used for E^b_t in the carbon scenarios. The sequestration program scenarios are based on an independently estimated path for P^C_t. The price path of carbon is assumed to be exogenous from the sequestration. This is not exactly correct, as an ambitious sequestration program will reduce carbon prices. However, in earlier research, it was found that this price effect was small (Sohngen and Mendelsohn 2003). The price of carbon is the present value of the damages caused by a carbon emission at each period of time. The magnitudes of these prices were calculated in an optimal control program balancing abatement costs against climate damages (Nordhaus and Boyer 2000).

As noted above, the version of the model considered in this paper contains 146 timber types distributed across 13 geographical regions. The total forest area has now been split into more regions compared to earlier versions of the model (i.e., Sohngen and Mendelsohn, 2003). Canada and the United States have been split apart; Central and South America have been split; Asia Pacific has been split into Southeast Asia, Central Asia, and Japan; the Former Soviet Union (FSU) has been split into Russia only; areas of the FSU in Europe are now in the European area and FSU areas in Central Asia have been included in the new Central Asia region.

In addition to changing regional definitions, the model has been updated in several additional ways. First, new data on age class inventories and yield functions for several major regions have been incorporated, including the United States, Russia, China, Australia, and New Zealand. Second, yield functions for subtropical plantations have been updated, and technological change in these plantations has been directly modeled.

Technological change for plantations is predicted to increase timber yields by 0.25% annually. Third, carbon conversion parameters in the U.S. (Smith et al., 2003) and China (Fang et al., 2001) have been updated. Carbon parameters in other regions have been adjusted so that the carbon content of forests corresponds to biomass estimates from the U.N. Food and Agricultural Organization (FAO, 2003).

3. Simulation Results

3.1. Baseline

The baseline for this analysis assumes that demand grows at a declining rate over time. Growth starts at 0.5% per year but declines 5% per year. The elasticity of demand function is assumed to be unitary, 1.0. The elasticity of land supply is assumed to be 0.25 for every timber producing region. Technical change is assumed to increase yields in subtropical plantations at 0.25% per year. The yield functions for all other species are assumed to remain constant over time. The baseline also assumes that harvesting costs and plantation establishment costs are constant over time. There is no carbon sequestration program in the baseline.

The model predicts that the area of forestland and global carbon storage will decline over the next century in the baseline (see Table 1). During the period 2005-2015, the net annual reduction in forest area is approximately 10 million hectares per year, and global carbon emissions from land use change are approximately 1.9 Pg per year, which are consistent with estimates from other authors (Dixon et al., 1999; Houghton, 2003). However, the model predicts that this deforestation rate will slow over time so that the rate is closer to 267,000 ha/yr in the second half of the century and the amount of carbon being lost will drop to 0.5 Pg/yr. Subtropical plantations are projected to expand during the period of analysis, rising from 73 million hectares in 2005 to nearly 136 million hectares by 2105. This relatively robust increase in plantations occurs largely in South America, China, and Oceania. The area of inaccessible temperate and boreal forests declines from 1,121 million hectares in 2005 to approximately 938 million hectares. Most of these losses occur in Canada and Russia.

The changes in subtropical plantation forests and inaccessible temperate and boreal forests have important implications for carbon sequestration. Within North America, for example, the baseline estimates in this study suggest that the carbon pool will be relatively stable, and even declining slightly over the coming century. The area of forests within the U.S. increases over time, but these increases do not offset carbon losses from harvests in forests that currently are natural and conversions from natural forests to plantations, particularly in the South. Natural forests have more carbon per hectare, and species conversions that enhance merchantable timber production do not also enhance carbon sequestration. Within Canada, continued harvests in inaccessible regions of the boreal forests offset many of the gains in carbon that occur with afforestation. Similar results occur for Russia, where fairly substantial harvests in inaccessible forests of Siberia are projected over the coming century.

3.2. Sensitivity Analysis With No Carbon Sequestration Program

We conduct a sensitivity analysis in order to see how these carbon storage projections might change as model parameters change. The full set of sensitivity analyses are shown in Table 2. Alternative scenarios are compared against the baseline to test the significance of the variable in question. First, although total wood harvests have been relatively constant globally for the past 20 - 30 years (FAOSTATS, 2003), it is possible that rising population and income in Asia, India, and other developing countries could substantially expand the demand for wood products. To address this possibility, demand growth is assumed to rise at 2% per year initially, with the growth rate falling by 5% per year. Second, we assume that the price elasticity of the supply of land from agriculture is 50% lower (0.13), suggesting that there is a high demand for land by farmers, or 50% higher (0.38), suggesting that there is a low demand for land by farmers. Third, we explore three scenarios about technological change in the forestry sector. We assume that technical change has a smaller beneficial effect on plantation yields, 0.05%/yr (rather than 0.25%/yr), or it reduces the cost of harvesting by 0.5%/yr, or it reduces subtropical plantation costs by 0.5%/yr. All of these assumptions imply that technical change will have a dynamic (not a one time) effect on forests.

The alternative scenarios in the sensitivity analysis have relatively small effects on total forestland and carbon storage in the world's forests. Higher demand for forest products increases the price of forest products substantially (timber prices are approximately 48% higher in 2105). These higher prices do increase the overall area of land in forests by approximately 61 million hectares in 2105 (Table 3), however, this represents a gain of only about 2% globally. The largest gains occur in the European Union, the U.S., China, and Canada.

Global carbon storage is projected to decline 7.8 Pg under the high demand assumption by 2105, despite the projected increase in forestland area. As with total forestland area, this represents a small proportional deviation in total global carbon storage in 2105, approximately 1%. The reduction in carbon results from more intensive harvests of inaccessible forests and more intensive harvesting of all forests. Regions that have large areas of inaccessible forests, the boreal and tropical regions, experience a decline in carbon sequestration. These additional harvests do not lead to land use change, but they do reduce carbon intensity in inaccessible forests. Canada, South and Central America, Russia, Southeast Asia, and Africa would likely hold less carbon with higher demand, while the U.S., Europe, China, and Japan are projected to hold more carbon.

Higher land supply elasticity (cheaper land from agriculture) leads to more forest area and more carbon sequestered. Lower land supply elasticity, higher agricultural demand for land, reduces forestland and the amount of carbon sequestered. Globally, the high elasticity assumption leads to approximately 66 million additional hectares in forestry, with the largest gains occurring in tropical regions. This is a relatively small change in both agricultural and forestry land. Currently, there are approximately 1.5 billion hectares of rainfed agricultural land globally (Fischer et al., 2003). If the entire 66 million hectares comes from rainfed agricultural land, this implies a 4% reduction in agricultural land (and a 1.7% increase in forestland). The carbon consequences of these changes amount to less than a 1% change in total carbon stored globally. Thus, each 1% increase or decrease in rainfed agricultural land leads to approximately a 0.25% change in carbon (i.e. 1 additional hectare of land in rainfed agriculture reduces carbon storage by an 80 - 141 Mg C).

The final three scenarios, low harvesting costs, low plantation establishment costs, and low technological change in plantation yields have relatively small impacts on total carbon storage and forestland. Low harvesting costs have the largest effects on C storage, lowering total C in forests in 2105 by 11 Pg C, or around 1.3%. These losses result mainly from larger incursions into inaccessible forest areas in boreal and tropical regions. Although lower plantation establishment costs do increase the area of subtropical plantations in regions like South and Central America, Oceania, Southeast Asia, and Africa, lower timber prices lead to offsetting reductions in forestland area in other regions. The net effects on forestland area amount to approximately 14 million additional hectares of land in plantations. The carbon consequences of these changes are quite small, with a less than 1 Pg gain in carbon. High valued timber plantations, while quickly producing timber for markets, do not sequester substantial carbon. Finally, the low technology change scenario has a surprisingly small effect on both land area and carbon sequestration.

3.3. Sensitivity Analysis of Carbon Sequestration Programs

We now introduce an efficient global carbon sequestration program (Sohngen and Mendelsohn 2003). The program relies on price paths for carbon that have been determined by optimal mitigation models, specifically DICE (Nordhaus and Boyer, 2000). The mitigation model balances the costs and benefits of controlling residential and industrial emissions of greenhouse gases. The model generates a price path for carbon that increases over time. As discussed in the theory section, we treat the price path of carbon as exogenous in this paper. The carbon price describes the marginal benefit of storing carbon. By equating the marginal cost of storing carbon in forests with the carbon price, we design an efficient sequestration program.

We examine two sets of carbon price paths, corresponding to a low and a high damage case. Carbon prices in the low damage case are initially $7.14 per ton C in 2005, and rise to $61.36 per ton C by 2105. For the high damage case, carbon prices are $21.82 in 2005, and rise to $187.63 in 2105. By 2105, the global carbon sequestration program will cause the area of forests to increase by 204 and 552 million hectares in the low and high damage scenarios respectively. This will in turn result in an additional 54.7 and 115.6 Pg C being stored in forests. Compared to the results in Sohngen and Mendelsohn (2003), the new model suggests approximately 50% more carbon will be stored in the low damage scenario and approximately 13% more carbon in the high damage scenario by the end of the century. Several modeling changes explain this increase in carbon sequestration projections. First, the new model captures the inaccessible boreal forests in Canada and Russia more carefully. The model now recognizes that the inaccessible forests in these regions are initially old growth forests when first harvested but they will be slow to regrow to that status. This increases the potential to use boreal forests to sequester additional carbon. Second, carbon intensity in Asia (including China and Southeast Asia), and Africa increases in this model relative to the earlier model. These forests will consequently be able to store more carbon at the same cost. A final change is that the carbon sequestration functions used in this study for most regions have been updated. While carbon storage levels for mature forests are consistent with the earlier study, the conversion parameters used in this study suggest more carbon in early periods of forest growth than in the earlier study.

Under the alternative scenarios, the carbon sequestration program stores between 46.3 and 62.6 Pg C globally for the low damage case, and 99.4 - 139.5 Pg C for the high damage case (Tables 5 and 6). The results are most sensitive to the alternative land supply elasticity assumptions. Higher land supply elasticity leads to approximately 14 - 21% more carbon than estimated under the baseline scenario, and lower land supply elasticity leads to 14 - 15% less carbon storage globally. Higher (lower) land supply elasticity generally reduces (increases) the slope of the land supply function, and reduces (increases) the costs of adding land to increase carbon sequestration.

The other sensitivity analyses have a relatively small effect on carbon sequestration globally. A larger increase in demand for forest products over time reduces potential sequestration 1% or 6% respectively in the high and low price scenarios. Lower harvesting costs and lower plantation establishment costs both increase potential carbon sequestration. Both these changes tend to increase the value of land in forests, and therefore increase the value of establishing forests for carbon and for timber. Slower yield growth reduces potential sequestration in the low carbon price scenario, but increases it slightly in the high carbon price scenario. The effect is relatively small, only around 1%. Globally, sequestration programs are most sensitive to factors that influence the supply of land to forests.

Carbon sequestration in some regions of the world appears to be more or less sensitive to the alternative scenarios than the global results indicate. For instance, under the high demand scenario, the U.S. potentially could sequester less carbon under the low price scenario, whereas Canada is projected to sequester more carbon in forests. Higher demand has little effect on the carbon sequestration program in the US because many of the low cost opportunities for adding carbon are captured in the baseline case. Further, the higher timber prices cause land to shift into intensive plantations that only reduce carbon. In Canada, the sequestration program can keep some of the inaccessible forests from being used to satisfy the high demand for timber. This turns out to be a relatively inexpensive sequestration option and so the Canadian program sequesters more carbon.

4. Discussion and Conclusion

This paper presents a sensitivity analysis of carbon sequestration in global forests using a global forestry model (Sohngen and Mendelsohn 2003). The model is updated with new inventory data and new information on potential carbon sequestration in global forests. Several analyses are presented with the new model. First, the model is used to see how much carbon would be stored globally without any carbon sequestration programs. The paper calculates an expected baseline estimate and then several alternative estimates using different assumptions about timber demand, land supply, and technological change in the forestry sector. Second, the paper examines two efficient global sequestration programs. The two programs are based on low and high paths for carbon prices that have been calculated from optimal mitigation models. A sensitivity analysis of these carbon sequestration programs is examined using the same alternative model assumptions discussed above.

The forestry model predicts that the economy and natural ecosystems without any carbon sequestration programs would convert 400 million ha of forestland to other land uses (primarily agriculture) resulting in the global loss of 76 Pg C of carbon over the next century. The rate that forestland is lost and the rate that carbon is lost falls gradually over the century. Higher demand for forest products increases the cumulative century long loss another 8 Pg C as more inaccessible forests are harvested. Higher agricultural demand for land that shifts another 72 million ha out of forestland over the coming century leads to a loss of approximately 7.1 Pg C. Lower harvest costs would result in the loss of another 11 Pg C. In contrast, other technical changes in the forestry sector, that would reduce plantation regeneration costs or increase plantation yields, have a very small net effect on carbon sequestration.

The paper also explores the implementation of two global forest sequestration programs. The two programs rely on dynamic price paths that have been generated by optimal mitigation models (Nordhaus and Boyer 2000). The low price path (from $7/ton to $61/ton) reflects a low estimate of climate damage and the high price path (from $22/ton to $188/ton) reflects a high estimate of the damages from climate change. By tying sequestration to these price paths, the analysis equates the marginal benefits and the marginal costs of sequestration over time. The resulting sequestration program is a dynamic and efficient policy. With the low set of price, the forestry model predicts the carbon sequestration program could sequester 55 Pg C and with the high set of prices, it will sequester 116 Pg C. These new estimates are slightly higher than projections in Sohngen and Mendelsohn (2003) because of new inventory data in regions like Russia, China, and the U.S., as well as updated information on carbon intensity in regions like Southeast Asia and Africa.

The carbon sequestration program is sensitive to alternative assumptions about land supply. Increasing the elasticity of land supply by 50% leads to approximately 20% more carbon sequestered globally, whereas reducing the elasticity by 50% leads to approximately 19% less carbon globally. The other scenarios have a relatively small effect on global carbon storage, with the exception of harvesting costs. With lower harvesting costs, a carbon sequestration program can save inaccessible forests at a relatively low cost thus increasing the amount of carbon stored at a given price per ton.

The research indicates that deforestation will add about 76 Pg C of carbon back into the atmosphere by the end of the next century. Efficient carbon sequestration programs that pay forest owners to store carbon can pull a substantial amount of that carbon back into the forest. If the damages from climate change turn out to be low, a carbon sequestration program could sequester between 46 - 63 Pg C and if the damages are high, the program could sequester between 99 - 140 Pg C by 2100.

These large estimates suggest that policy makers cannot afford to ignore program to sequester carbon in forests as an effective tool to control greenhouse gases. However, creating an efficient sequestration program is admittedly a big challenge. The research demonstrates that sequestration programs will affect timber in every region of the world. To enhance efficiency, programs consequently must equate the marginal cost of sequestration across regions. It is also critical to design dynamic policies that increase the incentives to sequester over time in concert with the price of carbon (the benefit of sequestration). Programs that are too aggressive too soon will be unnecessarily expensive. Only one-third of the carbon that should be stored this century should be set-aside by 2050 (Sohngen and Mendelsohn 2003). In this exercise, we relied on paying forest owners worldwide a price for each unit of carbon they stored. That price increased over time along the "known" price path of carbon. This is one way to design an efficient sequestration program, but there may well be other alternatives that have equivalent efficient properties.

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Table 1: Baseline scenario: Carbon Storage in Forests and Forest Areas.

	Carbon			Total Forest Area			Inaccessible Forest Area			Subtropical Plt. Area		
	2015	2055	2105	2015	2055	2105	2015	2055	2105	2015	2055	2105
	(Pg C Stored by Year)			(Million Hectares)								
U.S.	49.7	49.1	48.5	205.7	206.3	205.9	52.9	36.9	34.5	13.6	14.3	14.5
Canada	131.2	131.3	131.2	420.4	420.5	421.5	285.5	259.6	257.9	0.0	0.0	0.0
S. America	206.4	193.9	189.4	833.6	732.5	715.7	0.0	0.0	0.0	15.9	24.5	27.5
C. America	11.2	9.2	10.0	49.6	38.0	37.1	0.0	0.0	0.0	3.0	3.9	3.9
Europe	28.5	28.5	28.5	189.0	192.9	196.0	2.6	0.6	0.1	4.5	7.7	8.3
Russia	252.8	249.5	249.7	839.7	840.0	841.9	692.3	647.9	643.6	0.0	0.0	0.0
China	27.8	27.8	27.7	160.1	166.8	170.6	18.1	2.5	1.3	13.7	20.5	23.1
India	10.0	9.4	9.0	48.7	45.4	45.8	0.0	0.0	0.0	4.7	5.7	5.9
Oceania	25.5	25.8	25.6	195.9	180.0	164.8	0.0	0.0	0.0	7.5	11.6	13.2
SE Asia	51.4	39.0	35.1	184.3	127.6	117.3	0.0	0.0	0.0	12.4	15.0	16.0
Central Asia	6.3	6.2	6.1	38.4	39.8	39.9	0.0	0.0	0.0	2.5	3.8	3.8
Japan	4.1	4.3	4.7	23.6	24.2	24.5	0.0	0.0	0.0	10.4	10.6	10.7
Africa	75.8	62.5	57.6	305.0	202.7	211.1	0.0	0.0	0.0	5.4	8.2	9.3
Total	880.6	836.4	823.1	3493.9	3216.7	3192.0	1051.4	947.4	937.5	93.4	125.7	136.0

Table 2: Alternative Baseline Scenarios.

Scenario	Assumptions
Baseline	Demand growth = 0.5% per year, declining 5% per year Land supply elasticity = 0.25 Subtropical plantation Yield = 0.25%/yr Harvesting costs = Constant Plantation establishment costs = Constant
High Demand Growth	Demand growth = 2.0% per year, declining 5% per year
High land supply elasticity	Land supply elasticity = 0.38
Low land supply elasticity	Land supply elasticity = 0.13
Low Yield Growth	Subtropical plantation Yield = 0.05%/yr
Lowering harvesting costs	Harvesting costs = - 0.5%/yr
Lowering plantation establishment costs	Plantation establishment costs = -0.5%/yr

Table 3: Projected changes in total carbon and total forest area for alternative scenarios relative to the baseline in 2105.

	Carbon						Forest Area					
	High Demand	High Elasticity	Low Elasticity	Low Harvest Cost	Low Plt. . Cost	Low Yield. Chg.	High Demand	High Elasticity	Low Elasticity	Low Harvest Cost	Low Plt. Cost	Low Yield Chg.
	Pg C Stored Above Baseline by 2105						Million Hectares Above Baseline in 2105					
U.S.	1.2	0.3	-0.2	-0.4	-0.1	-0.3	10.3	3.4	-3.1	1.0	-0.7	-0.1
Canada	-0.4	0.2	-0.3	-0.8	0.0	-0.3	6.4	2.4	-1.9	0.9	-0.4	0.2
S. America	-3.0	4.0	-3.8	-2.5	0.3	-0.7	4.1	35.0	-34.0	1.1	3.7	-2.4
C. America	-0.1	0.1	-0.2	-0.1	0.0	0.0	-0.1	1.8	-1.7	-0.2	0.0	0.0
Europe	0.5	0.1	-0.1	0.0	-0.1	-0.4	18.6	-0.2	-0.3	2.2	-1.9	-1.6
Russia	-3.1	0.1	-0.1	-2.4	-0.1	-0.1	-1.0	-0.3	-0.4	1.4	-0.8	1.4
China	1.1	-0.2	0.4	0.3	0.2	0.4	9.8	1.2	-1.0	0.3	4.6	-3.4
India	0.4	0.1	-0.1	0.1	0.1	0.1	5.5	2.5	-2.0	0.4	2.4	0.6
Oceania	0.0	0.1	-0.2	-0.4	0.2	-0.2	0.8	5.1	-7.2	-4.8	2.8	-1.7
SE Asia	-2.0	1.1	-1.4	-1.5	0.2	-0.3	3.4	5.4	-9.1	-1.7	2.3	-0.8
Cent. Asia	-0.1	0.0	0.0	-0.1	0.0	0.0	1.4	-0.2	0.3	0.2	1.2	0.3
Japan	0.7	0.0	0.0	0.0	0.0	-0.4	3.1	0.1	-0.2	0.2	0.0	-0.7
Africa	-3.1	0.7	-1.0	-2.8	0.1	-0.4	-0.9	9.2	-12.0	-1.6	1.2	-1.3
Total	-7.8	6.6	-7.1	-10.6	0.9	-2.7	61.3	65.5	-72.6	-0.7	14.4	-9.5

Table 4: Projected changes in carbon and forest areas for low and high carbon price scenarios in 2105 for the baseline carbon sequestration program

	Carbon		Forest Area		Inac. For. Area		Subt. Plant.	
	Low Price	High Price	Low Price	High Price	Low Price	High Price	Low Price	High Price
	Additional Pg C Stored		Additional Hectares (Mill.)		Additional Hectares (Mill.)		Additional Hectares (Mill.)	
U.S.	2.17	6.27	12.59	57.24	3.36	7.05	0.84	2.55
Canada	1.60	3.95	12.68	37.47	8.66	14.73	0.00	0.00
S. America	8.9	20.4	54.6	132.2	0.0	0.0	1.6	4.7
C. America	1.19	2.39	4.40	11.56	0.00	0.00	0.00	0.00
Europe	2.47	7.07	7.88	30.46	0.31	0.66	0.00	0.00
Russia	3.88	7.09	7.99	21.68	35.45	65.12	0.00	0.00
China	4.19	7.56	19.35	39.65	6.19	13.00	4.81	6.04
India	1.00	3.05	7.86	16.48	0.00	0.00	0.42	0.99
Oceania	0.33	0.96	8.51	22.38	0.00	0.00	0.17	0.91
SE Asia	16.8	36.6	33.1	71.6	0.0	0.0	1.1	2.2
Cent. Asia	0.67	1.32	3.07	6.99	0.00	0.00	0.88	1.71
Japan	-0.02	0.37	2.87	11.53	0.00	0.00	0.15	0.45
Africa	11.52	18.61	28.82	92.48	0.00	0.00	1.68	2.66
Total	54.71	115.61	203.65	551.65	53.97	100.56	11.66	22.20

Table 5: Low Carbon Price Scenario: Comparison of carbon program gains by 2105 for alternative scenarios, and percentage change relative to baseline carbon storage program.

	Baseline	High Demand		High Elasticity		Low Elasticity		Low Harvest Cost		Low Plt. Est. Cost		Low Tech. Chg.	
	Pg C	Pg C	%	Pg C	%	Pg C	%	Pg C	%	Pg C	%	Pg C	%
U.S.	2.2	1.3	-40%	2.3	7%	1.4	-35%	2.1	-5%	2.0	-8%	2.1	-5%
Canada	1.6	1.9	18%	1.9	22%	1.4	-15%	2.5	58%	1.4	-9%	1.6	0%
S. America	8.9	8.9	0%	11.2	26%	6.5	-27%	10.5	18%	8.8	-2%	8.9	-1%
C. America	1.2	0.7	-39%	1.4	15%	1.0	-17%	1.2	2%	1.2	2%	1.2	-1%
Europe	2.5	2.4	-1%	2.8	12%	2.2	-10%	2.6	6%	1.9	-24%	1.8	-27%
Russia	3.9	4.7	22%	4.1	5%	4.0	2%	5.7	46%	3.9	2%	4.1	6%
China	4.2	2.0	-52%	5.2	23%	3.5	-17%	3.7	-12%	4.7	12%	3.5	-17%
India	1.0	0.5	-51%	1.5	54%	0.7	-33%	0.8	-16%	1.0	2%	0.9	-12%
Oceania	0.3	0.5	38%	0.4	30%	0.3	-16%	0.5	46%	0.4	7%	0.3	-2%
SE Asia	16.8	15.0	-11%	18.0	7%	15.0	-10%	18.1	8%	17.3	3%	17.3	3%
Cent. Asia	0.7	0.4	-44%	0.7	8%	0.6	-9%	0.7	-3%	0.7	-3%	0.7	-3%
Japan	0.0	0.0	na	0.1	na	-0.1	na	0.1	na	0.0	na	0.1	na
Africa	11.5	12.8	11%	12.5	9%	9.9	-14%	14.2	23%	11.4	-1%	11.7	2%
Total	54.7	51.3	-6%	62.1	14%	46.3	-15%	62.6	14%	54.6	0%	54.1	-1%

Table 6: High Carbon Price Scenario: Comparison of carbon program gains by 2105 for alternative scenarios and percentage change relative to baseline carbon storage program.

	Baseline	High Demand		High Elasticity		Low Elasticity		Low Harvest Cost		Low Plt. Est. Cost		Low Tech. Chg.	
	Pg C	Pg C	%	Pg C	%	Pg C	%	Pg C	%	Pg C	%	Pg C	%
U.S.	6.3	6.4	2%	8.3	32%	5.0	-20%	7.5	19%	6.2	-1%	6.6	5%
Canada	3.9	4.9	24%	5.3	35%	3.3	-17%	5.5	39%	4.1	3%	3.4	-15%
S. America	20.4	23.8	17%	27.3	34%	15.6	-24%	24.1	18%	20.1	-1%	21.6	6%
C. America	2.4	2.5	5%	3.0	25%	1.9	-22%	2.6	8%	2.4	0%	2.5	3%
Europe	7.1	7.2	1%	8.4	20%	6.1	-13%	7.5	6%	7.2	2%	7.4	5%
Russia	7.1	9.4	32%	7.7	9%	6.7	-6%	9.7	37%	7.2	1%	7.2	1%
China	7.6	7.8	4%	11.2	49%	6.1	-20%	8.4	12%	7.4	-3%	6.9	-8%
India	3.0	2.3	-23%	4.9	60%	3.6	18%	3.9	28%	2.7	-12%	3.1	3%
Oceania	1.0	1.5	57%	1.5	56%	0.9	-6%	1.5	56%	1.0	3%	1.1	15%
SE Asia	36.6	27.8	-24%	38.2	4%	32.7	-10%	39.1	7%	37.1	2%	35.9	-2%
Cent. Asia	1.3	1.4	4%	1.5	17%	1.2	-10%	1.5	13%	1.3	-4%	1.4	7%
Japan	0.4	0.3	-24%	1.1	200%	0.9	147%	1.3	261%	0.4	14%	0.8	105%
Africa	18.6	21.6	16%	21.0	13%	15.5	-17%	21.7	17%	18.5	-1%	19.2	3%
Total	115.6	116.9	1%	139.5	21%	99.4	-14%	134.3	16%	115.5	0%	117.1	1%