OPTIMAL FOREST CARBON SEQUESTRATION

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ABSTRACT

This study examines the optimal timing and incentives between carbon sequestration in forests and the optimal control of greenhouse gases. As carbon accumulates in the atmosphere, the carbon rental price should rise, increasing the incentive to sequester carbon over time. Although carbon sequestration is costly, a carbon rental incentive would encourage landowners to sequester substantial amounts of carbon in forests primarily by increasing forestland and lengthening rotations. Given optimal incentives, forest sequestration would account for about one-third of total carbon abatement. Tropical forests should store over two thirds of this added carbon.

INTRODUCTION

Over the last decade, there have been numerous articles describing the optimal strategy for controlling greenhouse gases (see Falk and Mendelsohn 1993; Nordhaus, 1994; Nordhaus and Boyer, 2000). As a stock or cumulative pollutant, the least cost strategy to control greenhouse gases is to allow the price or marginal cost of control to rise as the present value of damages increases. This literature has balanced the cost of reducing carbon emissions from the energy sector against the future damages from climate change. This paper extends this literature by integrating the costs of sequestering carbon in forests into an optimal control model for greenhouse gases. The paper describes the timing and incentives that greenhouse gases imply should be used to sequester carbon in forests. The results are "optimal" in the sense that sequestration is integrated into the overall optimal control problem of greenhouse gases. Of course, the paper is not "optimal" in a definitive sense since not all factors of social concern are included in the model as discussed in the conclusion.

Numerous experts have suggested that substantial amounts of carbon can be sequestered in the world's forests (IPCC, 1996; IPCC, 2000; IPCC, 2001). Forests currently store over 800 billion metric tons in trees and soil (Brown, 1998). Landowners could increase this stock by increasing the amount of land in forests (Stavins, 1999; Plantinga et al., 1999; Adams et al., 1999) or by increasing the carbon per hectare with more intensive management or longer rotations (Hoehn and Solberg, 1994; Van Kooten et al., 1995; and Murray, 2000). What is unknown is how much this would cost and how the program should be designed over time. Current estimates of the cost of forest carbon sequestration range from $1 to $150 per ton (Sedjo et al., 1995; IPCC, 2001).

Early field studies tended to assume that land prices would remain constant. More systematic analyses have revealed that land prices would notably rise if substantial amounts of additional land were devoted to forest sequestration (Stavins, 1999 and Plantinga et al., 1999). None of the studies have empirically derived the relative importance of increasing forestland, changing rotation length, or changing management intensity. Almost all of the studies done to date are regional and do not consider another important system-wide effect, changes in timber prices. Finally, the forest sequestration studies assume static incentives such as constant carbon prices (Plantinga et al., 1999; Stavins, 1999).

This paper addresses all of these shortcomings by integrating global carbon sequestration into an optimal control model of greenhouse gases. The model assumes that global institutions exist to encourage optimal behavior. The existing optimal control models for greenhouse gas mitigation have focused solely on reducing carbon emissions from the energy sector. The amended model in this paper adds carbon sequestration as another mitigation alternative. Adding sequestration lowers the overall cost of controlling carbon and results in more mitigation. The rising price of carbon from increasing atmospheric accumulations over time, in turn, suggests that the incentives to sequester carbon in forests must be dynamic, rising as the price of carbon rises. The increasing incentive to sequester carbon is communicated to landowners through a carbon rental fee for every additional ton of carbon they store each year. This rental fee increases the value of forestland causing conversion from other uses, it increases rotation lengths, and it increases management intensity so that forestlands are more fully stocked.

In Section III, the paper presents an empirical example using a well-known greenhouse gas model, DICE (Nordhaus and Boyer, 2000), and a global timber model (Sohngen et al. 1999). DICE presents two scenarios of the future projecting greenhouse gas emissions and optimal energy mitigation strategies for an expected case and a higher damage uncertain case. We have modified DICE to include a sequestration option where the costs and timing of sequestration have been elicited from the global timber model. We have also modified the global timber model to include a path of carbon rental rates from the DICE model. By carefully solving back and forth between these two models, we have calculated an endogenous set of rental rates that simultaneously solve the optimal control greenhouse gas model and the forest model with sequestration.

AN OPTIMAL CONTROL MODEL OF CARBON MITIGATION AND SEQUESTRATION

Following Falk and Mendelsohn (1993), we start with an abstract model of carbon mitigation. The objective is to minimize the present value of the costs of greenhouse gases where costs are the sum of abatement costs and climate damages. Carbon emissions accumulate in the atmosphere resulting in higher carbon dioxide concentrations. Without further emissions, the stock decays at a constant rate, λ. These unnaturally high CO_2 levels gradually cause climate to change, which imposes damages on society. The annual value of the damages associated with a stock of carbon of $X(t)$ is equal to D(X(t)). The annual abatement costs of reducing carbon emissions from the energy sector is equal to CE(A(t)). The model can be written formally:

(1) $\text{Min} \int [D(X(t),t) + CE(A(t))]\, e^{-rt}\, dt$

s.t. $X(t) = \int [f(A(n)) - \lambda X(n)]\, dn$

Sequestration in forests adds another carbon mitigation alternative. We examine three forestry actions: adding forestland, L(t), lengthening rotations, a(t), and increasing management intensity, m(t). Adding forestland, L(t), increases carbon sequestration by the difference between the carbon stock in forests versus the original land use. Note that one can increase forestland by either converting land to forests, as may be expected in the temperate zone, or reducing deforestation, as is more likely in the tropics. Lengthening rotations increases the size of trees per hectare directly increasing carbon storage. Increasing management intensity makes certain that forests are fully stocked. The cost function for sequestering carbon in forests is CF(L(t),a(t), m(t)). The amount of carbon sequestered depends upon L(t), a(t), and m(t) and t itself. Adding forest sequestration changes the above model to:

(2) $\text{Min} \int [D(X(t),t) + CE(A(t)) + CF(L_t,a_t,m_t)]\, e^{-rt}\, dt$

s.t. $X(t) = \int [f(A(n) - \lambda X(n)]\, dn – S(L_t,a_t,m_t,t)$

The hamiltonian for this problem can be expressed:

(3) $J = CE(A(t) + D(X(t),t) + CF(L_t,a_t,m_t) + \mu(t)\,[-A(t) - \lambda X(t) - S(L_t,a_t,m_t,t)]$

The first order conditions lead to the following solutions:

4) $\mu(t) = CE_A = D_x(X)/(\lambda+r)$

5) $CE_A = CF_a = CF_m = CF_L$

Equation (4) shows that the marginal costs of an additional ton of abatement should be equated to the shadow value of an additional ton of carbon removed from the atmospheric stock, S(t), and the present value of the stream of damages that ton causes. Equation (5) shows that the marginal cost of energy abatement should equal the marginal cost of adding forestland, increasing rotation lengths, or intensifying management. As the amount of carbon increases in the atmosphere, the marginal damages per ton rise calling for an increase over time of energy abatement and carbon sequestration. Carbon sequestration, just like energy abatement, should be dynamic, reflecting the increasing incentive to remove carbon over time as it accumulates in the atmosphere.

The carbon model assumes that permanently expanding the stock of forest carbon by one ton is equivalent to reducing carbon emissions by one ton. The marginal value of adding a ton of sequestration permanently to the earth's forests is the shadow value of carbon, $\mu(t)$. Much of the world's forests, however, are managed with harvests today leading to products that are slowly released back into the atmosphere. The land is then used to grow new trees. Managed forests do not sequester carbon permanently. In order to integrate the way forests are managed with the optimal control carbon model, we need a more facile tool to handle time. Rather than measuring the price of carbon, $\mu(t)$, this paper will rely on the rental rate of carbon, R(t):

(6) $R(t) = \mu(t) * [r - \varphi(t)].$

The rental rate of carbon is the value of storing a ton of carbon for one year. It is equal to the price of carbon, $\mu(t)$, times the difference between the interest rate and the rate of increase of the price of carbon, $\varphi(t)$ where $\varphi(t) = [d\mu(t)/dt]/\mu(t)$.

The underlying forest model assumes that landowners maximize the net present value of revenue from their forests (Sohngen and Mendelsohn 1998). This is a slight variation on the Faustmann model that allows timber prices to vary over time:

7) $$\max_{n,m} W = \Sigma (P(t) * Q_i(n,m)) e^{-rn} - C_i(m)$$

The above formula leads to the following first order condition that is again a slight variation from Faustmann:

8) $$\dot{P}\, Q(n) + P\, \dot{Q}(n) = r\, P\, Q(n) + r\, W$$

By allowing prices to change over time, the forest model becomes a forward-looking dynamic model.

The carbon sequestration problem adds a new wrinkle to the model. Landowners are now paid a rental rate each year times the amount of carbon stored in the forest. The present value of net revenue becomes:

$$9)\ \max_{n,m} W = \Sigma\, (P(t) * Q_i(n,m))\, e^{-rn} - C_i(m) + R(t)*s(t,m)$$

Adding the rental payment increases the value of land in forestry. Landowners will consequently shift land into forestry in response to this new incentive. The rental payment will also change the first order conditions. Landowners will now choose longer rotation lengths because of the rental payment:

$$10)\qquad \dot{P}\, Q(n) + P\, \dot{Q}(n) + Rs(n) = r\, P\, Q(n) + r\, W$$

The rental payment is larger for older trees so the marginal benefit of waiting increases. The rental payment also provides an additional incentive to increase intensity, m:

$$11)\qquad C_m = P\, Q_m\, e^{-rn} + R(t)\, s_m$$

There should be increased management intensity with the carbon rental payments.

AN EMPIRICAL MODEL

We now predict how much carbon sequestration in forests should occur given calibrated models of global forestry and greenhouse gases. The global forestry model comes from an optimal control model of global timber (Sohngen et al., 1999). The greenhouse gas model is an integrated assessment model of carbon and the world economy, DICE (Nordhaus and Boyer, 2000). We examine two scenarios in DICE.

First, we use the expected value of all parameters and examine an "expected case". Second, from a Monte Carlo study that Nordhaus and Boyer performed, we rely on a much higher damage function that reflects the "uncertain case". By examining these two scenarios, one can see how damage assumptions in the integrated assessment model affect the desired levels of sequestration over time.

Both models are large and complex and we do not attempt to build a new integrated model. Instead, we solve the two models simultaneously through an iterative process. We begin with the carbon prices and rental rates that the DICE model predicts without sequestration. We enter the rental rate path into the forestry model and calculate costs and quantities sequestered. From this data, we calculate a sequestration cost function and add it to DICE and resolve DICE for a new set of rental rates. These new rental rates are then entered in the forestry model and the process is repeated. After several iterations, we obtain a set of rental rates over time, a sequestration cost function, and sequestration levels that are consistent in the two models. The prices of carbon (the carbon rental rates) are endogenously determined through these iterations.

The sequestration cost function estimated through this process is:

(12) $$S(t) = -3.18*\mu(t)^{0.870}\ t^{0.706}$$

S(t) is the additional stock of carbon stored by time t in forests given the carbon price, $\mu(t)$. Note that time plays a direct role itself. It takes a long time to grow a tree. The more time available for sequestration, the more carbon can be stored at each price level.

DICE Model Description

The DICE model projects carbon prices in the absence of forest sequestration (Nordhaus and Boyer, 2000). Given the assumptions of the DICE model, world population, world GDP, energy consumption, and uncontrolled carbon emissions are projected to follow a modest path of increase. World population rises to over 10 billion by 2100 and world GDP climbs to $81 trillion. GDP per capita is projected to increase slowly. CO2/GDP falls over time because of falling energy use as a fraction of GDP and changes in energy composition. Energy use is falling partially because of changes in the makeup of GDP away from manufacturing and towards services and partly from technical change. The DICE model predicts uncontrolled carbon emissions as shown in Table 1.

Depending upon the damage function, DICE endogenously determines optimal energy abatement levels for the world. These in turn reduce the levels of carbon in the atmosphere, changing marginal damages over time. Solving this model yields the set of carbon prices shown in Table 1. The expected case leads to carbon prices starting at about $7/ton. The uncertain case leads to higher initial carbon prices of about $23/ton because it predicts higher damages from warming. Both sets of prices increase over time as carbon accumulates in the atmosphere. These dynamic prices lead to dynamic energy abatement paths over time. The higher the price, the more carbon is abated.

Forest-Carbon Model Description

The dynamic, global forestry model of Sohngen et al. (1999) is expanded to capture carbon. Sequestration is added to the model by adding a rental price from DICE to the forestry model. Owners are paid for any additional carbon that they sequester. The baseline is calculated as the carbon that the forest would have stored if rental rates were zero. The timber model has also been expanded to include all of the world's forests for this paper. The forest model now includes 50 different timber and management types in 9 continents. These include all major agricultural and forestry regions where carbon sequestration might occur.

The forest-carbon model maximizes the present value of the benefits minus costs of timber harvesting and carbon sequestration as stated in (9). We assume that new forests can only grow in places suitable for forests according to ecological models. We also assume that most of this additional land will come from agricultural cropland and pasture. Carbon storage parameters for this model are taken from Sohngen and Sedjo (2000). Both above and belowground biomass is incorporated, as well as soil carbon. When land is converted to forests, we credit the sequestration program only for the difference in carbon between the forest and agricultural soil.

The sequestration programs potentially affect very large amounts of land, so there is every reason to expect that the price of land will be affected (Plantinga et al, 1999; Stavins, 1999). We estimate different supply elasticities for land in different regions. Several studies suggest that the elasticity of land supply in forestry is relatively inelastic for North America (Parks and Hardie, 1997; Plantinga et al., 1999; and Stavins, 1999). Using predictions from these studies, we assume that the elasticity of forestland supply ranges from 0.01 to 0.26 in North America. Elasticity estimates for Western Europe are assumed to be between 0.6 and 0.8. Estimates for the other regions around the globe are more uncertain. We assume the land elasticity is 0.01 for the Former Soviet Union, 0.14 for China, 1.0 for India and Oceania, 0.14 to 0.35 for Asia-Pacific, 0.26 for South America, and between 0.26 and 0.35 for Africa.

The baseline for this paper is the amount of carbon stored in the forest when carbon rental rates are zero. This is a dynamic baseline because the model predicts that forests will change over time in the absence of a sequestration program. The model predicts current global carbon storage in the biosphere is 811 billion metric tons, which is consistent with recent estimates (Brown, 1998). Over the next century, we predict that carbon in forests declines to 766 billion metric tons from deforestation. This amounts to carbon emissions averaging 450 million metric tons per year from deforestation. Nearly all of this loss is predicted to occur in the tropics, with the temperate zone remaining stable.

We also model the proportion of carbon stored in timber products. The amount of carbon decays over time depending on the product (Plantinga et al., 1999 and Stavins, 1999). The baseline predicts that over the next 100 years, timber products will effectively store an additional 16 billion metric tons of carbon, or approximately 157 million metric tons per year.

RESULTS

We examine two scenarios in this paper: the expected and uncertain cases. As displayed in Table 2, the two sequestration programs for these two scenarios lead to substantial amounts of land being converted to forests. In the expected case, the sequestration program adds 416 million hectares of forest by 2100. That is a substantial change given that there is an estimated 3.5 billion hectares of forest today. The uncertain case, with its higher carbon rental rates, adds 963 million hectares of forest by 2100. Table 2 also reveals where the sequestration should occur. To be efficient, the program must be global. The mid-high latitudes, which include the temperate and boreal forests, should account for approximately 43% of the additional forestland with the rest lying in the low latitudes (tropics and semi-tropics).

Table 3 predicts how the sequestration program will affect the timber market. Initially, the sequestration program will reduce harvests as forest owners withhold timber from production in order to gain higher carbon rental payments. This is especially evident in the uncertain case. The largest impact occurs in the low latitudes where forest owners slow deforestation. Eventually, however, forest owners start harvesting trees of much higher age. Because most trees grow more rapidly as they reach economic maturity, extending rotations increases average growth and leads to an expansion of supply. The model predicts that timber supply will expand 333 million m^3 in the expected case and 785 million m^3 in the uncertain case (relative to a baseline of about 2.3 billion) by 2100. Approximately 80% of the increase in supply occurs in the mid-high latitudes. This large increase in timber supply means that the sequestration programs will eventually have global impacts on timber prices and will affect forestlands whether or not they are in the program.

Table 4 reveals exactly where and when the forest sequestration will occur. The model predicts that the program will start slowly and grow to almost 40 gigatons in the expected case and over 100 gigatons in the uncertain case. The assumed damage function for global warming consequently makes a huge difference to the magnitude of the desired sequestration program. Despite the huge commitment of land to sequestration in the mid-high latitudes, most of the carbon sequestered occurs on low-latitude forests. By limiting deforestation, low latitude forests can account for about 70% of the additional carbon sequestered in forests.

The uncertain scenario resembles the sequestration scenario raised by the IPCC for 2050 in their third assessment report (IPCC 2001). The IPCC predicts that they can sequester approximately 100 gigatons of carbon adding about 1 million hectares. The IPCC also expects to rely heavily on low latitude forests. However, it is important to note that achieving the target in 2050, as stated in the IPCC report, rather than 2100, as suggested here, would significantly increase the cost. Just using the parameters of the sequestration cost function (12), reducing the time to achieve the target in half (50/100 years), would increase the costs about 70%.

In order to put the results in perspective, we prepare one final table from the two models that compares cumulative outcomes. Table 5 begins with the cumulative emissions that DICE projects from 2000 to 2100, a total of 1008 gigatons. Columns 2 and 3 then describe the abatement that the model predicts would occur in the expected case with sequestration. The energy abatement estimates fall slightly compared to the case without sequestration (81.3) to 80.5 gigatons by the end of the century. Sequestration, in this case, comes to almost 38.6 gigatons. In the uncertain case, the last two columns, energy abatement amounts to 214.8 gigatons (instead of 220.3 gigatons without sequestration) and sequestration comes to 102.1 gigatons. In both the expected and uncertain cases, sequestration is almost one third of total abatement. It is clear that sequestration is important and should be included if possible. It is also interesting that sequestration remains equal to about one-third of abatement throughout the century. Optimal sequestration does not delay energy abatement but rather operates simultaneously with it. At least given the two damage functions explored in the analysis, one can also say that sequestration is virtually additive to energy abatement. That is, including sequestration has only the slightest effect on carbon prices and so does not reduce energy abatement a great deal.

The results also provide some perspective on how expensive sequestration is. When the price of carbon is relatively low, the sequestration program is quite modest. The cost of the program will rise rapidly the larger the program becomes. Carbon sequestration is clearly more expensive than some of the field studies suggest. The cost of the program is also quite sensitive to timing. The more time the sequestration program has to achieve its targets, the lower is the cost.

CONCLUSION

This paper develops an optimal greenhouse gas-carbon sequestration model by integrating an optimal control model for greenhouse gases (Nordhaus and Boyer, 2000) with an optimal control model of forest management (Sohngen et al., 1999). The greenhouse gas model balances the cost of carbon mitigation and carbon sequestration against the damages from having more greenhouse gases in the atmosphere. The global timber model optimizes welfare from timber consumption and carbon sequestration. The theoretical model suggests that the carbon sequestration program should be coordinated with the greenhouse gas mitigation program. The rental price of carbon should rise over time in response to the rising stock of greenhouse gases. Efforts to increase forestland area, rotation lengths, and management intensity should all be dynamic and increase with time.

Empirical estimates are generated by integrating DICE (Nordhaus and Boyer 2000) with an optimal control model for global timber markets (Sohngen et al., 1999). Two scenarios for the optimal price path for carbon sequestration are explored: an expected scenario and an uncertain scenario. Given each scenario, optimal energy abatement and sequestration programs are calculated. Both the greenhouse gas model and sequestration model explore global opportunities and find the most cost effective choices for the entire world.

The results suggest that 39 and 102 billion metric tons of carbon would be sequestered by 2100 in global forests for the expected and uncertain scenarios respectively. Most of the sequestration is predicted to occur near the end of the century when the price of carbon is high. The model predicts that about 400 million hectares of forestland would be added in the expected case and almost 1 billion hectares would be added in the uncertain case by 2100. Tropical forests will sequester approximately 70% of the carbon, a result consistent with other studies (IPCC, 2000, 2001).

The sequestration program at first reduces timber supply as landowners lengthen rotations. However, the longer rotations eventually increase timber supply especially in the mid-high latitudes. This leads to a dramatic increase in timber supply by 2100 of 333 million m^3 (14%) in the expected case and 785 million m^3 (34%) in the uncertain case. It is expected that the supply increase will in turn reduce global timber prices in the long run.

The two most important factors in carbon sequestration are land use change and lengthening rotations. Reduced deforestation and afforestation are most important in tropical regions, while afforestation is most important in temperate regions. The model predicts that lengthening rotations would effectively create conservation forests in the tropics that are not harvested. In the temperate zone, rotations would also be lengthened but the forests would continue to be harvested. Management intensity plays only a small role in supplying carbon because it is less effective at carbon storage and costly.

The study finds that carbon sequestration is more expensive than previously thought. Forests must permanently store carbon in order to provide the same benefits that energy abatement provides. Further, large sequestration efforts will have systematic effects on the price of land and the price of timber. Large programs are consequently expensive.

This study suggests that sequestration should be an important component of controlling greenhouse gases. As with abatement, the magnitude of the program should be tied to how serious warming is expected to be. If damages turn out to be close to expected estimates, then a modest sequestration program is desirable. However, if climate change is more harmful than expected, a more aggressive sequestration program should be implemented. In both cases, we estimate that sequestration should be equal to about one third of total abatement (or about one-half of energy abatement).

Although the paper makes a number of contributions to the sequestration literature, several issues remain that need to be addressed. The sequestration model does not treat the effect of climate change on forests. Although Sohngen et al. (2002) explore how climate change affects global timber markets, the effect of climate change on sequestration has not been explored. This study also does not explore the costs of administering a sequestration program. Because land use has traditionally been a local concern, there could be substantial costs and political problems associated with creating a global land use program. Efforts to adopt a sequestration program on a piecemeal basis may be subject to substantial leakage. The carbon saved on land in the program could be offset by carbon lost on lands not in the program. Given the system wide effects that sequestration is expected to have on forestland, this problem should not be underestimated.

The paper uses a dynamic baseline that reflects what landowners would have done if the carbon rental price was zero. In practice, the baseline may have to be the condition of the forest at some negotiated moment in time. The baseline is an important negotiating issue. Countries with forests clearly have an incentive to include the 811 gigatons in existing forest as national credits rather than having them counted as zero. Other potential abatement activities are not yet included. Preliminary work suggests that agricultural sequestration is also an important abatement activity (McCarl and Schneider 2000). A dynamic integrated model that captures both forestland and agricultural land is clearly needed. Finally, this study does not address the myriad of goods and nonmarket services that emanate from forests. The sequestration programs would affect habitat, water flows, and recreation services because it would cause forests to age. The value of these flows and what would happen in each ecosystem should be carefully integrated into a final analysis.

REFERENCES

Adams, D.M.; Alig, R.J.; McCarl, B.A.; Callaway, J.M.; and Winnett, S. M. 1999. Minimum cost strategies for sequestering carbon in forests. *Land Economics.* 75(3): 360-374.

Brown, S. 1998. Present and future role of forests in global climate change. In B. Goapl, P. S. Pathak, and K. G. Saxena (eds.), *Ecology Today: An Anthology of Contemporary Ecological Research*, International Scientific Publications, New Delhi, pp. 59-74.

Falk, I. And R. Mendelssohn. 1993. "The Economics of Controlling Stock Pollutants: An Efficient Strategy for Greenhouse Gases" *Journal of Environmental Economics and Management* **25:** 76-88.

Hardie, I.W. and Parks, P.J. 1997. Land Use with Heterogeneous Land Quality: An Application of an Area Base Model. *American Journal of Agricultural Economics. 79: 299-310.*

Hoehn, H.F. and Solberg, B. 1994. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. *Forest Science* 40(3): 429-451.

Intergovernmental Panel on Climate Change (IPCC). 1996. Scientific-Technical Analysis of Impacts, Adaptations, and Mitigation of Climate Change. Report of Working Group II. Climate Change 1995: IPCC Second Assessment Report. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2000. IPCC Special Report: Land Use, Land-Use Change, and Forestry. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2001. Mitigation. Report fo Working Group III. Climate Change 2001: IPCC Third Assessment Report. Cambridge: Cambridge University Press.

McCarl, B.A. and U. Schneider. 2000. Agriculture's Role in a Greenhouse Gas Emission Mitigating World: An Economic Perspective. *Review of Agricultural Economics*. 22(1): 134-159.

Murray, Brian C. 2000. Carbon Values, Reforestation, and “Perverse” Incentives Under the Kyoto Protocol: An Empirical Analysis. *Mitigation and Adaptation Strategies for Global Change*. 5(3): 271-295.

Nordhaus, W. 1994. Managing the Global Commons: The Economics of Climate Change. MIT Press, Cambridge, MA.

Nordhaus, W. and J. Boyer. 2000. Warming the World: Economic Models of Global Warming. Cambridge, MA: MIT Press. 232 pp.

Plantinga, A.J.; Mauldin, T.; and Miller, D.J. 1999. An econometric analysis of the costs of sequestering carbon in forests. *American Journal of Agricultural Economics.* 81(4): 812-824.

Sedjo, R. A., J. Wisniewski, A. V. Sample, and J. D. Kinsman. 1995. The economics of managing carbon via forestry: assessment of existing studies. *Environmental and Resource Economics*. 6: 139-165.

Sohngen, B., R. Mendelsohn, R. Sedjo. 1999. Forest Management, Conservation, and Global Timber Markets. *American Journal of Agricultural Economics*. 81(1): 1-13.

Sohngen, B. and R. Sedjo. 2000. Potential Carbon Flux from Timber Harvests and Management in the Context of a Global Timber Market. *Climatic Change* 44: 151-172.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 2002. A Global Model of Climate Change Impacts. In Press: *Journal of Agricultural and Resource Economics*.

Stavins, R. 1999. The Costs of Carbon Sequestration: A Revealed Preference Approach. *American Economic Review*. 89(4): 994 - 1009.

Van Kooten, G. Cornelius; Binkley, Clark S.; and Delcourt, Gregg. 1995. Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. *American Journal of Agricultural Economics*. 77(5): 365-374.

Table 1: Energy Abatement Choices Without Sequestration

Year	Uncontrolled Carbon Emissions Gigatons/yr	Expected Case Carbon Prices $/ton	Expected Case % Control of Emissions	Uncertain Case Carbon Prices $/ton	Uncertain Case % Control of Emissions
2000	6.8	7.22	4.4	22.65	11.7
2010	7.7	11.06	5.3	34.84	14.4
2020	8.4	15.19	6.1	47.97	16.6
2030	9.0	19.79	6.9	62.58	18.6
2040	9.6	24.83	7.5	78.53	20.3
2050	10.2	30.27	8.0	95.67	21.9
2060	10.7	36.07	8.6	113.68	23.3
2070	11.3	42.17	9.0	132.68	24.5
2080	11.8	48.51	9.4	152.06	25.5
2090	12.3	55.03	9.8	171.70	26.5
2100	12.8	61.74	10.1	191.65	27.3

From Nordhaus and Boyer, 2000.

Table 5: Cumulative Outcomes From 2000-2100 With Sequestration (Gigatons)

Year	Uncontrolled Cumulative Emissions	Expected Case Cumulative Energy Abatement	Expected Case Cumulative Sequestration	Uncertain Case Cumulative Energy Abatement	Uncertain Case Cumulative Sequestration
2000	0	0.0	0.0	0.0	0.0
2010	72.5	3.5	1.7	9.2	4.5
2020	153.0	8.1	3.7	21.3	9.7
2030	240.0	13.7	6.1	36.2	16.3
2040	333.0	20.3	9.1	53.8	24.3
2050	432.0	27.9	12.7	74.1	33.8
2060	536.5	36.5	16.8	97.1	44.8
2070	646.5	46.1	21.5	122.7	57.2
2080	762.0	56.6	26.7	151.0	71.0
2090	882.5	68.1	32.4	181.7	85.9
2100	1008.0	80.5	38.6	214.8	102.1

This table uses conditions in 2000 as the baseline.

Table 4: Carbon sequestered (gigatons).

	Expected Case			Uncertain Case		
	2010	2050	2100	2010	2050	2100
Mid - High Latitudes						
North America	-0.1	1.5	3.9	-0.1	2.7	14.7
Europe	0.2	0.7	1.7	0.3	1.3	4.3
Former Soviet Union	0.5	1.4	4.4	1.3	2.9	8.3
China	0.1	0.4	1.5	0.1	1.6	4.0
Oceania	0.0	0.1	0.3	0.0	0.4	1.0
Low Latitudes						
South America	0.5	3.1	10.6	1.5	8.2	27.3
India	0.0	0.0	0.2	0.0	0.2	0.8
Asia-Pacific	0.3	2.7	7.8	0.8	9.9	20.5
Africa	0.3	2.6	8.2	0.7	6.6	21.3
Total	1.7	12.7	38.6	4.5	33.8	102.1

Table 2: Increase in forestland from sequestration (million hectares).

	Expected Damages			Uncertain Damages		
	2010	2050	2100	2010	2050	2100
Mid - High Latitudes						
North America	9.2	26.1	44.6	27.5	68.9	123.6
Europe	8.5	12.8	25.9	22.3	39.8	66.0
Former Soviet Union	26.7	67.3	84.8	70.7	100.0	139.3
China	6.2	11.9	23.0	13.3	32.6	62.4
Oceania	1.4	2.8	3.9	2.7	6.8	15.2
Low Latitudes						
South America	4.0	24.8	93.7	11.9	86.5	225.3
India	0.1	1.3	4.7	1.1	7.8	18.6
Asia-Pacific	3.9	23.6	52.0	12.6	69.0	113.5
Africa	2.5	19.4	83.5	7.0	76.5	198.8
Total	62.3	189.9	416.0	169.0	488.0	962.7

Table 3: Change in timber harvests from sequestration (million m^3 per year)

	Expected Damages			Uncertain Damages		
	2010	2050	2100	2010	2050	2100
Mid - High Latitudes						
North America	22.4	8.0	59.2	(8.9)	202.1	451.9
Europe	(2.3)	10.2	61.2	10.1	(40.0)	94.7
Former Soviet Union	7.2	(9.2)	121.2	6.1	(7.2)	84.8
China	2.7	(2.3)	18.9	5.3	(50.7)	(51.2)
Oceania	0.1	8.2	7.3	(1.8)	28.1	46.5
Low Latitudes						
South America	(32.0)	47.3	59.5	(15.4)	37.1	205.6
India	0.2	2.8	5.2	0.7	(13.3)	53.5
Asia-Pacific	(5.9)	(7.6)	(7.5)	(17.1)	25.5	(97.4)
Africa	7.7	(4.4)	8.4	(2.7)	(1.7)	(3.1)
Total	0.1	52.9	333.3	(23.6)	179.8	785.4