An Optimal Control Model of Forest Carbon Sequestration

Brent Sohngen and Robert Mendelsohn

This study develops an optimal control model of carbon sequestration and energy abatement to explore the potential role of forests in greenhouse gas mitigation. The article shows that if carbon accumulates in the atmosphere, the rental price for carbon sequestration should rise over time. From an empirical model, we find that carbon sequestration is costly, but that landowners can sequester substantial amounts of carbon in forests mainly by increasing forestland and lengthening rotations. Forest sequestration is predicted to account for about one-third of total carbon abatement. Tropical forests store over two-thirds of this added carbon.

Key words: carbon sequestration, climate change, forestry, optimal control.

The least-cost strategy to control stock pollutants, such as greenhouse gases, is to allow the price or marginal cost of control to rise as the present value of damages increases (Falk and Mendelsohn). Following this strategy, policy makers should balance the cost of reducing carbon emissions from all options today against the future damages from climate change. For the most part, the previous literature has focused on describing optimal strategies for controlling greenhouse gases through energy abatement (i.e., Falk and Mendelsohn, Nordhaus, and Nordhaus and Boyer). This article extends this literature by integrating the costs of sequestering carbon in forests into an optimal control model for greenhouse gases. The article shows how the incentives to sequester carbon should rise over time with the increase of the price of carbon, and it shows what these incentives suggest about the timing and placement of carbon sequestration in different regions of the world. The results are "optimal" in the sense that sequestration is integrated into the overall optimal control problem of greenhouse gases. Of course, the analysis in this article is not "optimal" in a definitive sense since not all factors of social concern are included in the model.

Forestry experts with the Intergovernmental Panel on Climate Change (IPCC) suggest that up to 87 billion tons (1 ton = 1000 kilogram throughout) of carbon can be sequestered in the world's forests by 2050 (Watson, Zinyowera, and Moss; Watson et al.; and Metz et al.). Forests currently store approximately 800 billion tons of carbon in trees and soil (Brown), so this goal represents a more than 10% increase in total global forest carbon. While current estimates of the cost of forest carbon sequestration range from \$1 to \$150 per ton (Sedjo et al., Metz et al.), most of the studies are regional or they have considered a limited set of management actions for increasing carbon. For instance, landowners could increase this stock by increasing the amount of land in forests (Stavins; Plantinga, Mauldin, and Miller; Adams et al.) or by increasing the carbon per hectare with more intensive management or longer rotations (Hoehn and Solberg; Van Kooten, Binkley, and Delcourt; Murray).

No current studies have explored the potential costs of large, global programs suggested by the IPCC. Given the scale of these proposed sequestration programs, regional estimates of costs may be biased downward because they do not consider the potential effects of changes in timber supply and prices. In addition, most forest sequestration studies assume static incentives such as constant carbon prices (Plantinga, Mauldin, and Miller; Stavins). Rising carbon prices (i.e., Nordhaus

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and Boyer) would lead to different predictions about the timing of low-cost carbon sequestration in different forest management activities and regions of the world. Thus, optimal strategies for changing land use, timber management, and rotation lengths could vary over time and among regions, depending upon the path of global carbon prices.

This article addresses these issues by integrating global carbon sequestration into an optimal control model of greenhouse gases. Adding sequestration could lower the overall cost of controlling carbon if the marginal cost of some sequestration is lower than the marginal cost of energy abatement. Sequestration could also result in larger reductions in atmospheric carbon. Increasing atmospheric accumulations of carbon lead to rising carbon prices over time, and increasing dynamic incentives to sequester carbon in forests. The incentive to sequester carbon is communicated to landowners through a carbon rental fee for every additional ton of carbon they store each year. Renting carbon increases the value of forestland causing conversion from other land uses, increasing rotation lengths, and increasing management intensity. For this article, we assume that global institutions exist to encourage optimal behavior over time, and we ignore alternative institutional arrangements. Empirical results for this theoretical model are developed using a well-known greenhouse gas model, DICE (Nordhaus and Boyer), and a global timber model (Sohngen, Mendelsohn, and Sedjo, 1999). The DICE model is modified to include a sequestration option where the costs and timing of sequestration have been elicited from the global timber model. The global timber model is modified to include a path of carbon rental rates from the DICE model. By solving back and forth between these two models, we calculate 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, 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. 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 $D(X(t), t)$. The annual abatement costs of reducing carbon emissions from the energy sector is equal to $\mathrm{CE}(A(t))$. The model can be written formally as

$$(1) \qquad \min_{A(t)} \int_0^\infty [\mathrm{CE}(A(t)) + D(X(t), t)]e^{-rt}\,dt$$

$$\text{subject to} \quad \dot{X} = E(t) - A(t) - \lambda X(t).$$

For this model, we assume that the baseline emissions path is given, $E(t)$, and the choice in this model is the level of annual abatement. $E(t)$ can be thought of as the business as usual emissions path predicted by the IPCC (i.e., Houghton et al.).

Sequestration in forests adds an alternative for carbon mitigation. Three forestry actions that can increase carbon relative to the baseline are considered here: adding forestland, $L(t)$; lengthening rotations, $a(t)$; and increasing management intensity, $m(t)$. Because carbon is evaluated relative to the baseline, adding forestland can include either planting new forests on old agricultural land or reducing deforestation on lands projected to be converted to agriculture. Planting new forests is likely to be more important in the mid-high latitude forests while reducing deforestation is likely to be more important in the low-latitude forests.[1] Lengthening rotations increases carbon storage by increasing the size of trees on each hectare.[2] Increasing management intensity increases the stocking density of forests. The cost function for sequestering carbon in forests is $\mathrm{CF}(L(t), a(t), m(t))$. The amount of carbon sequestered above the baseline forest stock, $S(\cdot, t)$, depends upon $L(t)$, $a(t)$, and $m(t)$

[1] Throughout this article, we refer to mid-high latitude forests as those in North America, Europe, the Former Soviet Union, Australia, New Zealand, and China. These include temperate deciduous and coniferous forests, as well as boreal forests in northern or mountainous regions of the United States, Canada, Europe, and the Former Soviet Union. Low-latitude forests include sub-tropical and tropical species that generally occur in South America, India, Asia-Pacific, and Africa.

[2] The concave shape of forest yield functions limits the potential for lengthening rotations to increase carbon substantially.

and time (t) itself. Adding forest sequestration changes the model above to

$$(2)\quad \min_{A(t),L(t),a(t),m(t)} \int_0^{\infty} [\mathrm{CE}(A(t)) + D(X(t),t) + \mathrm{CF}(L(t),a(t),m(t))]e^{-rt}\,dt$$

$$\text{subject to}\quad \dot{X} = E(t) - A(t) - \lambda X(t) - S(L(t),a(t),m(t),t).$$

For the model with sequestration, $E(t)$ includes emissions from both the energy sector and land-use change. In this model, each additional ton of carbon stored in the biosphere is assumed to be a ton subtracted from the atmosphere.[3]

Upon forming a Hamiltonian and solving, the first-order conditions lead to the following solutions to this problem:

$$(3)\quad \mu(t) = \mathrm{CE}_A = \frac{D_X(X(t)) + \dot{\mathrm{CE}}_A}{(\lambda + r)}$$

$$(4)\quad \mathrm{CE}_A = \frac{\mathrm{CF}_L}{S_L} = \frac{\mathrm{CF}_a}{S_a} = \frac{\mathrm{CF}_m}{S_m}.$$

Equation (3) shows that the marginal costs of an additional ton of abatement should be equated to the shadow value, $\mu(t)$, of an additional ton of carbon removed from the atmospheric stock, $X(t)$, and the present value of the stream of damages and rising abatement costs that the ton causes. Equation (4) shows that the marginal cost of energy abatement should equal the marginal cost of adding forestland, increasing rotation lengths, or intensifying management. Given baseline emissions, as the amount of carbon increases in the atmosphere, the marginal damages per ton rise, calling for an increasing amount of energy abatement and carbon sequestration over time. Carbon sequestration, just like energy abatement, should be dynamic, reflecting the increasing incentive to remove carbon over time as it accumulates in the atmosphere.

One of the difficulties with implementing this model is the issue of "permanence." The 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, $\mu(t)$. However, managed forests do not sequester carbon permanently. Managed forests are harvested and the carbon in the resulting products is slowly released back into the atmosphere. Lands are planted and they gradually capture carbon over time as the trees grow. In order to capture the timing of these flows accurately, we measure carbon storage per year. Rather than using the price of carbon, $\mu(t)$, the forestry model in this article relies on the price per year, the rental rate of carbon, $R(t)$ is as follows:

$$(5)\quad R(t) = \mu(t) * [r - n(t)].$$

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, $n(t)$, where $n(t) = [d\mu(t)/dt]/\mu(t)$. As discussed below, by relying on the relationship in (5), we can numerically estimate optimal carbon abatement and sequestration paths with two large models from the energy and forestry sectors.

Empirical Investigation of Carbon Sequestration Costs

This section develops empirical values for the theoretical model described above. An existing optimal control model of global timber markets (Sohngen, Mendelsohn, and Sedjo, 1999) is used to measure the cost function for forest sequestration. The greenhouse gas model is an integrated assessment model of carbon and the world economy, DICE (Nordhaus and Boyer). Two scenarios in DICE are examined to account for uncertainty over the climate change damage function. First, we use the expected value of all parameters and examine an "expected case." The expected case reflects climate change damages measured in the literature (Nordhaus and Boyer; Bruce, Lee, and Haites). Second, from a Monte Carlo study that Nordhaus and Boyer performed, we rely on a much higher damage function, which we call the "uncertain case." The uncertain case assumes that society places more weight on the tail of the distribution for the underlying damage estimates for different sectors. By examining these two scenarios, one can see how damage assumptions in the integrated assessment model affect the desired levels of sequestration over time.

[3] We assume that an additional ton stored permanently in forests is equivalent to an additional ton of reduced energy emissions. As pointed out by a reviewer, there may be more uncertainty about tons stored in forests than tons reduced by energy emissions. Differences in uncertainty between the two could lead to discounts for forest carbon relative to carbon from energy abatement (or vice versa).

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 that the DICE model predicts without sequestration, and we generate rental rates. 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

$$(6) \qquad S(t) = 0.042 * \mu(t)^{0.870} t^{0.706}.$$

$S(t)$ 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. This function is accurate in the neighborhood of carbon prices explored. Under alternative damage functions, prices for carbon could depart from the time paths we consider, and the equation should be re-estimated. For example, it is clear from the forestry and ecological models that the amount of carbon that can be stored in forests reaches a saturation level. We suspect that this saturation level is not far above the maximum amount showed in this analysis.

DICE Model Description

The DICE model projects carbon prices in the absence of forest sequestration. 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. Carbon intensity in the economy, however, is projected by DICE to fall from 259 tons CO_2 per million $ GDP in 2000 to 143 tons CO_2 per million $ GDP in 2100 as technology changes, as the makeup of GDP shifts from manufacturing to services, and as the composition of inputs in the energy sector changes. Despite these changes, uncontrolled carbon emissions are predicted to rise from 6.8 billion tons per year in 2000 to 12.8 billion tons per year by 2100 (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 per ton. The uncertain case leads to higher initial carbon prices of about $23 per 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

Table 1. Energy Abatement Choices from DICE without Sequestration

		Expected Case		Uncertain Case	
Year	Uncontrolled Carbon Emissions (Billion Tons Per Year)	Carbon Prices ($/ton)	Emission Control (%)	Carbon Prices ($/ton)	Emission Control (%)
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

over time. The higher the price, the more carbon is abated.

Forest Carbon Model Description

To parameterize the forestry cost function, the dynamic, global forestry model of Sohngen, Mendelsohn, and Sedjo (1999) is expanded in several ways. First, we incorporate the rental price from DICE into the forestry model, so that the forest carbon model maximizes the present value of the benefits minus costs of timber harvesting and carbon sequestration. The carbon rental payments are based on the stock of new carbon stored in the biosphere, and the annual tons stored "permanently" in the timber market. The baseline is calculated as the carbon that the forest would have stored if rental rates were zero. The marginal value of storing a ton of carbon in the biosphere for a year is $R(t)$, and the marginal value of storing a ton in timber markets is $\mu(t)$. Carbon storage can be increased by moving lands from farming to forests, by increasing the amount of carbon per hectare of forest through management intensity and harvest age, and by storing carbon in market products such as houses and furniture.

Second, the timber model has been expanded to include all of the world's forests. Earlier versions included only forests that were important for timber markets. The forest model now includes fifty timber and management types in nine continents, encompassing all major agricultural and forestry regions where carbon sequestration might occur. Third, we include land supply functions for all forestland regions to account for the sensitivity of land prices to forest sequestration programs, as suggested by numerous authors (Alig et al.; Adams et al.; Stavins; and Plantinga, Mauldin, and Miller). We also assume that new forests can only grow in places suitable for forests according to ecological models, and that sequestration programs start with the least productive agricultural land and take more and more valuable lands thereafter. The marginal cost will also increase because the price of farm products rises as farm products get scarce. We do not, however, build a complete model of the agricultural sector as has been done for several studies of the United States alone (Alig et al. and Adams et al.).

The cost functions, the timber product demand function, and other economic parameters are taken from Sohngen, Mendelsohn, and Sedjo (1999). Parameters for the rising land rental cost functions are also included for each of the fifty timber types in this study. It is difficult to find this data for many regions, but several studies suggest that the elasticity of land supply in forestry is relatively inelastic in North America (Hardie and Parks; Plantinga, Mauldin, and Miller; and Stavins). 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. Unfortunately, the studies used for these parameters hold forest and agricultural prices constant, so that the elasticity estimates may be lower than general equilibrium results would suggest. Integrating global agriculture and forestry models to study dynamic sequestration is an important innovation for future analysis.

Carbon storage parameters are taken from Sohngen and Sedjo. Both above and belowground biomass are 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.[4] Following Johnson; and Johnson and Curtis, we assume that carbon in forest soil remains constant when forests are harvested, but regenerated as forests. The proportion of harvested timber stored in timber products depends on how the timber is used. A number of authors have pointed out that this carbon stock will change over time as carbon decays (for example, see Plantinga and Birdsey, and Stavins). For this study, we use the proportion that is stored initially, minus the present value of the future decay. Decay rates for each species depend on the proportion used for each type of timber end-use (e.g., paper or houses).

The baseline for this artcle 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

[4] The results of Post and Kwon (2000) are used to calibrate the net soil carbon gains for different types of forests in our model. On average, their study suggests that carbon increases 0.30 tons per hectare per year when land is converted from agriculture to forests, with rates rising from temperate zones to subtropical zones. As suggested by Post and Kwon (2000), annual gains in our model are assumed to last for only fifty years.

Table 2. Integrated Results: Cumulative Change in Forestland (in Million Hectares) Arising from Sequestration

	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

will change over time in the absence of a sequestration program. The model predicts that current global carbon storage in the biosphere is 811 billion tons, which is consistent with recent estimates (Brown). Over the next century, the model predicts deforestation will lead to forest carbon emissions averaging 450 million tons per year so that total carbon in forests declines to 766 billion tons by 2100. Nearly all of this loss results from deforestation in the tropics, with the temperate zone remaining stable. Although we follow the current literature and assume that the amount of carbon in products decays over time, depending on the product (Plantinga, Mauldin, and Miller, and Stavins), increasing consumption causes timber products to store an additional 16 billion tons of carbon, or approximately 157 million tons per year, over the next 100 years.

Results

The two carbon sequestration scenarios (expected and uncertain damages) lead to substantial conversions of land to forests (table 2). In the expected and uncertain scenarios respectively, the sequestration program is projected to add 416 and 963 million hectares of forest by 2100. Both are large increases over the estimated 3.5 billion hectares of forest today. Approximately 43% of the land is projected to occur in mid-high latitude regions of temperate and boreal forests, with the rest lying in low-latitude tropical and sub-tropical forest regions.

The sequestration programs are predicted to have large effects on timber markets (table 3). Initially, forest owners withhold some timber from production to gain higher

Table 3. Integrated Results: Annual Change in Timber Harvests (in Million m^3 Per Year) Relative to Baseline for Sequestration Scenarios

	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

Note: Numbers in parentheses denote lower harvests.

carbon rental payments, particularly in the uncertain case. The largest change in harvests occurs in the low latitudes where forest owners slow deforestation. Eventually, supply increases as forest owners start harvesting older trees. Because most trees grow most rapidly near economic maturity, extending rotations increases average growth and causes supply to expand. The combination of expanding forest area and longer rotations suggests that timber supply will expand 333 million m^3 in the expected case and 785 million m^3 in the uncertain case by 2100 (baseline harvests in 2100 = 2.3 billion m^3). Approximately 80% of the increase 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.

Under these scenarios, carbon sequestration starts slowly, but grows to almost 40 billion tons in the expected case and over 100 billion tons in the uncertain case by 2100 (table 4). The assumed damage function for global warming consequently makes a large difference to the magnitude of the sequestration program. Table 4 also shows where and when our global timber model predicts carbon sequestration should occur. Despite the commitment of land to sequestration in the mid-high latitudes, most sequestration (about 70%) occurs in low-latitude forests, where deforestation is reduced.

It is also useful to consider which actions (land use, rotation ages, forest management) are used for sequestration. When globally averaged, our results suggest that most, 80%, of the carbon arises from land-use change (reduced deforestation and planting new forests), with approximately 16% coming from increased rotation ages, 3% from enhanced management, and the remainder from increased storage in markets. Note that much of the new land in forestry is not harvested in the 100-year time period considered. These forests effectively become carbon reserves. The results also vary by region. For example, more of the carbon in mid-high latitude regions arises from increasing rotation ages on managed forests (30%) and increased management (6%), while less comes from land-use change (63%).

Finally, table 4 presents the endogenously determined carbon prices and carbon rental rates. For the expected damage case, sequestration reduces carbon prices by less than 1% by 2100 ($61.74 per ton without versus $61.34 per ton with sequestration in 2100), and for the uncertain damage case, sequestration reduces carbon prices by only 2% by 2100 ($191.65 per ton without sequestration versus $187.54 per ton with sequestration in 2100). Because these carbon price changes are so small, sequestration is not expected to have a large effect on energy abatement.

Forest carbon sequestration does not delay energy abatement, but rather operates simultaneously with it. Because carbon prices remain almost the same with or without sequestration, energy abatement is almost the same in both cases. Table 5 shows cumulative

Table 4. Integrated Results: Carbon Prices and Cumulative Carbon Sequestration (in Billion Tons) by the Year Given

	Expected Case			Uncertain Case		
	2010	2050	2100	2010	2050	2100
Carbon price ($/Ton)	7.14	29.87	61.34	21.80	92.19	187.54
Carbon rental value ($/Ton/Year)	0.04	0.83	2.23	0.11	2.57	6.88
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 5. Cumulative Outcomes with and without Sequestration (in Billion Tons)

	Expected Case			Uncertain Case		
	2010	2050	2100	2010	2050	2100
Baseline emissions	66.9	410.8	970.4	66.9	410.1	965.6
Without sequestration						
Energy abated	2.9	25.4	75.6	7.9	68.4	203.1
With sequestration						
Energy abated	2.9	25.1	75.0	7.6	66.2	197.3
Carbon sequestered	1.7	12.7	38.6	4.5	33.8	102.1

Note: This table uses conditions in 2000 as the baseline.

abatement for the different scenarios. Total emissions in the baseline case are shown in the first row of table 5. The cumulative amount of energy abatement without sequestration is shown in the second row. Adding sequestration (comparing the second and third row of data) does not change cumulative energy abatement much except for the final years in the uncertain case. Examining the third and fourth rows for the expected and uncertain scenarios reveals that sequestration is almost one-third of total abatement. Cumulative sequestration equals about one-half of cumulative energy abatement throughout the century. Note that this would not continue indefinitely into the 22nd century as eventually the amount of carbon that can be sequestered in forests would reach a biological limit.

Attempts to speed up sequestration would raise the costs. For example, the IPCC (Metz et al.) predicts that 60–87 billion tons of carbon could be sequestered by 2050. This magnitude is similar to our uncertain case, except we set aside this amount of carbon by 2100. Using the parameters of the sequestration cost function in equation (6), achieving 100 billion tons in half the time (fifty years) would increase the marginal costs of sequestration by about 70%.

Compared with some regional studies, the results in this paper suggest significantly higher costs. For example, Stavins predicts that a large program could sequester 518 million tons per year in the United States alone for $136 per ton. We achieve similar prices in 2075 in the uncertain damage case, but average sequestration between 2070 and 2080 is only 243 million tons per year for the entire North American continent. Our results for smaller programs are similar to estimates by Adams et al. When the price of carbon is relatively low, the sequestration program is modest. The cost of the program will rise rapidly the larger the program becomes.

Conclusion

This article develops a theoretical model to show how carbon sequestration programs should be coordinated with overall greenhouse gas mitigation programs so that the marginal costs of energy abatement and carbon sequestration are equalized. As carbon emissions increase over time, rising prices for carbon abatement cause energy abatement and carbon sequestration to rise as well. The integrated model balances the cost of carbon mitigation and carbon sequestration against the damages from having more greenhouse gases in the atmosphere. To link carbon prices from a greenhouse gas model to a forestry model, annual rental values for carbon sequestration are derived from carbon prices predicted by the energy model. As with carbon prices, rental values rise over time in response to the rising stock of greenhouse gases. Efforts to increase forestland area, rotation lengths, and management intensity should be dynamic.

Numerical estimates of carbon sequestration potential and costs are generated by integrating the DICE model of greenhouse gases (Nordhaus and Boyer) with an optimal control model of global timber markets (Sohngen, Mendelsohn, and Sedjo, 1999). Two scenarios for the optimal price path for carbon sequestration are used to capture variation in potential climate change damages: an expected scenario and an uncertain scenario. Given each scenario, optimal energy abatement and carbon sequestration are calculated for the next century. Both the greenhouse gas model and sequestration model explore global opportunities and find the most cost effective choices for changing world forest area or management.

The results suggest that 39 and 102 billion tons of carbon could be sequestered in global forests by 2100 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. In the expected case, the results suggest that 400 million hectares of forestland would be added by 2100, and almost 1 billion hectares would be added in the uncertain case. Tropical forests are predicted to sequester approximately 70% of the carbon, a result consistent with other studies (Watson, Zinyowera, and Moss; Metz et al.).

This study finds that 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, whereas afforestation is most important in temperate regions. The model predicts that lengthening rotations would effectively create conservation forests that are not harvested. Many of these forests are in the tropics, although some temperate forests are set aside. Many temperate forests, however, continue to be harvested, albeit with longer rotations. Changing management intensity plays only a small role in supplying carbon because it is less effective at carbon storage and costly.

Increasing forest area and lengthening rotations have large implications for timber markets. At first supply declines as landowners lengthen rotations. However, additional forestland area and 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. The supply increase will in turn reduce global timber prices in the long run.

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. The large programs are consequently expensive. Despite the costs, the study suggests that sequestration can 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 article makes a number of contributions to the sequestration literature, several additional issues should be addressed. The sequestration model does not consider the effect of climate change on forests. Sohngen, Mendelsohn, and Sedjo (2001) show that climate change will affect global timber supply so this effect is important. But integrating the effect of climate change on sequestration is a difficult task that we leave for a future article. 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 and managing a global land-use program. Adopting sequestration on a piecemeal basis may also be subject to substantial leakage. Any carbon saved on lands in the program could be offset by carbon lost on lands not in the program. Given the system-wide price effects shown in this article, leakage should not be underestimated.

The article 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 billion tons in existing forest as national credits rather than having them counted as zero. Other potential abatement activities are not yet included, although McCarl and Schneider show that agricultural sequestration is also an important abatement activity. 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 encourage older managed forests and substantial conservation forests that are not harvested at all. The resulting changes in ecosystems and the value of these flows should also be carefully integrated into the model and decision making.

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