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OPTIMAL FOREST CARBON SEQUESTRATION

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ABSTRACT: This study examines the optimal timing and amount of carbon sequestration as a component of an optimal control model of greenhouse gases. As carbon accumulates in the atmosphere, the carbon rental price should rise suggesting an increasing incentive to sequester carbon over time. A general equilibrium model of sequestration, taking into account global timber prices and the increasing scarcity of land, suggests that substantial amounts of carbon could be sequestered in forests reducing the price of carbon. The bulk of this carbon should be kept in tropical forests with a large proportion of the carbon resulting from reduced deforestation initially. Though important, carbon sequestration is more costly than many estimates in the literature, suggesting it plays only a partial role controlling greenhouse gases.

KEYWORDS: carbon sequestration, optimal control, timber markets

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In recent years, a number of economists and other experts have suggested sequestering carbon in forests to help mitigate the accumulation of greenhouse gases in the atmosphere (Adams et al., 1993; Adams et al.,1999; IPCC, 1996; IPCC, 2000). Forests currently store a substantial stock of carbon, amounting to 826 billion metric tons in trees and soil (Brown, 1998), and society can potentially remove carbon from the atmosphere by taking steps to increase this pool of carbon. These steps may include increasing the amount of carbon stored per hectare through management intensity or rotations ages (Hoen and Solberg, 1994; Van Kooten et al., 1995; and Murray, 2000) or increasing the area of land in forests (Stavins, 1999; Plantinga et al., 1999; Adams et al., 1999). Carbon sequestration thus offers the promise of reducing the cost of greenhouse gas mitigation, which could lower the price of carbon and reduce global warming.

There are, however, many hurdles that must be overcome to fully understand what role carbon sequestration could play in controlling greenhouse gases. First, an optimal control model that integrates carbon sequestration into greenhouse gas control has yet to be developed. Neither the timing nor the amount of carbon that could optimally be sequestered in the terrestrial ecosystem is clear. Nor is it clear how adding a carbon sequestration program changes the path of climate change. Second, a general equilibrium model that takes into account how global sequestration might affect timber prices and the price of land has also not been developed, although some researchers have addressed this issue on a regional level (see Alig et al., 1997). Consequently, it is unclear how costly and effective a sequestration program might be. Third, problems of management and verification plague global sequestration programs because land use, traditionally a local concern, will suddenly become of global interest. Fourth, carbon sequestration programs will likely change the supply of a host of nontimber forest products and ancillary nonmarket services such as wildlife habitat, soil protection, and clean water. Fifth, carbon mitigation programs will also affect energy prices and agriculture that will have additional effects on forestry. All these impacts need to be considered in designing an overall program.

This paper addresses the first of these hurdles by constructing an optimal control model of greenhouse gases with an explicit carbon sequestration program embedded in it. The optimal control model is based on the Regional Integrated model of Climate and the Economy (RICE), a well-known regional model of greenhouse gases (Nordhaus and Boyer, 2000). The RICE model, however, only includes energy mitigation. This paper adds a carbon sequestration cost function to this model. The price of carbon over time is recalculated with this additional cost function. Compared to the case with just energy mitigation, adding carbon sequestration reduces the price of carbon and the stock of carbon in the atmosphere (though by less than what is sequestered). The new price path of carbon suggests that carbon sequestration should be a dynamic program increasing in intensity as the price of carbon rises.

The carbon sequestration cost function is calculated from a dynamic model of world timber markets (Sohngen et al., 1999). The forest model is a forward-looking model that takes future timber and land prices into account as it manages timber stocks (Sohngen and Mendelsohn,1998). The model is expanded in this study to account for carbon sequestration by rewarding forest owners for holding carbon each year. Carbon is rented at rising prices so that owners have an incentive to hold increasing amounts of carbon in forests over time. Owners can change land use (converting land to forestry or holding it in forestry if they were about to convert it), extend rotations, or increase the intensity of forest management (increasing stocking density of stands, enhancing growth, fire suppression, etc). All of these changes can affect the stock of timber and carbon, and land prices over time. The model assumes that owners will maximize profits given the rewards of market outputs and carbon rental payments.

The paper does not address the final three hurdles facing carbon sequestration. Designing global programs that can be enforced locally is a difficult management and negotiation task. Whether countries should be rewarded for current stocks of carbon, all changes in carbon, or just selected changes remains to be negotiated. Whether such programs simply need to examine land use or whether they should also capture forest management is a question for future research. The carbon sequestration programs must also be designed to take into account other forest products and forest services. The intertemporal model should also take into account other changes from mitigation such as rising energy prices and changes from agricultural mitigation efforts (McCarl and Schneider, 2000a). Although these tasks are certainly important, we are unable to address them in this paper.

Current estimates of the cost of carbon sequestration in forests range from $1 to $150 per ton (Sedjo et al., 1995). Many of the early estimates may have been biased downwards because they focused on average and not marginal costs (Stavins, 1999 and Plantinga et al., 1999). These two recent studies estimate the marginal cost of land conversion from agriculture to forestry in particular regions, but they do not consider alternative forestland management options, such as changing rotation lengths and changing management intensity. Further by focusing on particular regions, they have failed to incorporate system-wide effects that could cause leakage elsewhere. For example, large expansions of forestland area in the US could have important feedback effects throughout global markets, thus affecting timber supply, altering prices and management, and changing carbon storage in other places (see Alig et al., 1997 for a discussion of potential feedbacks within the US alone).

I. AN OPTIMAL CONTROL MODEL OF CARBON MITIGATION AND SEQUESTRATION

We start with the optimal control model of carbon mitigation from Nordhaus and Boyer (2000). The objective is to maximize a social welfare function based on consumption, population, and a discount rate. The RICE model assumes that this discount rate gradually declines over time. Population is assumed to grow exponentially at a declining rate as well. Production is a Cobb-Douglas function of labor, capital, and energy. Given increases in population and capital, production is expected to grow over time at a decreasing rate of growth. Improvements in technology lead to a reduction of energy per unit of production. Nonetheless, energy consumption is also expected to grow over time although at a decreasing rate. All of the above constructions concern a standard economic growth model.

This paper focuses on the environmental component of the RICE model, which considers an externality, carbon dioxide, associated with energy consumption. The inverse demand for energy, ES(t), is:

$$P_E(t) = \beta\ Y(t)\ ES(t)^{1/(\beta -1)} \tag{1}$$

where $P_E(t)$ is the price of energy and $Y(t)$ is GDP. The marginal cost of producing energy, $MC(t)$, is:

$$MC(t) = C_E(t) + h(t)\ \delta + \tau(t)\ \delta \tag{2}$$

where $C_E(t)$ is the cost of carbon energy, $h(t)$ is the Hotelling rent on carbon energy, δ is energy per unit of carbon emission, and $\tau(t)$ is the carbon tax. The model assumes that the Hotelling rent for carbon-energy is a function of carbon, not the energy itself. Carbon emissions, $E(t)$, are simply $ES(t)/\ \delta$. In a competitive market, the price of carbon will be set equal to marginal cost. Equating (1) to (2) (demand to supply) and simplifying yields:

$$E(t) = \delta\ \{[\ C_E(t) + h(t)\ \delta + \tau(t)\ \delta] / \beta\ Y(t)\}^{1/(\beta -1)} \tag{3}$$

Carbon energy, and therefore carbon emissions, depends upon the supply and demand parameters for carbon energy.

Energy production leads to carbon dioxide emissions that then lead to the accumulation of carbon in the atmosphere and climate change. The amount of carbon in the system is a lagged function of carbon in different reservoirs. Carbon in the atmosphere (M_{AT}), biosphere, upper ocean (M_{UP}), and lower ocean (M_{LO}) reservoirs have the following properties:

(4) $M_{AT}(t) = 10*E(t-1) + \varphi_{11} M_{AT}(t-1) + \varphi_{21} M_{UP}(t-1)$

$M_{UP}(t) = \varphi_{12} M_{AT}(t-1) + \varphi_{22} M_{UP}(t-1) + \varphi_{32} M_{LO}(t-1)$

$M_{LO}(t) = \varphi_{23} M_{UP}(t-1) + \varphi_{33} M_{LO}(t-1)$.

The accumulating stock of carbon in the atmosphere leads to an increase in radiative forcing, F(t):

(5) $F(t) = \eta \{\log(M_{AT}(t) / M_{AT}^*)/\log(2)\} + O(t)$

where M_{AT}* is the preindustrial level of carbon in the atmosphere and O(t) is the contribution of other noncarbon greenhouse gases.

The increased radiative forcing pushes the temperature up in the following lagged fashion:

(6) $T(t) = T(t-1) + \sigma_1 \{F(t) - \lambda T(t-1) - \sigma_2 [T(t-1) - T_{LO}(t-1)]\}$

$T_{LO}(t) = T_{LO}(t-1) + \sigma_3 [T(t-1) - T_{LO}(t-1)]$

where T(t) is the global atmospheric temperature and T_{LO} is the temperature of the deep ocean. It takes a long time to warm the ocean causing the atmospheric temperature to lag behind increases in greenhouse gases.

The final link in the environmental model is a damage function. The damage function in the RICE model is a quadratic function of global temperature:

(7) $$D(t) = \theta_1 T(t) + \theta_2 T(t)^2 \quad .$$

The model maximizes the present value of the net benefits of consumption over time where both the cost of abatement and damages are considered part of consumption. This leads to the imposition of a carbon tax that increases over time as the level of greenhouse gases rises. The rising carbon tax leads to increasing amounts of abatement over time.

In this paper, we will add an additional mitigation cost function. We consider the possibility of storing carbon in the terrestrial biosphere. In the energy market, when the government purchases a unit of emission, it eliminates that emission for all time. In forestry, carbon on any hectare of land may be stored for some time, but then some of it may be released when the forest is harvested. Only carbon stored permanently above the baseline in forests should be valued at $\tau(t)$. We consequently rent carbon in forests at a rate equal to the energy carbon tax rate times the interest rate, r:

(8) $$R(t) = r * \tau(t)$$

Units of carbon stored above the baseline are rented at R(t) for the entire time they are stored.

In the optimal sequestration model, land owners include this carbon rent in their choice of land use (forestry or agriculture), rotation age, and management intensity. They weigh the additional cost of choosing more forestland over farmland, rotations longer than Faustmann, and higher management intensity against the additional carbon rental payments they would get. As carbon storage programs increase in scale, the programs will affect timber prices and land rents. These must also be taken into account. The net response taking into account all these factors is to create an additional global mitigation option of sequestering carbon in the terrestrial biosphere. The annual supply of carbon through sequestration, S(t), is assumed to have the following form:

$$(9) \qquad S(t) = \alpha\, R(t)^{\kappa 1}\, t^{\kappa 2}$$

The supply of sequestration is a function of the annual rent for carbon, R(t). It is also a function of time because many forestry projects take a long time to become effective.

Adding the sequestration option to energy mitigation effectively lowers the cost of reducing carbon in the atmosphere. This has the effect of reducing the price of carbon. As prices fall, the incentive to mitigate carbon in the energy sector falls. One byproduct of adding sequestration is that the amount of energy mitigation falls. The total reduction of carbon in the atmosphere is therefore less than the increase in carbon in the terrestrial biosphere. Nonetheless, another outcome of lower overall carbon mitigation costs is that less carbon is added to the atmosphere thereby reducing the damages from greenhouse gases. Sequestration does help reduce the damages from greenhouse gases.

In this paper, we specifically examine the additional sequestration expected through sequestration management actions. Because carbon prices are expected to increase over the next century, the stock of carbon in an optimal sequestration program is expected to monotonically increase. Actual sequestration plans, however, might focus on total carbon in terrestrial ecosystems not just the carbon from approved mitigation actions. To examine this question, future modeling must follow all the changes in carbon in the terrestrial ecosystem, especially those caused by climate change itself and those caused by random environmental conditions. A more complicated effort designed to estimate the effects of these changes will provide better insights into how to design actual programs.

The full extent to which sequestration assists energy mitigation requires a calibrated model of both greenhouse gases and sequestration. In the next section we develop a more complete forest model of sequestration. We then calibrate and integrate these two models in Section III.

II. A FOREST CARBON SEQUESTRATION MODEL

In this section, we develop a more explicit representation of forest sequestration, including changing land use, management intensity, and rotation length. Our forest carbon sequestration function values both marketed timber (industrial roundwood) and carbon sequestration. Although forests provide many additional market and nonmarket goods and services, such as nontimber forest products, wildlife, biodiversity, water, and recreation, these additional services are not modeled in this paper. We abstract from place specific descriptions in this theoretical development. The benefits and costs from any specific hectare will vary over space because of productivity, access, and wages. Although we introduce these important empirical considerations into the quantitative model, we do not present them in the theoretical model in order to focus on the intertemporal and conceptual issues presented.

We are interested in maximizing the present value of the benefits minus costs of timber harvesting and carbon sequestration across time:

$$(10)\qquad \int_0^{\infty} \{B_F\left(Q(a(t), m(t), L(t))\right) + B_X\left(X\left(a(t), m(t), L(t), Q(t)\right)\right) - C_m\left(m(t), L(t)\right) - C_L\left(L(t)\right)\} e^{-rt}\, dt$$

The benefits include a stream of timber benefits net of harvesting costs, $B_F(\cdot)$, and carbon rental payments, $B_X(\cdot)$. The net benefits of harvesting timber are a function of the quantity harvested each year, Q[a(t),m(t),L(t)]. The quantity harvested is a function of the age of the timber harvested, a(t), and management intensity, m(t). Because we track area of timber in each age class, the age at harvest defines both the area of land harvested and the volume. Forestry is a renewable resource, so L(t) is included to capture effects of expanding or decreasing the area of forests on long-run supply. Carbon rental payments are based on tons of carbon stored in the biosphere and the timber market. Carbon storage can be increased by moving lands from farming to forests, by increasing the amount of carbon per hectare of forest, and by storing carbon in market products such as houses and furniture. The benefit of each ton of carbon stored is determined by the optimal control model of greenhouse gases. The cost of managing timber stocks, $C_m(m(t),L(t))$, depends upon the area of forestland planted, which is a function of total forestland, L(t), and the management intensity for those hectares, m(t). The cost function for renting forestland, $C_L(L_t)$, reflects the value of land lost from agriculture. The marginal cost of new hectares in forestland increases as the area of forestland grows because the forest will 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. Specifically, we do not explore how changes in the price of carbon would encourage mitigation in agriculture and thus the cost of land (see McCarl and Schneider, 2000b).

Carbon supply is measured relative to a baseline, and an annual carbon rental fee is paid to each landowner who stores carbon. The baseline in this paper is the level of carbon that would have been stored if carbon rental payments were zero. This baseline has a dynamic path over time as landowners in different regions move land in and out of forestry and as they change management practices. This specific baseline is arbitrary. International negotiations might determine an alternative baseline such as the carbon in the biosphere at a specific moment or no carbon at all. Choosing alternative baselines should not affect the efficiency of sequestration as long as the choice does not limit sequestration actions or the land base. The choice of baseline, however, defines a property right in carbon. The choice of baseline will consequently matter to countries, as it will define their wealth. Clearly alternative baselines should be explored so that international negotiators understand what is at stake.

In this paper, we are interested in maximizing the present value of timber and carbon benefits. Carbon stored in forests is a function of the total biomass, which is in turn a function of the area of forests, the age of forests, and management. While we keep track of all these components in our empirical model, for presentation purposes we only show carbon stocks. Tracking carbon stocks, however, allows us to define the state of the stock of merchantable timber as well because we can convert to merchantable timber stocks using parameters from the literature.

Foresters can increase the stock of carbon in forests to take advantage of carbon rental payments by holding trees longer than their optimal rotation age, by increasing management intensity, by avoiding deforestation, by planting additional forests, and by storing carbon in harvested products. If the stock of carbon in forests is X(t), the equation of motion for our carbon sequestration function is:

(11) $dX/dt = X_L dL/dt + X_m dm/dt + X_a da/dt + \theta Q_t$

The annual supply of carbon then, depends on how land use changes over time (dL/dt), how timberland management changes over time (dm/dt), how the age of timber harvested changes over time (da/dt), and the quantity of timber stored in market products, where θ converts the quantity of timber consumed into carbon stored.

The Hamiltonian for this problem can be written as

(d 12)

$$J = B_F\left(Q(a(t), m(t), L(t))\right) + B_X\left(X\left(a(t), m(t), L(t), Q(t)\right)\right) - C_m\left(m(t), L(t)\right) - C_L\left(L(t)\right)$$

$$- \mu(t)\left\{X_L\, dL/dt + X_m\, dm/dt + X_a\, da/dt + \theta Q(t)\right\}$$

Solving the Hamiltonian, one derives a set of first order conditions for the timber market and for carbon sequestration:

(13) $B_F' dQ/dL + B_X' dX/dL - C_m' dL - C_L' dL = \mu(t)[dX/dL + \theta\, dQ/dL]$

(14) $B_F' \, dQ/dm + B_X' \, dX/dm + C_m' dm = \mu(t)[dX/dm + \theta \, dQ/dm]$

(15) $B_F' \, dQ/da + B_X' \, dX/da = \mu(t)[dX/da + \theta \, dQ/da]$

(16) $dB_X/dX = r\mu(t) - d\mu/dt$

Equations (13), (14), and (15) describe how forest decisions should change over time to take into account carbon consequences. $\mu(t)$ is the shadow value of removing an additional unit of carbon from the atmosphere and storing it in the terrestrial biosphere or markets. The left hand side of (13) is the net marginal benefit of an additional hectare of land in forests. Benefits accrue as markets harvest additional forests and as forests store additional carbon. Costs are incurred however in planting and renting land. Net marginal benefits are set equal to the shadow value of carbon times the change in carbon associated with an additional hectare of land. The change in carbon occurs as additional hectares are added and as carbon is stored in marketed products. Similar conditions occur for management intensity and increasing rotation ages (equations 14 and 15). The annual rental value of an additional ton of carbon stored is $dB_X/dX = R(t) = r\tau(t)$. Equation (16) shows that the shadow value of carbon in timber stocks is larger than the carbon tax from the integrated assessment model because landowners gain benefits from timber in addition to carbon.

In this paper, we assume that a global institution pays an annual rent for storing carbon in forests. We pay all landholders this rental fee whether or not they would have stored carbon anyway. Actual carbon sequestration programs will have to decide whether to pay for every ton stored, to pay for just the additional tons stored over business as usual, or to regulate that the carbon must be stored by the landowner. This is a property rights question that can only be resolved through international negotiation. As long as all the additional tons of carbon are stored, the program will be efficient regardless of the property rights. However, choosing the property rights for the program will make a large difference to the governmental costs of the sequestration program, the wealth of forest landowners, and the wealth of forested nations.

The optimal decision to harvest and plant is changed to encourage more forestland as a way of reducing atmospheric carbon. Note that if land in trees were increased but the additional land was not allowed to be used for timber, the carbon storage in biomass benefits would remain but the benefits from storing carbon in the economy would disappear. Carbon intensity is increased in order to get more carbon in standing forests and to get more carbon into the economy. Increasing rotation lengths will increase the amount of carbon stored per hectare. Depending upon the importance of storing carbon in the economy, rotation lengths may go up or down. All of the carbon incentives rise as the price of carbon increases.

The strategy encourages deviations from the "business as usual" forest plan by renting additional carbon at R(t). The business as usual plan is the optimal forest plan in the absence of carbon payments. In most developed countries, forestland is expected to increase as these countries abandon low productivity agricultural lands. In many developing countries, forestland is expected to fall as forests are cut down, and often burned, to make way for agriculture. We measure the effectiveness of the program in terms of carbon stored over and above business as usual. Because the baseline is designed to be optimal in the absence of carbon damages, all deviations for storage are costly. The planner must decide whether the carbon benefits warrant the additional sequestration costs.

To give the reader a better sense of how these sequestration plans work for a marginal hectare, the results above are presented for a single hectare of land. The volume of timber on a marginal hectare depends upon its age and management intensity, V(a,m). The present value of this hectare starting from bare land is:

(17) $$W(a,m) = \frac{\left[P(t)V(a,m)e^{-ra} - C_m(m)\right]}{\left(1 - e^{-ra}\right)}$$

The optimal rotation age can be calculated by taking the derivative of (17) with respect to harvest age, a. The resulting first order condition is the familiar Faustmann equation:

(18) $$P(t)\frac{dV}{da} + \frac{dP}{da}V(a,m) = rP(t)V(a,m) + rW(a,m)$$

If we assume that the amount of carbon stored in the growing forest each year is αV(a,m), and the amount of harvested carbon stored in the economy is θV(a,m), then the new objective function for this marginal hectare is:

(19)

$$W^C = \left\{ \frac{\left[P(t)V(a,m) + \tau(t)\theta V(a,m)\right]e^{-ra} - C_m(m) + \int_0^a R(n)\alpha V(n,m)e^{-rn}dn}{1 - e^{-ra}} \right\}$$

Note that all prices can vary over time in this analysis. Taking the derivative of (19) with respect to harvest age a, and rearranging yields:

$$(20)\qquad P(t)\frac{dV}{da}+V(a,m)\frac{dP}{da}+\theta V(a,m)\frac{d\tau}{da}+\tau(t)\theta\frac{dV}{da}+R(t)\alpha V(a,m)=$$
$$rP(t)V(a,m)+rW^{C}+r\tau(t)\theta V(a,m)$$

Compared to (18), the first two additional terms on the left hand side of (20) capture the increased value of carbon stored in the economy. The last term on the left hand side of (20) captures the value of carbon stored in the biosphere. Given that the rental value of carbon is expected to increase, all three additional terms suggest that there are benefits to lengthening the rotation period. The last term on the right hand side of (20) reflects the opportunity cost of lengthening the rotation. By postponing future rotations, the additional benefits of storing more carbon in the economy are postponed. Ignoring the increase in the shadow price, the storage of carbon in the economy has a similar effect on rotation lengths as an increase in the price of timber. The fact that the shadow price of carbon is likely to rise, however, tends to lengthen the rotation. Carbon storage in the biosphere will lengthen rotations as long as the marginal growth rate is greater than the average growth rate. The value of the extra growth, $R(t)\alpha V(a,m)$, will exceed the opportunity cost of postponing future rotations captured by rW^{C}. In general, renting carbon will tend to increase rotations, although the exact size of the effect for each species will depend on timber and carbon prices, as well as empirical parameters for α and θ for each species.

Because we measure the carbon stored in the biosphere each year, we use the annual rent for carbon, not the permanent removal of a ton of stock. The sequestration literature has often confused the value of the stock stored in the biosphere with the rent on that stock, e.g. it has often confused τ(t) with R(t). The literature has consequently underestimated the cost of carbon sequestration in the biosphere by 1/r, or by about twenty times.

One can also store carbon by increasing management intensity. Managers can increase the quantity of timber and carbon on a site by choosing to regenerate timber more intensively. Taking the derivative of (19) with respect to m and equating to zero yields:

$$(21)\qquad \left(P(t)\frac{dV}{dm}+\tau(t)\theta\frac{dV}{dm}\right)e^{-ra}+\int_0^a\left[R(n)\alpha\left(\frac{dV}{dm}\right)\right]e^{-rn}dn=\frac{dC}{dm}$$

Valuing carbon increases the incentive to intensify forest management. Both the flow of carbon into the economy and the storage in the biosphere increase with increased intensity.

A final management option for increasing carbon is to convert agriculture to forests. Over the last several hundred years, most land use conversion has taken the opposite tack as forestland has been converted to farmland. In low latitude countries, it is predicted that conversion of forestland into farmland will continue into the near future whereas in mid-high latitude countries the amount of agricultural land is expected to stabilize in the baseline scenario. Land use change for carbon will consequently involve reforestation in mid-high latitude countries and, at least initially, reducing deforestation in low-latitude countries. Rearranging (19) to take into account a single rotation yields:

$$(22) \quad \mathrm{W}^{\mathrm{CR}} = \left(P(t)V(a,m) + \tau(t)\theta V(a,m)\right)e^{-ra} - C_m(m) + \int_0^a R(n)\alpha V(n,m)e^{-rn}\,dn - C_{LA}$$

Equation (22) evaluates reforestation and treats the opportunity cost of the land as agriculture, C_{LA}. The longer the rotation is extended, the further future agriculture is postponed. The carbon stored in the biosphere and the carbon stored in the economy both add to the value of forestry over agriculture suggesting an additional incentive for reforestation.

A similar formula applies to preventing deforestation. In modern times, most deforestation is occurring in low latitude tropical countries in mature forests. Many of these forests become accessible due to road construction and migration. Our empirical model reflects the costs of this access, so we adjust equation (22) to reflect these empirical considerations for this type of deforestation. While we still consider a marginal hectare, each hectare has a specific cost of access (due to proximity to existing roads) that affects the marginal value of timber harvests. As one moves farther from roads, the marginal value of timber declines to 0. Harvests can take place beyond this point if the opportunity costs of agriculture are high enough, although the forest is generally just cut and burned.

Equation (23) represents the value of a single rotation in the tropics:

(23) $W_T^{CR} =$

$$\big((P(t)-AC)V(a,m)+\tau(t)\theta V(a,m)\big)e^{-ra}-C_m(m)+\int_0^a R(n)\alpha V(n,m)e^{-rn}\,dn-C_{LA}$$

In (23) AC is the access cost associated with the marginal hectare under consideration, and $C_m(m)$ is the cost of regeneration, although this is usually 0 due to reliance on natural regeneration in these regions. Close to roads, the marginal value of harvests is likely to be relatively high, and some land will be harvested. Depending on opportunity costs of agriculture, this land may be reforested or converted to agriculture. On marginal hectares where access costs are high and P(t) – AC = 0, land may still be converted to agriculture if

(24) $C_{LA} > \tau(0)\alpha V(a)$

The stabilization of mature forests effectively stores the carbon in the biosphere for all time. One can consequently value this stored carbon at its permanent value at the time of conversion, $\tau(0)$. The primary cost for inaccessible forests is the lost agriculture that the deforestation would have provided. Note that land that would have been left as forest anyway is not counted in this analysis. Such land is part of the baseline. In this analysis, low latitude countries cannot get credit for more than the amount of deforestation that they would have undertaken. If they wish to sequester more carbon than this limit, the countries would have to engage in reforestation.

In the empirical model, the cost of land use change programs depend upon the prices of food and timber. As more and more land is converted from farmland to forest, forest prices will fall and food prices will rise. The sequestration programs will be increasingly expensive as they get larger. Partial equilibrium analyses that fail to capture these general equilibrium price effects will underestimate the cost of sequestering carbon.

III. INTEGRATING THE MODELS

We rely on Nordhaus and Boyer (2000) to determine what carbon prices would have been in the absence of sequestration. Given the assumptions of the RICE model, world population, world GNP, energy consumption, and uncontrolled carbon emissions would follow the path described in Table 1. Growth is assumed to follow a less than exponential path. World population rises to almost 10 billion by 2100 and world GNP climbs to $81 trillion. GDP per capita is projected to increase slowly. CO2/GNP falls over time largely because of falling energy use as a fraction of GNP. Energy use is falling partially because of changes in the makeup of GNP away from manufacturing and towards services and partly from technical change.

Given the abatement cost parameters in RICE, the optimal abatement that the world should follow and the optimal prices in the absence of forest carbon sequestration are shown in Table 2. According to the best guess values for each parameter, the 1990 price of carbon would have been about $5 per ton. This is the present value of damages from a ton of emissions given the stock of carbon in the atmosphere in 1990. In 2000, this price would be $6.75 and would gradually rise to $65 by 2100. The amount of abatement as a fraction of emissions is relatively low. Starting from 4.0% in 2000, the fraction of carbon emissions that should be abated rises to just 10.8% by 2100.

Nordhaus and Boyer (2000) argue that one should take into account the parameter uncertainty in their model. Because the model is nonlinear, this uncertainty increases the expected damages from a ton of carbon. They estimate that the expected value of a ton of carbon under uncertainty would be close to $20 in 1990. We include this uncertainty analysis by constructing a case where the damage function in RICE is multiplied by 4. The resulting model thus begins with a price of $20/ton in 1990. Starting in 2000, the price per ton is $23 and increases to $238 by 2100. The higher price of carbon, in turn, encourages more energy abatement. The fraction of carbon abated starts at 7.2% in 2000 and rises to 18.6% by 2100. We refer to the scenario using expected parameters as the $5 case and the scenario using the uncertainty outcomes as the $20 case.

A dynamic, global forestry model is used to estimate sequestration (Sohngen et al., 1999). For this carbon sequestration problem, the model is expanded to value carbon in addition to timber, as shown above. It is also expanded to include important agricultural and forestry regions where carbon sequestration might occur in subtropical and tropical regions of South America, Africa, and Asia-Pacific. Agricultural land rental functions, $C_L(L(t))$, are specified for each region in the model using parameters in the literature.[i] Carbon storage parameters for α and θ are taken from Sohngen and Sedjo (2000).[ii]

We begin by estimating baseline timber harvests and forest product prices over time, and the quantity of carbon stored in the biosphere when there is no value placed on carbon sequestration. This amounts to maximizing equation (10) assuming that there are no benefits from changing terrestrial carbon. The results for this baseline are consistent with the results presented in Sohngen et al. (1999), although there is additional detail here on land use and forestry in tropical and subtropical regions. This additional detail has little effect on baseline timber prices because these additional regions contribute little to global timber production, although they contribute significant amounts to global deforestation and conversion of land to agriculture. Timber prices rise slightly over time to accommodate a rising demand function for timber products. Supply expands in response to the higher prices resulting in higher management intensity, particularly in emerging subtropical plantation regions. Managed forestland expands slightly but the border with the inaccessible forest does not increase dramatically. The baseline scenario predicts that increases in timber supply will be met largely by increasing intensity in productive regions, not by harvesting substantially more forest in the inaccessible boreal and tropical regions. The inaccessible boreal region will remain wilderness. The inaccessible tropical region will remain under pressure to convert to farmland, and these conversions are measured in the baseline.

The amount of carbon stored in the system under baseline conditions is a function of the inventory at each point in time as well as the carbon stored in the timber market itself. The model predicts current global carbon storage in the biosphere is 811 billion metric tons, which is consistent with recent estimates (Brown, 1998).[iii] Over the next century, we predict that this amount declines to 766 billion metric tons, or by and average of 450 million metric tons per year. Nearly all of this loss is predicted to occur in the tropics, with the temperate zone remaining stable.[iv]

We measure the carbon stored in timber market products: buildings, furniture, and dumpsites. We predict that over the next 100 years, timber markets will store an additional 16 billion metric tons, or approximately 157 million metric tons per year. There are few global estimates of future market storage to which to compare this estimate. However, US consumption is approximately 26% of global forest product consumption (FAO, 1999). Assuming this remains constant, the US will store approximately 41 million metric tons per year in forest products and waste dumps over the next 100 years. This is slightly lower than Heath et al.'s (1996) prediction of 45 million metric tons per year and Skog and Nicholson's (1998) prediction of 68 million metric tons per year. Both of these studies suggest larger increases in US consumption over the next 50 years than our estimate.

In order to integrate the two models of carbon control, we begin with the price solution to the greenhouse gas model without sequestration. Using these prices for carbon in the forest model, we calculate the amount of sequestration that the forest model predicts would occur. We then estimate a reduced form supply model from these results that predicts the amount of carbon sequestered at each price (equation 9). This reduced form model is entered into the greenhouse gas model and the problem is resolved. Through several iterations, it was possible to determine a solution consistent with both models. Both models are estimated in 10-year time increments.

The solutions for the \$5 and \$20 scenarios are displayed in Table 2. In the \$5 scenario, starting in 2000, the global forest sequesters increasing amounts of carbon from 16 billion metric tons by 2050 to 48 billion tons by 2100. In the \$20 scenario, the forest sequesters 47 billion tons by 2050 and 128 billion tons by 2100. Both storage paths increase over time as the price incentive rises and also as sequestration programs have time to reach full capacity (i.e. trees grow on agricultural land that is converted to forestland). The end-of-century estimates of global carbon storage for the \$20 scenario are similar to the potential estimates in the literature (IPCC, 1996; IPCC, 2000).

However, this analysis predicts that it takes the high end-of-the-century carbon prices of the $20 scenario ($201 per ton) to warrant using this potential. The marginal cost of carbon sequestration is much higher than the literature reports.

With sequestration added to the model, carbon prices do not rise as quickly as before (see Table 2). Instead of reaching $65 by 2100 in the $5 case, adding sequestration lowers carbon prices to $61. In the $20 case, carbon prices only rise to $201 by 2100 instead of $238. This lower level of prices reduces the amount of abatement in the energy sector. Thus, although sequestration has set aside 48 billion tons by 2100 in the $5 case, carbon in the atmosphere is reduced only by 29 billion tons. In the $20 case, carbon in the atmosphere is reduced by only 72 billion tons even though the forest has sequestered 128 billion tons by 2100.

The largest gains in carbon storage occur in tropical forests in the low latitudes (Table 3). In the $5 scenario, 74% of the carbon stored by 2100 is in tropical forests. In the $20 scenario, 63% of the carbon stored by 2100 is in these low latitude tropical forests. The sequestration model chooses optimal strategies in each time period so that these gains initially result from reductions in deforestation of tropical rainforests. Later, they arise from reforestation efforts, first on degraded agricultural lands, and then on more highly valued agricultural land in subtropical regions. Reducing deforestation in the tropics has more immediate effects on carbon sequestration because it leaves mature, often old growth, standing forests that would have otherwise been cut. As carbon prices rise, the value of reforestation in the tropics becomes high, and there are large additional flows of land into forests in these regions.

One major component in sequestration is land use change (Table 4). The $5 path encourages an additional 491 million hectares to be converted to forests by 2100 and the $20 path encourages an additional 1,052 million hectares. The changes in land use in the $20 scenario mirror other global estimates (IPCC, 1996; IPCC, 2000). In low latitude regions, initial efforts are reduced deforestation and later efforts involve planting new forests. In mid to high latitude regions, efforts focus almost entirely on planting new forests. Planting efforts are small when carbon prices are low, but they intensify as carbon prices rise.

Comparing Tables 3 and 4, one can see differences in the regional distribution of new land versus new carbon. In the $5 scenario, the temperate forest initially accounts for 75% of the new land devoted to forests but only 35% of the carbon. Temperate forests appear to have little effect at first because it takes a long time for the long-lived temperate species to accumulate large amounts of carbon. In tropical forests, on the other hand, carbon intensities in standing forests are large, and it does not take large reductions in deforestation to increase sequestration. Because the optimal program responds by balancing land opportunity costs with future forest and carbon values (equation 22), the policy in temperate zones concentrates in northern regions and marginal southern regions where land opportunity costs are relatively low. In North America, for example, 32% of the land conversion occurs in northern softwoods, 25% occurs in temperate deciduous forests, 25% occurs on mixed softwoods and hardwoods in the south, and only 8% occurs on high value southern plantations.

Timber harvests fall initially and prices rise (Table 5). Initial programs pull old-growth forests out of potential production, lengthen rotations, and invest in immature stands that do not contribute to production. In both scenarios, timber prices are predicted to rise at first as timber is withdrawn from the market, although the effect is much larger in the \$20 scenario. Over time, the stock of forest grows, and this supports higher harvest levels. By the end of the century, harvests increase by 445 million cubic meters in the \$5 scenario and 788 million cubic meters in the \$20 scenario, or approximately 20 to 35%.

The regional distribution of harvests changes as a result of the carbon program. While the high prices of carbon convert many tropical forests into conservation forests that are not harvested at all, substantial forestland is added and rotations are increased. Overall harvests therefore rise in tropical regions in the long run, even though the hectares of forestland harvested per year declines. The exception is the Asia-Pacific region, which has relatively high carbon intensities. Tropical harvests increase by 146 million m^3 per year in the \$5 case and 172 million m^3 in the \$20 case. Harvests increase in the temperate zone by 299 million m^3 in the \$5 scenario and by 616 million m^3 in the \$20 scenario.

In the long run, 69% of the carbon stored comes from land use change, 24% from lengthening rotations, and 5% from increased management intensity. These percentages vary regionally. For example, in the low latitudes, most of the carbon storage is from setting aside forests as carbon conservation areas. In contrast, extending rotation ages and management intensity are relatively more important in mid-high latitude regions. By 2100, land use change accounts for 41% of carbon gains, extending rotation ages 47%, management 9%, and market storage 1% in the mid-high latitudes. While land use is clearly important, focusing solely on land use misses a number of important low cost alternatives. Studies that consider only land use changes miss a large part of potential sequestration, particularly in the mid to high latitude regions. In contrast, the inclusion of carbon in market products does not appear to be very important.

Increases in the rotation age play a surprisingly important role in carbon sequestration. Some forests, especially in the low latitude countries, are simply never harvested. Other forests remain part of the market inventory but their rotation lengths are extended beyond the Faustmann rotation to allow more stock to accumulate. Over time, as carbon prices rise, the optimal rotation age rises, particularly in species that can contribute significant carbon sequestration. The exact change in harvest for each species differs, depending on the initial age distribution and the relative proportions of additional growth stored in the forest versus the market. For example, rotation lengths for a number of species shrink initially in Europe because they are currently managed as relatively old timber stocks that are already close to maximum sustained yield. Higher prices in early periods induce managers of these relatively older stocks to sell some forests earlier.

Management intensity helps store carbon by increasing the stocking density of stands. Initially, management intensity has only a minimal effect. Over time, its importance increases, but even by 2100, management intensity contributes only about 5% to global carbon storage in the $20 scenario. This effect is relatively small compared to land use and extending rotations because increased intensity is reserved for productive plantations and because it takes several decades for management gains to have noticeable effects.

IV. 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 must be coordinated with the greenhouse gas mitigation programs in other sectors.

The optimal control model for greenhouse gases suggests that the rental price of carbon rises over time in response to the rising stock of greenhouse gases. This in turn suggests that the incentives to increase forestland area, rotation lengths, and management intensity should rise over time. The marginal cost of sequestration should be equated with the marginal cost of abatement in the economy. Because the price of carbon is rising over time, sequestration activities should increase over time, implying a dynamic program.

Empirical estimates are provided for forestry by using an empirical model of global timber markets. Two scenarios for the optimal price path for carbon sequestration are explored. Using the expected value of parameters leads to a carbon price path beginning at \$5 in 1990 but using the expected outcome of uncertain parameters leads to a higher price path starting at \$20. Given each scenario, optimal greenhouse gas and sequestration programs are estimated. 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 between 48 and 128 billion metric tons of carbon would be sequestered in global forests for the $5 and $20 scenarios respectively by 2100. Most of this gain is predicted to occur near the end of the century when the price of carbon is high. Approximately 65% of the sequestration occurs in tropical forests and 35% in temperate and high latitude forests. Despite these relatively large gains in carbon sequestration in forests, carbon in the atmosphere declines less because carbon prices fall and energy abatement is reduced. The net reductions in atmospheric carbon are 29 billion tons in the $5 case and 72 billion tons in the $20 case.

With forest sequestration, carbon prices fall from $65 to $61 by 2100 in the $5 case. In the $20 case, prices fall from $238 to $201 by 2100. The change in the $5 scenario is quite small, implying climate change damages would be slowed by approximately 4 years because sequestration is included. That is, in the scenario without sequestration, prices would reach $61 in 2096. The change in the $20 scenario is more substantial. The scenario without sequestration would reach $201 in 2087. Having a sequestration option buys a 13 year slow down in damages over a century. Note that the reduction in damages is less than the reduction of the stock of carbon in the atmosphere. The stock of carbon in 2100 is 1033 with sequestration. Without sequestration, the stock would have reached this level by 2070, implying sequestration purchased a 30 year slow down of stock accumulation. However, the slower accumulation of stock allows temperatures to catch up to stocks more quickly, so that the temperature and therefore damage gains from sequestration are smaller than the stock reductions.

The two most important factors in carbon sequestration are land use and lengthening rotations. Reduced deforestation and afforestation are most important in tropical regions, while afforestation is important in temperate regions. However, the bulk of carbon sequestration is expected to occur in the tropics, a result that is consistent with a number of other studies (IPCC, 1996). However, the results also indicate that lengthening rotations, and even creating conservation forests, is also quite important. Most of these conservation areas occur in tropical forests. In the temperate zone, the market value of the forests is too high to convert them to conservation forests but the rotation lengths are nevertheless increased. Management intensity plays only a small role in supplying carbon because it is less effective at carbon storage and it is costly. Storing carbon in market products appears to be a minor influence.

The study finds that carbon sequestration is more expensive than previously thought. There are two explanations. First, much of the literature has equated temporary storage of carbon in sequestration with the removal of a unit of carbon emission in the energy sector. This causes underestimation of the cost of carbon sequestration. For example, the Second Assessment Report of the Intergovernmental Panel on Climate Change estimated the costs of carbon sequestration in forests to be only \$3-7 per ton (IPCC, 1996). Second, the literature has not considered the effect of global sequestration programs on timber prices and the price of land. For instance, Stavins (1999) (who deals with the first problem) estimates that the marginal cost for a US program that sequesters 518 million tons per year over 90 years is \$136 per ton of discounted carbon. That study considers only land use changes, and it extrapolates timber growth rates for the Southern US to the entire country. This study accounts for differences in regional carbon intensity, and how changes in timber and land prices from global sequestration programs affect carbon storage on the land or in markets. At a price of $136 per ton in this study, increasing forestland alone accounts for only around 164 million tons in North America by 2100. Changes in land rent and carbon intensity are important if one is considering a large sequestration program.

This study suggests that sequestration could be an important component of controlling greenhouse gases depending upon how important climate change turns out to be. If damages turn out to be relatively low ($5 or less/ton) as recent studies suggest (Mendelsohn and Neumann, 1999; Mendelsohn, 2000), then sequestration has little effect. In this case, it may not be worth having a sequestration program given the difficulties associated with implementing such a program. However, if climate change is more harmful than expected (the $20 scenario), then a sequestration program should be implemented, because it will make a substantial difference. Note that the current Kyoto targets are more ambitious abatement targets than even the $20 scenario recommends. Thus, if the world decides that climate change is important enough to meet the Kyoto targets, a sequestration program should be implemented.

Although this paper models many effects not previously considered in the literature, there are many improvements that remain to be made. The sequestration model does not treat the effect of climate change on forests. Some authors suggest that forests will act as a net sink during climate change (Prinn et al., 1999), while others suggest that forests will act as a source during climate change (King and Neilson, 1992; Smith and Shugart, 1993; and Solomon and Kirilenko, 1997).   Although Sohngen et al (2000) explore what will happen to global forests as climate changes from rising greenhouse gases, the dynamic adjustment of ecosystems and human management to climate change could affect the cost of carbon sequestration. This study also does not explore the costs of administering a sequestration program. Because land use has traditionally been of only local concern, there could well be substantial costs and problems associated with creating a global land use program. This study does not include interaction effects with other sectors such as energy and agriculture. The study does not explore the role that technical change might play in future outcomes. Finally, this study does not address the myriad of goods and services that emanate from forests. Many of these flows would be affected by sequestration programs and the resulting costs and benefits should be included in the analysis. The paper makes a contribution towards designing an optimal sequestration program. However, we fully expect future research to refine these estimates.

REFERENCES

Adams, R. M., D. M. Adams, J. M. Callaway, C. C. Chang and B. A. McCarl. 1993. Sequestering Carbon on Agricultural Land: Social Cost and Impacts on Timber Markets. *Contemporary Policy Issues*. 11: 76-87.

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.

Alig, R.; Adams, D.; McCarl, B.; Callaway, J.M.; and Winnett, S. 1997. Assessing effects of carbon mitigation strategies for global climate change with an intertemporal model of the U.S. forest and agriculture sectors. *Environmental and Resource Economics*. 9: 259-274.

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.

FAO. 1999. State of the World’s Forests, 1999. United Nations Food and Agricultural Organization. Rome, Italy.

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.*

Heath, L.S.; Birdsey, R.A.; Row, C.; and Plantinga, A.J. 1996. Carbon pools and fluxes in U.S. forest products. *NATO ASI Series I* 40: 271-278.

Hoen, 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.

King, G.A. and Neilson, R.P. 1992. The transient response of vegetation to climate change: A potential source of CO2 to the atmosphere. *Water, Air, and Soil Pollution.* 94: 365-383.

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

McCarl, B.A., and U. Schneider. 2000b. Economic Potential of Biomass Based Fuels from Agricultural Sources. *Proceedings of Conference Sustainable Energy: New Challenges for Agriculture and Implications for Land Use*. Wagenengin, the Netherlands. Edited by E. van Ierland, A. Oude Lansink and E. Schmieman.

Mendelsohn, R. (ed). 2001. Global Warming and the American Economy: A Regional Assessment of Climate Change. Edward Elgar Publishing, UK.

Mendelsohn, R. and J. Neumann (eds). 1999. The Impact of Climate Change on the United States Economy. Cambridge University Press, Cambridge, UK. 331 pp.

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

Plantinga, A.J. and Birdsey, R.A. 1993. Carbon Fluxes Resulting From U.S. Private Timberland Management. *Climatic Change.* 23: 37-53.

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.

Prinn, R.; Jacoby, H.; Sokolov, A.; Wang, C.; Xiao, X.; Yang, Z.; Eckhaus, R.; Stone, P.; Ellerman, D.; Melillo, J.; Fitzmaurice, J.; Kicklighter, D.; Holian, G.; and Liu, Y. 1999. Integrated global system model for climate policy assessment: Feedbacks and Sensitivity Studies. *Climatic Change.* 41: 469-546.

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.

Skog, K.E. and G.A. Nicholson. 1998. Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. *Forest Products Journal.* 48(7/8): 75-83.

Smith, T.M., and H.H. Shugart. 1993. The Transient Response of Terrestrial Carbon Storage to a Perturbed Climate. *Nature* 361: 523-526.

Sohngen, B. and R. Mendelsohn. 1998. “Valuing The Market Impact of Large-Scale Ecological Change: The Effect of Climate Change on US Timber", *American Economic Review.* 88: 686-710.

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., R. Mendelsohn, and R. Sedjo. 2000. Measuring Climate Change Impacts with a Global Timber Model. Working Paper. Department of Agricultural, Environmental, and Development Economics. The Ohio State University.

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.

Solomon, A.M. and AP Kirilenko. 1997. Climate change and terrestrial biomass: what if trees do not migrate? *Global Ecology and Biogeography Letters.* 6: 139 - 148.

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: Underlying Growth Model

Year	Population Billion	GNP Trillion $$	CO2/GNP Ton/Million $	Uncontrolled Carbon Emissions Gigatons/yr
2000	6.1	25.9	258	6.7
2010	6.8	32.7	230	7.5
2020	7.5	39.1	209	8.2
2030	8.0	45.1	194	8.8
2040	8.5	50.8	184	9.3
2050	8.9	56.1	176	9.9
2060	9.2	61.2	170	10.4
2070	9.4	66.2	166	11.0
2080	9.6	71.1	163	11.6
2090	9.8	77.0	161	12.2
2100	9.9	81.0	159	12.9

From Nordhaus and Boyer, 2000.

Table 2: Carbon Prices and Control With and Without Sequestration

PANEL A: $5 Scenario

	Without Sequestration		With Sequestration		
Year	Carbon Price $$/ton	% Control	Carbon Price $$/ton	% Control	Sequestration Billion Tons
2000	6.8	4.0	6.8	4.0	0.0
2010	9.2	4.8	9.1	4.8	2.7
2020	12.5	5.6	12.4	5.6	5.1
2030	16.8	6.3	16.5	6.3	8.1
2040	21.9	7.1	21.3	7.0	11.8
2050	27.7	7.7	26.8	7.6	16.2
2060	34.1	8.4	32.9	8.3	21.2
2070	41.1	9.0	39.4	8.9	27.0
2080	48.5	9.7	46.3	9.5	33.3
2090	56.4	10.3	53.6	10.0	40.1
2100	64.6	10.8	61.1	10.5	47.5

PANEL B: $20 Scenario

	Without Sequestration		With Sequestration		
Year	Carbon Price $$/ton	% Control	Carbon Price $$/ton	% Control	Sequestration Billion Tons
2000	23.3	7.2	23.3	7.2	0
2010	32.7	8.3	32.1	8.2	7.9
2020	45.7	9.4	43.9	9.3	15
2030	62.1	10.7	58.3	10.4	23.9
2040	81.3	11.9	74.9	11.5	34.5
2050	103.2	13.1	93.3	12.5	46.8
2060	127.1	14.3	113.0	13.5	60.6
2070	152.9	15.5	133.8	14.5	75.8
2080	180.2	16.5	155.4	15.4	92.1
2090	208.6	17.6	177.8	16.2	109.4
2100	238.1	18.6	200.7	17.0	127.6

Table 3: Carbon sequestered over time. Change all the remaining tables to reflect new data from integrated model

	$5 Scenario			$20 Scenario		
	2010	2050	2100	2010	2050	2100
	Billion Metric Tons Carbon					
Carbon Price ($ per ton)	$6.80	$26.80	$61.10	$23.30	$93.30	$200.70
Mid - High Latitudes						
North America	0.4	1.7	4.5	0.8	5.4	19.9
Europe	0.0	0.7	1.7	0.1	1.8	6.1
Former Soviet Union	0.5	1.5	4.2	1.7	3.4	10.6
China	0.1	0.4	1.4	0.2	1.4	8.2
Oceania	0.0	0.2	0.5	0.1	0.5	2.0
Low Latitudes						
South America	0.9	4.5	13.2	2.1	12.3	28.8
India	0.0	0.0	0.2	0.0	0.2	1.2
Asia-Pacific	0.5	3.8	11.9	1.7	12.2	26.9
Africa	0.4	3.3	10.1	1.1	9.5	24.0
Total	2.7	16.2	47.5	7.9	46.8	127.6

Table 4: Change in forestland cover over time.

	$5 Scenario			$20 Scenario		
	2010	2050	2100	2010	2050	2100
	Million Hectares Above Baseline					
Carbon Price ($ per ton)	$6.80	$26.80	$61.10	$23.30	$93.30	$200.70
Mid - High Latitudes						
North America	11.7	28.8	48.1	39.3	89.7	134.8
Europe	11.0	13.9	26.6	24.4	44.0	71.4
Former Soviet Union	24.7	67.3	86.0	75.0	115.7	145.3
China	6.7	12.4	24.9	16.8	42.7	68.7
Oceania	1.6	3.0	4.6	4.4	10.1	22.7
Low Latitudes						
South America	6.9	35.0	124.4	24.3	142.2	238.2
India	0.1	1.4	5.0	2.0	10.5	19.9
Asia-Pacific	6.7	30.7	62.7	26.0	92.4	148.4
Africa	4.5	28.7	108.1	14.6	139.6	202.8
Total	73.8	221.3	490.6	226.9	686.9	1052.1

Table 5: Change in regional timber harvests over time.

	$5 Scenario			$20 Scenario		
	2010	2050	2100	2010	2050	2100
			Million m^3 per year			
Carbon Price ($ per ton)	$6.80	$26.80	$61.10	$23.30	$93.30	$200.70
Mid - High Latitudes						
North America	(27.6)	84.5	132.0	(57.1)	189.0	303.3
Europe	(8.0)	(26.7)	41.8	(29.2)	(15.3)	142.3
Former Soviet Union	0.6	(18.7)	119.5	(6.5)	(12.5)	41.0
China	(2.5)	4.3	(15.3)	(33.5)	(26.4)	42.2
Oceania	0.3	17.1	20.5	1.7	35.2	86.9
Low Latitudes						
South America	(0.5)	57.3	62.0	(12.7)	94.7	138.2
India	0.3	(15.3)	7.2	1.2	(12.5)	79.0
Asia-Pacific	(10.5)	(13.1)	65.5	(37.5)	(3.8)	(62.5)
Africa	4.7	(7.5)	11.5	(3.3)	27.5	17.8
Total	(43.0)	82.0	444.8	(176.9)	276.1	788.3

Endnotes:

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[i] A number of studies provide information on elasticity of land supply in forestry for North America. Hardie and Parks (1997); Plantinga et al. (1999); and Stavins (1999) suggest that forest land supply is relatively inelastic with respect to changes in rental rates. For that region, our elasticity estimates range from .01 to .26. Elasticity estimates are harder to obtain for other regions around the globe. For South America, we use 0.26. For Western Europe, we use 0.6 – 0.8. While Europe looks very elastic, European forests are already managed in long rotations, and it takes large shifts in timber or carbon prices to substantially change forestland rental rates. The remaining regions are: Former Soviet Union = 0.01; China = 0.14; India and Oceania = 1.0; Asia-Pacific = 0.14 – 0.35; Africa = 0.26 – 0.35.

[ii] α and θ are expressed as tons per cubic meter of merchantable timber. α captures both carbon in above and belowground biomass, as well as soil carbon. When land is converted to forests, soil carbon accounts only for net gains above pre-existing soil conditions, which are assumed to be consistent with agricultural soil carbon storage. θ captures the proportion of harvested timber stored in timber products, which will depend on how the timber is used. A number of authors have pointed out that this carbon stock will change over time as carbon decays (see Plantinga and Birdsey, 1993 and Stavins, 1999 for example). θ is thus the proportion that is initially stored, 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).

[iii] IPCC (2000) predicts larger total storage in forest ecosystems: 1146 billion metric tons. The difference arises from boreal and temperate regions, where we exclude some inventories due to high access costs. Sensitivity analysis indicates that these inventories are not harvested even under extreme price scenarios.

[iv] IPCC(2000) predicts that net carbon emissions from forests range from 1200 to 1600 million metric tons per year over the next 10 years. Over the next 10 years, our estimates predict approximately 530 million metric tons per year. We predict less deforestation in general than the IPCC.