POTENTIAL CARBON FLUX FROM TIMBER HARVESTS AND MANAGEMENT IN THE CONTEXT OF A GLOBAL TIMBER MARKET *

April 23, 1999

Brent Sohngen
Department of Agricultural Economics
The Ohio State University
2120 Fyffe Rd.
Columbus, OH 43210-1067
614-688-4640
sohngen.1@osu.edu

Roger Sedjo
Resources For the Future
1616 P Street, NW
Washington, D.C. 20036
202-328-5065

* This research was funded by the Department of Energy and Resources For the Future. The authors thank Robert Mendelsohn, Linda Heath, Richard Birdsey, and an anonymous reviewer for comments, although the authors remain responsible for any errors.

POTENTIAL CARBON FLUX FROM TIMBER HARVESTS AND MANAGEMENT IN THE CONTEXT OF A GLOBAL TIMBER MARKET

ABSTRACT

This paper presents carbon flux estimates arising from the effect of increasing demand on harvests and management of industrial forests in a global timber market. Results are presented for specific regions and the globe. Harvests and management of forests is predicted to store an additional 184 Tg (1 Tg = 10^{12} grams) of carbon per year in forests and wood products over the next 50 years, with a range of 108 to 251 Tg per year. Although harvests in natural boreal and tropical forest regions will cause carbon releases, new plantation establishment in subtropical emerging regions more than offsets these losses. Unlike many existing studies, these results suggest that harvests and management of North American forests will lead to carbon emissions from that region over the next 50 years. The results are quantitatively sensitive to the assumed growth in demand although the results are qualitatively similar in the sensitivity analysis.

KEYWORDS: Carbon flux, climatic change, timber market, plantations.

INTRODUCTION

As policy makers and researchers continue to develop institutions to address the possibility of climate change, researchers have focused on developing estimates of future carbon emissions (for example, see Houghton et al., 1996). One component of future carbon emissions is the net flux of carbon to or from forests. Because of the large inventory of carbon stored in forests, and the potentially large flux of carbon if the forest inventory changes, many researchers have attempted to estimate past, current, or future forest carbon emissions. Carbon flux from forests may arise from a wide range of stressors, disturbances, or land management practices. Dixon et al. (1994), for example, examine the effects of tropical deforestation, Sedjo (1992) and Kauppi et al. (1992) address afforestation on old agricultural lands in termperate regions, and Kurz et al. (1995) and Dixon and Krankina (1993) consider natural fire disturbance.

While many of these studies have focused on past or current forest carbon emissions, other researchers have examined how future demand for timber products is likely to affect future carbon flux through harvests, regeneration, and management (see for example, Plantinga and Birdsey, 1993; Birdsey at al.,1993; Heath and Birdsey 1993; Turner et al., 1994;Turner et al., 1995; and Sohngen et al., 1998). For the United States, which has well-developed timber market modeling methods, these studies have predicted that U.S. forests will sequester 10 - 50 Tg of carbon per year as inventories increase over time. This study builds on the carbon methodologies developed in these previous timber market-carbon studies, but uses a global timber market model (Sohngen et al., 1999) to predict global prices and regional harvests, timberland management, and inventories.

Using a global model is an important improvement because timber prices, harvests, and inventories in any region are a function of global market forces, not just those within a particular region. Thus, if U.S. inventories are predicted to rise, as many of the studies above predict, timber supply will increase, prices will not rise as rapidly as in the past (or they may decline), and other regions in the world will respond by harvesting fewer trees, planting fewer trees, managing their forests less intensively, or even converting more land into agriculture. The global model allows us to determine how inventory management in any one region affects global prices and consequently inventory management and carbon flux in other regions.

Modeling global timber markets, however, requires us to pay attention to issues that other timber market models have not addressed. First, if demand continues to rise and prices increase, markets may expand supply by harvesting forests that are currently inaccessible. The regional models discussed above do not address harvests in these regions, and some global models, such as the Timber Supply Model of Sedjo and Lyon (1990), cannot capture these effects because they treat these forests as non-responsive to global prices. Capturing the economic conditions under which inaccessible forests (which include the boreal forests of Canada and the Soviet Union, and tropical forests near the equator) are likely to be harvested is important because the conversion of old growth forests to younger forests could cause large releases of carbon dioxide over time (see for example Harmon et al., 1990).

Second, if future prices are predicted to rise, landowners will respond by increasing management intensity (Wear, 1994 and Wear and Newman, 1991). Management intensity includes a range of activities, such as the conversion of natural forests to plantations, genetically engineered species, and the establishment of new plantations. Most of the previous timber market-carbon studies in the U.S. use exogenous predictions of management intensity (see Plantinga and Birdsey, 1993; Birdsey at al., 1993; Heath and Birdsey, 1993; Turner et al. 1994; and Turner et al., 1995), while the model employed by this study predicts timberland management endogenously. Further, some global studies of carbon, such as Solomon et al., (1993) and Goldewijk et al. (1994), do not attempt to capture changes in management intensity, and they consequently may underestimate carbon sequestration in forests.

Third, while inaccessible harvests and increasing management intensity are two important sources of increased supply, several global timber studies have suggested that subtropical "emerging" plantation establishment will be an important source of supply in the future (Sedjo and Lyon, 1990, 1996; FAO, 1997; and Sohngen et al., 1999). Recent evidence from FAO (1995) suggests that these regions have already responded to current prices and predicted future supply shortages by establishing quick-growing plantations. These new supplies of timber can have consequences for future carbon flux either directly through the increase in forest biomass (increased forest area) and the subsequent increase in storage of marketable products, or indirectly through global prices and harvests and management elsewhere. The model used in this paper predicts plantation establishment in subtropical regions endogenously in order to capture the effects of this new source of supply on established forests in other regions.

The dynamic timber market model of the world used here predicts how markets adjust harvests in accessible and inaccessible regions, management intensity, and plantation establishment to increasing demand over time (Sohngen et al., 1999). While fuelwood harvests and disturbance regimes (i.e. bug infestations or fires) affect the overall flux of carbon to or from forests, they are not considered in this paper. With these predictions, carbon flux in forested ecosystems and marketed products is calculated and reported. In order to show how future price predictions can have an impact on carbon flux to or from forests, we consider three demand scenarios (baseline, high, and low).

We begin with a discussion of our modeling methods. The paper then presents estimates of global and regional carbon flux from the timber market model. Regional estimates include flux calculations for harvests from northern and tropical inaccessible forests, and subtropical plantation forests. In addition, North American carbon flux is considered in detail to show how predictions from a global timber market model may differ from regional models. Finally, alternative demand scenarios are considered to show that the baseline results are sensitive to alternative assumptions about future demand.

MODELS AND METHODS

Dynamic Timber Market Model of the World

The economic model is a dynamic optimization model of global timber markets that predicts harvests and management in industrial forests in 46 ecosystem and management types in 9 general regions around the globe. The economic theory and empirical results of this model are published elsewhere (Sohngen et al., 1999). Dynamic optimization models like this have been used in forestry economics for a number of years, dating from earlier efforts by Sohngen and Mendelsohn (1998); Adams et al. (1996); Sedjo and Lyon (1996 and 1990); Brazee and Mendelsohn (1990); and Lyon and Sedjo (1983).

In addition to capturing global markets, the model solution techniques used for the model in this paper differ from those used by timber market models in many of the timber market-carbon studies to date (i.e. Plantinga and Birdsey, 1993; Birdsey at al., 1993; Heath and Birdsey, 1993; Turner et al. 1994; and Turner et al., 1995). Sohngen and Sedjo (1998) examined some of these differences in more detail. The model used in this paper equates supply and demand in each period, but it predicts that supply responds to current and future prices. If, for example, prices are predicted to be high in the future, this model predicts that supply will respond today by increasing management intensity. These responses have little effect on supply today, but they do affect future supply.

There are thus three ways in which the results of this paper provide a useful comparison to existing carbon flux estimates from timber market-carbon studies. First, they provide estimates from a different set of models that are accepted in the economic literature. Second, they capture global market interactions. Third, they estimate harvests in industrial forests and inaccessible forests, timberland management intensity, and plantation establishment, all important components of both future supply and carbon flux.

The regions utilized in the model are presented in Table I. The first column of the table presents the initial area of land in industrial forests in each region. These include timberlands that are not excluded from harvests by administrative actions. One exception is the United States, where all National Forest lands have been excluded, whether they are excluded by administrative action or not. This has little effect on price predictions because National Forests have become a small proportion of global timber supply in recent years, and they are expected to remain a small proportion of timber supply in the future. Past harvesting activities on these lands, however, may have a large impact on future carbon flux from National Forests, so that estimates of these carbon fluxes should be added to our results to determine total predicted carbon fluxes for North America. The model also tracks the age class distribution of each hectare of land in the timber inventory over time. Harvest and management of each class are determined within the timber model.

Inventory data was obtained from a variety of sources (table II). Yield function data was determined in one of two ways. First, where data was available, yield functions were estimated. In some regions, however, data was not available, and yield functions were determined using information on current volume estimates and age distribution from forest inventory information. Information for yield functions was obtained from the following sources: Sohngen (1996); Sedjo and Lyon (1990); Backman and Waggener (1991); Kuusela (1994); and Pandey (1992).

Harvesting costs were generally obtained from Sedjo and Lyon (1990). Where harvesting cost data was not available, costs were determined using costs from similar regions in other parts of the globe. Data from US Forest Service (1996) was used to develop access cost functions for building roads in different regions of the US. This data was used to estimate cost functions for other regions of the world with similar terrain and access characteristics. Plantation establishment and regeneration costs were obtained from Sedjo (1983), and Sedjo and Lyon (1990).

Given the importance placed on timberland management and harvests in forests that are currently inaccessible, it is useful to examine in more detail how the model treats these issues. Timberland management involves a wide range of activities that may be used to increase the quantity of merchantable timber on a given hectare. For example, rather than allowing stands to regenerate naturally, land managers may plant new stands in order to increase the number of valuable trees. Alternatively, land managers can plant genetically altered trees, thin stands as they grow in order to increase the size of remaining trees, or prune branches to provide clear wood at harvest time. All of these activities will increase either the quantity or quality (and hence value) of stands when they are mature. These activities, however, come at a cost, and landowners will only engage in them if they believe that future prices are high enough to justify the additional costs. The timber model predicts current management practices based on current and future prices predicted within the model.

As discussed in the introduction, this model predicts harvests of forests that are currently inaccessible. Inaccessible forests are defined as forests that have not been harvested in the past, but which are not restricted from harvest by administrative action (i.e. forests protected as biological or wilderness reserves). These include northern forests such as the boreal forests of Canada, Europe, and Siberia, and some montane forests in the western U.S., Canada, and China. Inaccessible forests typically have low industrial timber yield per hectare and high access, harvest, and transportation costs. As such, timber is only harvested in these regions if the price of a cubic meter of industrial wood is greater than the cost of accessing and harvesting the timber. Stocks in these regions are assumed to remain at steady state unless the economic model harvests them.

When a hectare of inaccessible northern forest is harvested, it enters a new land class, which is then considered accessible; it can be harvested again when the forest matures.

The model also accounts for inaccessible forests in tropical regions of South America and Africa. Like northern inaccessible forests, these forests are assumed to remain at steady state unless they are harvested. As before, harvests in this region occur as long as prices are greater than the costs of harvest. The yield of industrial wood for each hectare of land is low, and the cost of harvesting each cubic meter of industrial timber is typically high. Harvests do occur in this region, however, but they are typically small. Note that we do not attempt to capture land use changes that may arise from conversion of tropical forests to agriculture. While these changes are important, they do not represent a large component of wood products entering timber markets and are therefore not considered.

Tropical forests in the Asia-Pacific region are treated differently. Harvests in that region are assumed to occur in rotations that remove only $1/5^{th}$ of the wood on any hectare harvested. Harvests on forest land in this region occur approximately every 10 years, but they remove only part of the total material available. These cycles depend on prices: If prices are rising rapidly the cycle will speed up, and if prices are rising slowly, it will slow down.

Carbon Flux Model

The carbon flux model keeps track of carbon storage on hectares in the timber inventory described above. Carbon is estimated for four pools: Vegetation, forest floor, soil, and market. Changes in carbon storage between time periods measure flux. Positive fluxes imply that forests or forest products are sequestering additional carbon from the atmosphere, and negative fluxes imply that forests or industrial wood products are emitting carbon to the atmosphere.

The vegetation component of the model consists of carbon stored in live woody material in the forest, including both the tree and understory components. Tree carbon stored on each hectare is calculated as,

(1) $$TreeC_i(a_i(t)) = (\phi_i)(\pi_i)(\omega_i)V_i(a_i(t); m_i(t_h)),$$

where ϕ_i is the ratio of total wood biomass to industrial wood biomass, π_i is the proportion of wood biomass that is carbon, ω_i is the wood density, $V_i(a_i(t); m_i(t_h))$ is the yield of industrial wood per hectare of timber at age class $a_i(t)$ in time t, and $m_i(t_h)$ defines the management intensity of the forest at time t_h. Note that management intensity can shift over time, depending on prices. Management intensity can range from 0 when stands regenerate naturally, to large positive numbers in the case of plantations. This calculation allows for carbon storage to increase as timber ages, taking into account the yield function and management intensity.

The second component of vegetation storage is understory carbon. Carbon accumulates in living woody matter that grows below the canopy in forests. Understory carbon storage is assumed to be 2% of the carbon stored in mature forests (Birdsey, 1992). However, the model accounts for the fact that understory vegetation peaks well before trees age because growing conditions are favorable for understory vegetation early in the succession cycle. The model assumes that understory vegetation attains its maximum in year 10 for all species, and is then stable until harvested. At harvest, understory vegetation becomes 0 and begins growing again. Vegetation carbon at time t for timber of age $a_i(t)$ is given as:

$$(2) \qquad VegC_i(a_i(t)) = TreeC_i(a_i(t)) + UnderC_i(a_i(t)),$$

where $UnderC_i(a_i(t))$ is the storage of carbon in the understory.

Forest floor storage includes detrital matter that accumulates on the forest floor as leaves and branches fall and decay. When a stand is harvested, floor storage is assumed to return to near 0 levels. Carbon begins accumulating on the floor as forests grow in proportion to the yield function for timber. The amount of carbon stored on the forest floor in any year for a hectare of land is:

$$(3) \qquad FloorC_i(a_i(t)) = \frac{V_i(a_i(t); m_i(t_h))}{V_{i,Max}}(\gamma_i)$$

γ_i is the steady state maximum quantity of carbon stored at the forest floor for late successional stands. $V_{i,Max}$ is the yield of late successional forests of type i. Thus, as forests grow, the quantity of carbon stored in detrital matter at the forest floor increases with age to a maximum steady state value for older stands.

Soil storage includes organic matter that accumulates in soil, but does not include storage in roots and other living matter associated with growing trees (these components are included in vegetation as discussed above). Johnson (1992) suggests that harvests do not lead to large quantities of carbon emissions from soils. Some authors, however, include carbon emissions from forests after harvest (see Plantinga and Birdsey, 1993). In order to account for the fact that some carbon may be emitted in the form of soil erosion or other factors, this model assumes that 20% of soil carbon is lost in the first decade after harvest, and that carbon stocks then "regenerate" to steady state levels over time.

For land that is harvested and then regenerates in forests, the initial soil carbon is therefore 20% of the steady state maximum soil quantity, $K_i(T)$ in Table I. Soil carbon then begins to accumulate according to the following logistic growth function:

$$\text{(4)} \qquad \frac{d\text{SoilC}_i(t)}{dt} = (r_i)\text{SoilC}_i(t)\left[\frac{K_i(t) - \text{SoilC}_i(t)}{\text{SoilC}_i(t)}\right]$$

In equation (4), $\text{SoilC}_i(t)$ is the soil carbon in the current year t, r_i is the growth rate of soil carbon, $K_i(t)$ is the steady state level of soil carbon for mature forests of type i.

Note that this model allows $K_i(t)$ to be a function of t. The steady state maximum is assumed to be constant on land that has been in forests for many years. Because some land in this model (i.e. new plantations) is converted from old agricultural land, steady state soil carbon is allowed to adjust from lower to higher levels over time. When land converts to forests from agricultural and grazing land, $K_i(t)$ will rise over several rotations from agricultural levels to the steady state maximum forest levels indicated in Table I. While $K_i(t)$ changes over rotations, it is constant for any given rotation.

The total soil carbon stored on a hectare of land in forests of type i at time t can therefore be calculated by integrating (4) between t_h and t and adding that to the initial soil carbon level:

(5) $$Soil_i C(t) = Soil_i(t_h) + \int_{t_h}^{t} \left(\frac{\mathrm{dSoilC_i}(n)}{dn} \right) dn$$

$Soil_i(t_h)$ is the initial soil level after regeneration (or afforestation in the case of plantations). $Soil_i(t_h)$ is $0.8K_i(T)$ for lands that have been forested for many years. It is set at a regional agricultural or grassland value for lands that have just been converted, and it lies between these two levels for lands that have been converted within the time frame of this model.

If land were to convert out of forests, if prices decline for example, the model allows soil carbon to decay at a rate of 5% per year. This is measured as a net flux of carbon from the forests to the atmosphere. Over time, total net loss in forest carbon is the difference between steady state soil carbon in forests and steady state soil carbon in the new land use, such as agriculture. Under the scenarios examined in this paper, forests are not lost due to timber market price effects, so that these changes are not incorporated.

Market storage of carbon is calculated by tracking annual harvests. As trees are harvested, only some of the wood will be removed from the forest. The wood removed is the merchantable biomass, which is measured by the parameter ϕ_i (the ratio of total wood biomass to merchantable wood biomass). Much of the carbon in merchantable biomass is converted immediately to wood products such as pulp, paper, furniture, or houses, and stored for some period of time. Using data from FAO (1997), we estimate the proportion of harvests in each region which end up in sawnwood and pulpwood products, and use these values to determine into which products harvested timber flows.

Only some of the merchantable timber flows into products, however. Heath et al. (1996) and Plantinga and Birdsey (1993), for example, suggest that between 40% and

58% of merchantable timber is used for end products, while the rest is waste material or is used for energy. The percentage used in end products depends in part on whether the merchantable product is sawnwood or pulpwood. The estimates provided by Plantinga and Birdsey (1993) suggest that approximately 50% of sawnwood harvests and 42% of pulpwood harvests flow immediately into end products.

Over time, these end products will decay into atmospheric carbon. Using the estimates provided by Plantinga and Birdsey (1993) and Heath et al. (1996) for industrial wood products, we estimate that pulpwood products decay at a rate of 1.03% per year, and solidwood products decay at a rate of 0.79% per year. The quantity of carbon stored in wood products can then be tracked through time. The following equation presents a representative equation for carbon stored in pulpwood products ($t-t_h$) years after harvest in time t_h:

$$(6) \qquad PulpC_i(t-t_h) = (0.42)(\pi_i)(\omega_i)Q_{p,i}(t_h)\exp[-0.0103*(t-t_h)],$$

As in equation (1) above, we must account for wood density and carbon storage to determine the quantity of carbon stored in each unit of timber harvested for pulp, $Q_{p,i}(t_h)$, in period t_h.

Note that equation (6) tracks carbon storage in wood products for each year after harvests in the year t_h. To determine the total quantity of carbon stored in the market in a given year, we integrate equation (6) over t_h from the initial time period in the model, t_0 to the current time period t, and add this to the state of the initial stock of carbon in pulp products at time t, $TPWC_i(t_0)\exp[-0.0103t]$. This is:

(7) $$TPWC_i(t) = TPWC_i(t_0)e^{-0.0103t} + \int_{t_0}^{t} PulpC_i(t-n)dn$$

where $TPWC_i(t)$ is the total storage of carbon in pulp wood products at time t harvested from type i. Similar equations can be used to determine the storage of carbon in solid wood products, $TSWC_i(t)$.

With equations (1) – (7), the model tracks carbon storage in all components of forests. Summing carbon stored in the i different types of forests, the model determines the total storage. Since the objective of this paper is to determine carbon flux, carbon storage in successive time periods is compared.

Carbon Model Parameter Values

The parameters used in equations (1) - (7) are shown in Table I. We begin with a discussion of parameters for equation (1). The methods used in this paper for calculating tree carbon storage builds a carbon inventory based on the age class distribution of trees in our timberland base, and the merchantable yield function. The first estimate needed is the ratio of total biomass to merchantable biomass, ϕ_i. While many authors use 1.75 (see Dixon et al., 1994 for example), for North American and European forests, we instead use values consistent with Birdsey (1992) and Kauppi et al. (1992). For forests in the Former Soviet Union and China, we use 1.75, an estimate that is consistent with Dixon et al. (1994).

For subtropical emerging plantations we use a more conservative number, 1.6, while for tropical forests our values range from 3.0 in South America and Africa to 5.0 in Asia-Pacific. These higher numbers for tropical forests account for the fact that our yield functions for forests in those regions capture only merchantable timber. Higher numbers are used because the merchantable component in these regions is typically only a small part of the total biomass on any hectare that is harvested. This assumes that when a harvest occurs in these regions, all of the biomass is lost, so it may overestimate carbon fluxes in these regions. Timber market harvests in these regions, however, are only a small part of global harvests, so this does not have a big impact on our estimates. For π_i, the proportion of carbon per unit of biomass, a uniform assumption of 0.5 is used for all species. Our assumption appears to be consistent with estimates used in the literature: Birdsey's (1992) values range between 0.50 and 0.53, while Kauppi et al. (1992) and Kolchugina and Vinson (1993) use 0.50, and Dixon and Krankina (1993) use 0.45.

Estimates of wood density (ω_i) are expected to vary from species to species (Birdsey, 1992). Some authors, however, use average values when they aggregate across different species. Kauppi et al. (1992), for example, use 400 kg per m^3 for all European forests. We therefore use Birdsey's estimates for North American forests, and we apply Kauppi et al.'s (1992) assumption for European, Former Soviet Union, and Chinese forests. Hardwood plantation species are also assigned a value of 400 kg per m^3. Softwood plantations in Oceania are given the value for Douglas Fir in North America because this species is often transplanted to that region. Softwood plantations in other regions are given a wood density of 450 kg per m^3 because these plantations typically use southern US pines or similar species, suggesting a higher density than for hardwoods.

Forest floor carbon (γ_i) and soil carbon are estimated from Vogt et al. (1996) and Vogt et al. (1995). These values were compared to those in Post et al. (1982), and several small adjustments were made. r_i was selected to be 0.4 uniformly across species. While our model builds carbon inventories based on these parameters, the average carbon density per hectare (Table III) estimated by our model does not differ dramatically from others who have used different approaches (see for example Dixon et al., 1994).

MARKET SCENARIOS

We begin with a baseline prediction of the growth in demand for timber products. In this case, the demand for industrial wood products is assumed to rise at 1.0% per year initially, but declines to 0.0% per year by the year 2140. The 1.0% demand increase is consistent with recent studies of global timber demand (Sedjo and Lyon, 1990, 1996). The decline in growth represents an assumed slow down in population growth over the next 150 years, as well as technological improvements that reduce the growth in demand for harvests of timber. High and low demand scenarios are then developed. The high demand scenario predicts that industrial wood demand rises at 1.5% per year, declining to 0.0% per year by 2140, and the low demand scenario predicts that demand increases 0.5% per year, declining to 0.0% per year by 2140.

Industrial wood prices are expected to increase under all three scenarios, as shown in Figure 1. Rising prices generally indicate increasing global scarcity for timber products. While higher prices are the result of increased future demand, markets respond by increasing timberland management today. Increased management includes increasing the stocking density of forests that are regenerated, replanting forests in temperate zones rather than letting them regenerate naturally, and increasing the area of land in plantations. The high demand scenario predicts that timberland management across the globe increases 20 – 40% today relative to the baseline, and the low demand scenario predicts that it declines 20 – 30%. Additional information about the economic predictions of the three scenarios used in this paper, as well as the timber model can be found in Sohngen et al. (1999).

CARBON FLUX ESTIMATES

In the baseline case, industrial timber market activity is predicted to store an additional 9.5 Pg of carbon in forest vegetation, soils, and marketed products over the next 150 years (Table IV), amounting to an average of 63 Tg carbon per year. The estimates in Table IV are obtained by summing the predicted annual carbon fluxes for each region and storage component from the year 1995 to 2045 (short term) or to 2145 (long term). Most of the long-term gain is predicted to occur in marketable timber products, as rising demand increases timber harvests and product storage. This result is not constant over time, however. In the short-run, 3.7 Pg, or 40%, of the total carbon gain occurs as vegetation carbon, a result of increasing management intensity and plantation establishment due to higher prices.

The economic model therefore emphasizes the role of economic forest plantations in subtropical emerging regions in future carbon flux. Between 1995 and 2145, the area of these plantations is expected to increase from 41 million hectares to 83 million hectares.

The long-term carbon gain in vegetation and marketed products from plantations is 10.3 Pg. Each hectare of plantations therefore provides approximately 124 Mg (1 Mg = 1000 Kg) of additional long-term carbon storage.

One question that arises is whether or not this expansion in industrial plantations is realistic. Between 1995 and 2040, we predict that the average annual rate of new plantation establishment is 556,000 hectares per year, but this rate of establishment declines to 0 in the long run. This predicted rate of establishment is well below the rate of plantation establishment estimated by FAO (1995) in the 1980's of 6.0 million hectares per year. We note that many of the new plantations predicted by FAO are established for firewood markets rather than industrial timber markets, so that FAO's estimates should be larger than our estimates. The decreased rate of establishment reflects a predicted slow down in future price growth by the economic model.

Plantations are assumed to be established on agricultural land that converts back to forests (Sedjo, 1995), so that there is a net gain of carbon. Given that one option discussed for carbon mitigation involves subsidizing plantation establishment, it is interesting to note that a large area of new, economically efficient plantations is predicted to be established without subsidies for carbon mitigation. Policies that subsidize plantations for carbon storage may crowd out this investment by reducing global prices if these plantations are opened to harvests in the future.

The economic model also predicts the conversion of 81 million hectares of northern inaccessible forests, and 74 million hectares of tropical inaccessible forests to accessible forests. This conversion leads to a 1.6 Pg release of carbon to the atmosphere over the next 150 years in the baseline case. While these long-term losses appear large, they amount to a loss of 18.9 Mg of carbon for each hectare of inaccessible northern forests harvested. One reason for the small loss per hectare is that both northern and tropical inaccessible forests in this model are assumed to be reforested eventually. While regenerated forests do not sequester as much carbon as the inaccessible forests they replace, they do gain some advantage due to the storage of carbon in harvested timber products.[1]

These broad results mask carbon flux in specific regions (Table V). Temperate zone forests are predicted to store additional carbon overall, but these gains occur in Europe and China. Although there is some question about the density of regenerated forests in China, that region has re-forested extensive areas in recent years, and these trends are predicted to continue, although at slower rates (Richardson, 1990). Although harvests are predicted to decline in the Former Soviet Union, that region is a net sink because forest inventory statistics (Backman and Waggener, 1991) suggest that biomass density on many regenerated forests in that region is relatively low. There is also continued encroachment on boreal inaccessible forests there. Unlike the temperate zones, the emerging plantation regions are all predicted to be net sinks in both the short and the long run as new plantations are added. Although this does not account for future deforestation due to subsidies for agricultural conversion or other policy factors, it does suggest that plantations may have a strong role to pay in future carbon fluxes from forests.

Figure 2 presents decadal carbon flux estimates for North America, Europe, and the rest of the world, which includes the remaining 7 producing regions. The economic

[1] These results contrast sharply with those of Harmon et al. (1990). There are two reasons for these differences. First, the numbers in this paper reflect averages from a variety of inaccessible species around the globe, and second, the northern inaccessible forests in this model occur at the accessible fringe. These forests are generally not the high quality "old growth" forests as considered in Harmon et al. (1990).

model predicts that carbon flux will shift from region to region as the age class distribution of trees shifts. Because trees in different regions have different rates of growth and different harvest cycles, the relationship between growth and harvest of trees, and consequently carbon flux, will not remain constant over time. For example, North America harvests its forests heavily in early periods because it has large tree volumes at or above optimal rotation ages. Europe and the rest of the world, on the other hand, build timber stocks by waiting to harvest and establishing plantations. After 2035, these regions begin to harvest more heavily. Global timber market models allow us to capture this adjustment of stocks across regions in response to global prices.

The estimates for North America depart from the existing literature. Our results suggest that private timberlands in North America store 46 Tg of carbon per year between 1995 and 2005, but they release an average of 43 Tg per year between 2005 and 2045. Birdsey et al. (1993), on the other hand, predict that US private timberlands sequester 53 Tg of carbon per year between 1987 and 2000, and 13 Tg per year between 2000 and 2020. Private forests are then predicted to release 15 Tg carbon per year until 2040, the end of their model run. Turner et al. (1995) predict that U.S. private timberlands sequester 29 Tg carbon per year between 1990 and 2010, and they then release 23 Tg carbon per year.

In one respect, the results are similar in that they all predict an eventual release of carbon from North American forests. The timing of these events, however, differ as our model predicts these releases earlier rather than later. One reason is that the global model used in this paper predicts heavier harvests over the first 30 years of the projection in the southern U.S. than the model used by Birdsey et al. (1993) and Turner et al. (1995).

Given that global prices are affected by harvests, timberland area, and management elsewhere, and in particular in the subtropical "emerging" planation region, it is optimal for timberland managers in North America to harvest more heavily during early periods in the baseline. Harvests of inaccessible boreal forests of northern Canada are also partly responsible for these predicted emissions. Because these harvests are concentrated in early periods when prices are rising most rapidly, this adds to release of carbon during the period 2005 to 2035.

Perhaps the most important difference between the studies is that this study assumes that public timberlands in the U.S. are in equilibrium. Birdsey et al. (1993) predict that National Forests and other public lands will sequester 50 Tg per year between 2000 and 2140, while Turner et al. (1995) predict that public lands will sequester 40 Tg per year over the same time period. These gains in carbon storage on public lands make up a large proportion of their carbon sequestration predictions over the next 40 years. If these estimates for public timberlands in the U.S. are added to our own, North American timberlands are predicted to be roughly in carbon balance between 2000 and 2140.

Higher demand is predicted to increase the flux of carbon stored in forest vegetation and products (Tables IV and V). These increases occur because supply expands to meet higher demand and prices. There are three ways for supply to expand in our model: increased harvests of inaccessible forests, greater timberland management, and an increase in the area of plantations. The model predicts that the area of northern inaccessible forests harvested increases to 108.1 million hectares (an increase of 34% over the baseline) and the area of tropical inaccessible forests harvested increases to 103.2 million hectares (an increase of 40%). In the high demand scenario, 2.1 Pg of carbon are emitted from northern and tropical inaccessible forests over the long term, a 31% increase over the baseline.

The additional loss of carbon from inaccessible forests is compensated by an increase in the area of plantations, which expand to 106 million hectares by 2140 in the high demand case. The resulting long-term carbon sequestration in vegetation and marketed products from all plantations is 13.8 Pg, representing a net gain of 3.6 Pg carbon relative to the baseline case. In addition to increased plantation area, higher prices also bring more intensive management. Under the high demand scenario, each hectare of industrial plantations provides 130 Mg of additional carbon sequestration, a gain of 5% per hectare relative to the baseline.

While most of the additional carbon stored in the long run occurs because the stock of forest products is increasing in size, the effect of increasing timberland management and plantation establishment can have important consequences for carbon sequestration in the short run. One way to gauge this effect is to consider the difference in vegetation storage between the baseline and the high demand scenarios in 2045. In that year, 43% of the additional carbon stored in forests in the high demand scenario is found in vegetation components. Higher demand leads to higher prices, and consequently to greater incentives to manage all forests and to invest in subtropical emerging plantations. For example, by 2045, there are 75 million hectares of emerging region plantations in the high demand scenario, and management intensity is 34% greater than the baseline in temperate forests, and 24% greater in emerging region plantations. Higher demand does lead to increased harvests and carbon emissions from inaccessible forests, but these losses are more than balanced by gains in subtropical plantation establishment and increased management intensity in other forests around the world.

The higher demand scenario alters the timing of carbon emission and carbon sequestration periods both at the global level and within regions. Compared to the baseline case above, North American forests and forest products are predicted to sequester an average of 59 Tg of carbon per year between 1995 and 2015 in the high demand case. They then release an average of 83 Tg per year between 2015 and 2045. The increase in carbon sequestration in early periods in North America occurs despite heavier harvests in inaccessible forests. Timber owners in North America hold some mature, standing stocks for future periods when prices are higher. Between 2015 and 2045, these prices are high enough to induce heavy harvests throughout North America, which becomes a source of carbon.

Alternatively, lower demand reduces prices and harvests, and it decreases net sequestration in forests and forest products over time (Tables IV and V). Not only does product storage decline, but vegetation storage also declines as management intensity and plantation establishment respond to lower world prices. Plantations expand to only 68 million hectares with long-term carbon sequestration of 7.8 Pg. The average plantation hectare sequesters an additional 115 Mg of carbon. Under the lower demand scenario, there are fewer plantations, and they become less efficient at sequestering carbon.

One of the perceived benefits of lower demand is a reduction in industrial timber harvests in northern and tropical inaccessible regions. The area of land accessed in these regions for industrial timber market purposes declines to 53.1 million hectares in northern inaccessible forests and 51.7 million hectares in tropical inaccessible forests. Carbon losses from these harvests amount to 1.1 Pg by 2145, a 31% reduction from the baseline case.

DISCUSSION AND CONCLUSION

This paper presents global and regional carbon flux estimates arising from harvests and management of industrial forests based on a global timber model. The interaction between price, harvest, inventory, and management intensity is captured for industrial forests in 46 ecosystem and management types around the world. Although rising demand leads to higher future prices and harvests, carbon storage in global forests is expected to increase in the future. Between 1995 and 2045, these increases are predicted to average 184 Tg (10^{12} grams) per year. The high and low demand cases can provide bounds for these estimates, suggesting a range of 108 Tg per year in the low demand case to 251 Tg per year in the high demand case. Although this is only 3% of the estimated current annual emission of carbon dioxide from fossil fuel burning of approximately 6200 Tg per year, these increases result from normal market activity rather than market intervention (i.e. plantation subsidies).

Growing demand increases forest carbon emissions through harvests, but this leads to additional sequestration as carbon is stored in wood products. Higher (lower) levels of demand lead to more (less) storage of carbon in wood products. Carbon storage in wood products, however, is only part of the story. The models generally predict higher future prices, which in turn induce additional management. More management-- for example, human rather than natural regeneration, genetically altered species, and establishment of quick-growing plantations-- enhances the ability of forests to sequester carbon. Both temperate and subtropical plantations become more efficient at storing carbon when prices are higher.

A related effect is the increase in plantation establishment in subtropical regions. Forests in subtropical plantation regions are predicted to sequester an additional 112 Tg per year over the next 50 years, with a range of 102 Tg per year to 126 Tg per year in the low and high demand scenarios. Additional sequestration in subtropical plantation species amounts to 58% of total additional storage by 2045, and 90% by 2145. Despite this gains, rising future prices do suggest that additional harvests and carbon emissions will occur in inaccessible forests in both boreal and tropical regions. Timber harvests in northern and tropical inaccessible forests are predicted to emit 40 Tg per year over the next 50 years in the baseline case, with a range of emissions from 25 Tg in the low demand case to 43 Tg in the high demand case.

Forests and forest products in North America and the Former Soviet Union are predicted to be sources of carbon emissions in the next 50 years, while European and Chinese forests are predicted to be net sinks. Our results for North America differ from estimates provided by other modelers because we predict heavier harvests in North American forests (and particularly in the southern U.S.) than many existing U.S. timber market studies (see for example Haynes, 1990, which was used by many of the studies described above), and we predict harvests in inaccessible boreal forests. Longer term model predictions suggest that these losses are reversed beyond 2035.

Higher demand scenarios predict that carbon storage in forests and forest products increases relative to the baseline, while lower demand reduces carbon storage. Higher (lower) demand implies higher (lower) prices than the baseline, and consequently increased (decreased) harvests and storage in wood products, increased (decreased) management intensity, and increased (decreased) plantation establishment. Although higher demand does cause additional carbon emissions from harvests of northern and tropical inaccessible forests, these losses of carbon are balanced by gains in plantations.

It is useful to compare these results to some other studies relating to carbon flux. Dixon et al. (1994), for example, estimates that land use changes in global forests released of 0.9 Pg (1 Pg = 10^{15} grams) of carbon each year between the1980's and early 1990's. Although we do not address deforestation, our estimates suggest that over the next 50 years, harvests and management of existing forests may reduce this loss by 0.2 Pg per year.

Kauppi et al. (1992), on the other hand, estimated that European forests sequestered as much as 0.12 Pg of additional carbon per year between 1971 and 1990 as some lands converted from agriculture to forests. The estimates in this paper suggest that these trends will continue for the next 50 years in Europe at an average rate of 0.08 Pg of additional carbon per year. Similarly, Sedjo (1992) suggests that forests in North America, Europe, and the Former Soviet Union sequestered approximately 0.7 Pg carbon per year in the late 1980's. When these regions are considered together in our model, the results suggest that forests in these regions may sequester 0.3 Pg carbon per year over the next 50 years.

REFERENCES

Adams, Darius M., Alig, Ralph J., McCarl, Bruce A., Callaway, J.M., and Winnett, S.M.: 1996, "An Analysis of the Impacts of Public Timber Harvest Policies on Private Forest Management in the United States," *Forest Science*, **42(3)**, 343-358.

Backman, Charles A. and Waggener, Thomas R.: 1991, "Soviet Timber Resources and Utilization: An Interpretation of the 1988 National Inventory," CINTRAFOR Working Paper 35, Center for International Trade in Forest Products, University of Washington, Seattle, 296 p.

Bazett, Michael: 1993, *Industrial Wood. Shell/WWF Tree Plantation Review Study No. 3,* WWF (UK), Panda House, Weyside Park, Godalming, Surrey.

Birdsey, R.A., Plantinga, A.J., and Heath, L.S.: 1993, "Past and Prospective Carbon Storage in United States Forests," *Forest Ecology and Management*, **58**, 33-40.

Birdsey, R.A.: 1992, "Carbon Storage and Accumulation in United States Forest Ecosystems," U.S. Department of Agriculture, Forest Service, General Technical Report WO-59, Washington, DC.

Brazee,R. and Mendelsohn, R.: 1990, "A Dynamic Model of Timber Markets," *Forest Science*, **36**, 255-264.

China Center for Forest Inventory: "Dynamic Changes in China's Forest Resources," Working Report, Ministry of Forestry, Beijing, China.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J.: 1994, "Carbon Pools and Flux of Global Forest Ecosystems," *Science*, **263,** 185-190.

Dixon, R.A. and Krankina. O.N.: 1993, "Forest Fires in Russia: Carbon Dioxide Emissions to the Atmosphere," *Canadian Journal of Forest Resources*, **23**, 700-705.

FAO: 1997. *FAO Provisional Outlook for Global Forest Products Consumption, Production, and Trade to 2010.* Forestry Policy and Planning Division, Forest Department, The Food and Agriculture Organization of the United Nations, Rome.

FAO: 1995, *Forest Resource Assessment 1990: Global Synthesis,* FAO Forestry Paper 124, The Food and Agriculture Organization of the United Nations, Rome.

FAO: 1993a, *Forestry Policies of Selected Countries in Asia and the Pacific*, FAO Forestry Paper 115, The Food and Agricultural Organization of the United States, Rome.

FAO: 1993b, *Forest Resource Assessment 1990: Tropical Countries,* FAO Forestry Paper 112, The Food and Agriculture Organization of the United Nations, Rome.

FAO: 1982. *Forestry in China*. FAO Forestry Paper 35, The Food and Agriculture Organization of the United Nations, Rome.

Goldewijk, K.K., van Minnen, J.G., Kreileman, G.J.J., Vloebeld, M. and Leemans, R.: 1994, “Simulating the Carbon Flux Between the Terrestrial Environment and the Atmosphere,” *Water, Air, and Soil Pollution*, **76**, 199-230.

Harmon, M.E., Ferrell, W.K., and Franklin, J.F.: 1990, “Effects of Carbon Storage of Conversion of Old-Growth Forests to Young Forests,” *Science*, **247**, 699 - 702.

Heath, L.A., 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.

Heath, L.A. and Birdsey, R.A.: 1993, “Carbon Trends of Productive Temperate Forests of the Coterminous United States,” *Water, Air, and Soil Pollution*, **70**, 279-293.

Johnson, D.W.: 1992, “Effects of Forest Management on Soil Carbon Storage,” *Water, Air, and Soil Pollution*, **64**, 83-120.

Kauppi, P.E., Mielikainen, K., and Kuusela, K.: 1992, “Biomass and Carbon Budget of European Forests, 1971-1990,” *Science*, **256**, 70-74.

Kolchugina, T.P. and Vinson, T.S.: 1993, "Equilibrium Analysis of Carbon Pools and Fluxes of Forest Biomes in the Former Soviet Union," *Canadian Journal of Forest Resources*, **23**, 81-88.

Kurz, W.A., Apps, M.J., Beukema, S.J., and Lekstrum, T.: 1995, “20^{th} Century Carbon Budget of Canadian Forests,” *Tellus*, **47B**, 170-177.

Kuusela, Kullervo: 1994, *Forest Resources in Europe, 1950-1990*, University of Cambridge Press, Cambridge, 154 p.

Lowe, J.J., Power, K., and Gray, S.L.: 1994, *Canada’s Forest Inventory 1991*. Information Report PI-X-115, Canada Forest Service, Petawawa National Forest Institute.

Lyon, Kenneth S. and Sedjo, Roger A.: 1983, “An optimal control theory model to estimate the regional long term supply of timber,” *Forest Science*, **29(4)**, 798-812.

Mills, J.R. and Kincaid, J.C.: 1992, *The Aggregate Timberland Assessment System: A User's Guide.* General Technical Report PNW-GTR-281, US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 160 p.

Pandey, D.: 1992, *Assessment of Tropical Forest Plantation Resources,* Draft Report. Swedish University of Agricultural Sciences. Department of Forest Survey. 140 p.

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

Post, W.M., Emanuel, W.R., Zinke, P.J., and Stangenberger, A.G.: 1982, “Soil Carbon Pools and World Life Zones,” *Nature*, **298**, 156-159.

Richardson, S.D.: 1990, *Forests and Forestry in China, Changing Patterns of Resource Development*. Island Press, Washington, 340 p.

Sedjo, R.A. and Lyon, K.S.: 1996, “Timber Supply Model 96: A Global Timber Supply Model with a Pulpwood Component,” Discussion Paper 96-15, Resources For the Future, Washington, D.C. 60 p.

Sedjo, Roger A.: 1995, “The Potential of High-Yield Plantation Forestry For Meeting Timber Needs: Recent Performance and Future Potentials,” Discussion Paper 95-08, Resources For the Future, Washington, D.C. 30 p.

Sedjo, R.A.: 1992, “Temperate Forest Ecosystems in the Global Carbon Cycle,” *Ambio*, **21(4)**, 274-277.

Sedjo, R. A. and Lyon, K. S.: 1990. *The Long Term Adequacy of the World Timber Supply*, Resources For the Future, Washington, 230 p.

Sedjo, R.A.: 1983, *The Comparative Economics of Plantation Forestry*, Resources For the Future, Washington.

Sohngen Brent and Mendelsohn, Robert: 1998, “Valuing the Impact of Large Scale Ecological Change in a Market: The Effect of Climate Change on US Timber,” *American Economic Review*, **88(4)**, 686-710.

Sohngen, B., Mendelsohn, R., and Neilson, R.A.: 1998, “Predicting CO2 Emissions From Forests During Climatic Change: A Comparison of Natural and Human Response Models,” *Ambio*, **27(7),** 509-513.

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

Sohngen, Brent and Sedjo, Roger: 1998, "A Comparison of Timber Market Models: Static Simulation and Optimal Control Approaches," *Forest Science*, **44(1)**, 24 - 36.

Sohngen, Brent L.: 1996, “Integrating Ecology and Economics: The Economic Impacts of Climate Change on Timber Markets in The United States,” Unpublished Dissertation, Yale School of Forestry and Environmental Studies, New Haven, CT.

Solomon, A.M., Prentice, I.C., Leemans, R., and Cramer, W.P.: 1993, "The Interaction of Climate and Land Use in Future Terrestrial Carbon Storage and Release," *Water, Air, and Soil Pollution*, **70**, 595-614.

Turner, D.P., Koerper, G.J., Harmon, M.E., and Lee, J.J.: 1995, "A Carbon Budget for Forests of the Coterminous United States," *Ecological Applications*, **5(2)**, 421-436.

Turner, D.P., Koerper, G.J., Harmon, M.E., and Lee, J.J.: 1994, "Carbon Sequestration by Forests of the United States. Current Status and Projections to the Year 2040," *Tellus*, **47B**, 232-239.

US Forest Service: 1996, *Report of the Forest Service, Fiscal Year 1995*, US Department of Agriculture, Forest Service, Washington, 169 p.

Vogt, K.A., Vogt, D.J., Palmiotto, P., Boon, P., O'Hara, J., Asbjornsen, H.: 1996. Review of Root Dynamics in Forest Ecosystems Grouped by Climate, Climatic Forest Type, and Species. *Plant and Soil*, **187**, 159-219.

Vogt, K.A., Vogt, D.J., Brown, S., Tilley, J., Edmonds, R., Silver, W., and Siccama, T.: 1995. Forest Floor and Soil Organic Matter Contents and Factors Controlling Their Accumulation in Boreal, Temperate, and Tropical Forests. *Advances in Soil Sciences*, 159-178.

Wear, David N.: 1994, "Measuring Net Investment and Productivity in Timber Production," *Forest Science*, **40(1)**, 192-208.

Wear, David N. and Newman, David H.: 1991, "The Structure of Forestry Production: Short-Run and Long-Run Results," *Forest Science*, **37(2)**, 540-551.

Yin, Runsheng: 1995, *Forestry and the Environment in China, The Current Situation and Strategic Choices*, Paper presented at the 22nd PAFTAD Conference, Ottawa, Canada, September, 1995.

Table I: Initial inventory in 46 ecosystem and management types, and parameter values used in carbon flux model for equations (1) - (7):

PANEL A. TEMPERATE AND NORTHERN INACCESSIBLE FORESTS							
	Initial Area[1]	Vegetation			Floor	Soil	
		ϕ_i	π_i	ω_i	γ_i	r_i	$K_i(T)$
		Total/Merch Biomass	Carbon Proportion	Wood Density	Steady-state Carbon	Rate of growth of soil carbon	Steady-state Carbon
Region and Type	Million ha	Ratio	Prop.	Kg m^{-3}	Mg ha^{-1}		Mg ha^{-1}
North America							
PNW Conifer	6.11	1.68	0.5	450	23	0.4	122
Southern Pine Plantation	1.02	1.68	0.5	510	23	0.4	122
Southern Mixed	72.47	1.90	0.5	490	21	0.4	145
Northern Mixed	30.26	2.35	0.5	380	35	0.4	193
Northern Hardwood	26.27	2.35	0.5	400	20	0.4	299
Interior Softwood	25.00	2.30	0.5	420	10	0.4	165
PNW Inaccessible	61.90	1.68	0.5	400	23	0.4	122
Northern Inaccessible	165.6	2.35	0.5	400	42	0.4	193
Boreal Inaccessible	388.7	2.35	0.5	400	40	0.4	206
Europe							
Nordic Conifer	28.52	1.90	0.5	400	40	0.4	150
Central Softwood	31.10	1.90	0.5	400	38	0.4	186
Central Hardwood	24.26	1.60	0.5	400	18	0.4	172
Mediterranean Softwood	28.57	1.70	0.5	400	19	0.4	150
Mediterranean Hardwood	47.15	1.90	0.5	400	15	0.4	70
Iberian Plantation	0.85	1.60	0.5	400	7	0.4	48
Nordic Inaccessible	32.39	1.90	0.5	400	40	0.4	125

[1] Sources for the initial area of land in the forest types are given in the appendix.

Table I Continued

PANEL B. TEMPERATE AND NORTHERN INACCESSIBLE FORESTS CONTINUED							
	Initial Area[1]	Vegetation			Floor	Soil	
		ϕ_i	π_i	ω_i	γ_i	r_i	$K_i(T)$
		Total/Merch Biomass	Carbon Proportion	Wood Density	Steady-state Carbon	Rate of growth of soil carbon	Steady-state Carbon
Region and Type	Million ha	Ratio	Prop.	Kg m^{-3}	Mg ha^{-1}		Mg ha^{-1}
Former Soviet Union							
Temperate Softwood	55.13	1.75	0.5	400	38	0.4	186
Taiga Softwood	100.8	1.75	0.5	400	40	0.4	190
Northern Hardwood	55.79	1.75	0.5	400	19	0.4	172
Taiga Inaccessible	574.14	1.75	0.5	400	40	0.4	206
China							
Southern Softwood	33.58	1.75	0.5	400	20	0.4	145
Temperate Mixed	9.66	1.75	0.5	400	30	0.4	180
Northern Mixed	14.01	1.75	0.5	380	40	0.4	180
Southern Inaccessible	34.83	1.75	0.5	400	20	0.4	145
Northern Inaccessible	39.62	1.75	0.5	380	40	0.4	193

[1] Sources for the initial area of land in the forest types are given in the appendix.

Table I Continued

PANEL C. EMERGING SUBTROPICAL AND TROPICAL INACCESSIBLE							
	Initial Area[1]		Vegetation		Floor	Soil	
		ϕ_i	π_i	ω_i	γ_i	r_i	$K_i(T)$
		Total/Merch Biomass	Carbon Proportion	Wood Density	Steady-state Carbon	Rate of growth of soil carbon	Steady-state Carbon
Region and Type	Million ha	Ratio	Prop.	Kg m^{-3}	Mg ha^{-1}		Mg ha^{-1}
Oceania							
Softwood Plantation	2.20	1.4	0.5	450	7	0.4	122
Hardwood Plantation	0.13	1.6	0.5	400	3.5	0.4	155
Natural Forest	150.8	1.6	0.5	400	3.5	0.4	100
South America							
Softwood Plantation	5.52	1.6	0.5	450	9	0.4	133
Hardwood Plantation	5.16	1.6	0.5	400	7	0.4	155
Tropical Inaccessible	917.4	3.0	0.5	700	50	0.4	120
India							
Long Rotation Plantation	3.78	1.6	0.5	450	9	0.4	133
Short Rotation Plantation	7.56	1.6	0.5	400	7	0.4	155
Asia-Pacific							
Tropical	290.2	5.0	0.5	700	10	0.4	130
Plantation	12.35	1.6	0.5	400	9	0.4	130
Africa							
Softwood Plantation	3.17	1.6	0.5	450	9	0.4	133
Hardwood Plantation	1.14	1.6	0.5	400	7	0.4	155
Tropical Inaccessible	545.1	3.0	0.5	700	40	0.4	120

[1] Sources for the initial area of land in the forest types are given in the appendix.

Table II: Sources for industrial timberland inventory data used in global timber model and carbon model.

Region	Source
United States	Mills and Kincaid (1992)
Canada	Lowe et al. (1994)
Europe	Kuusela (1994), Bazett (1993)
Former Soviet Union	Backman and Waggener (1991)
Oceania (Australia and New Zealand)	FAO (1995), and Pandey (1992)
China	Yin (1995); FAO (1993a); Richardson (1990); FAO (1982); and China Center for Forest Inventory, "A Working Report on the Forest Inventory in China," Ministry of Forestry
South America	FAO (1993b) and Pandey (1992)
India	FAO (1993b) and Pandey (1992)
Asia-Pacific	FAO (1993b), Pandey (1992), Sedjo and Lyon (1990)
Africa	FAO (1993b) and Pandey (1992)

Table III: Average vegetation and soil carbon per hectare in the nine regions considered in this model.

Region	Vegetation and Floor Mg ha^{-1}	Soil Mg ha^{-1}	Total Mg ha^{-1}
Temperate			
North America	63	146	209
Europe	70	127	197
Former Soviet Union	73	198	271
China	81	157	238
Emerging and Tropical			
Oceania	50	95	145
South America	130	117	247
India	14	112	126
Asia-Pacific	166	126	292
Africa	107	116	223

Table IV: Gain or loss in global carbon storage in forest ecosystem components between 1995 and the year given. Positive numbers indicate that the component is sequestering carbon, while negative numbers indicate the component is releasing carbon.

	Baseline		High Demand		Low Demand	
	Short Term 2045	Long Term 2145	Short Term 2045	Long Term 2145	Short Term 2045	Long Term 2145
			Pg			
Vegetation/Floor	3.70	0.50	5.92	2.50	0.69	(0.91)
Soil	(0.95)	(0.52)	(0.97)	0.13	(0.67)	(0.53)
Market	6.43	9.53	7.63	11.92	5.40	7.51
Total	9.18	9.51	12.57	14.55	5.42	6.07

Table V: The effect of timber market activity on forest carbon flux for different regions. The estimates represent the gain or loss in carbon stored in forested ecosystems between 1995 and the year given.

	Baseline		High Demand		Low Demand	
	Short Run 2045	Long Run 2145	Short Run 2045	Long Run 2145	Short Run 2045	Long Run 2145
	Pg Carbon					
TEMPERATE (INCLUDES NORTHERN INACCESSIBLE)						
North America	(1.26)	0.44	(2.01)	(0.80)	(2.78)	(0.77)
Europe	3.62	0.87	4.71	2.30	2.70	1.40
Former Soviet Union	(2.13)	(2.92)	(0.22)	(1.95)	(2.84)	(3.37)
China	3.56	1.26	3.80	1.51	3.08	0.85
Total Temperate	3.79	(0.35)	6.28	1.05	0.16	(1.89)
EMERGING SUBTROPICAL (INCLUDES TROPICAL INACCESSIBLE)						
Oceania	2.63	3.57	2.83	4.30	2.43	2.99
South America	1.13	2.17	1.20	2.89	1.02	1.61
Asia-Pacific	0.86	2.57	1.34	3.80	1.01	2.35
India	0.43	0.48	0.52	0.93	0.48	0.29
Africa	0.35	1.07	0.40	1.59	0.32	0.72
Total Emerging	5.39	9.86	6.29	13.50	5.27	7.96

FIGURES

1) Global prices for industrial timber logs for the baseline, high demand, and low demand scenarios.

2) Baseline average annual carbon flux arising from industrial timber log harvests and management in North America, Europe, and the rest of the world.

FIGURES

Figure 1: Global prices for industrial timber logs for the baseline, high demand, and low demand scenarios.

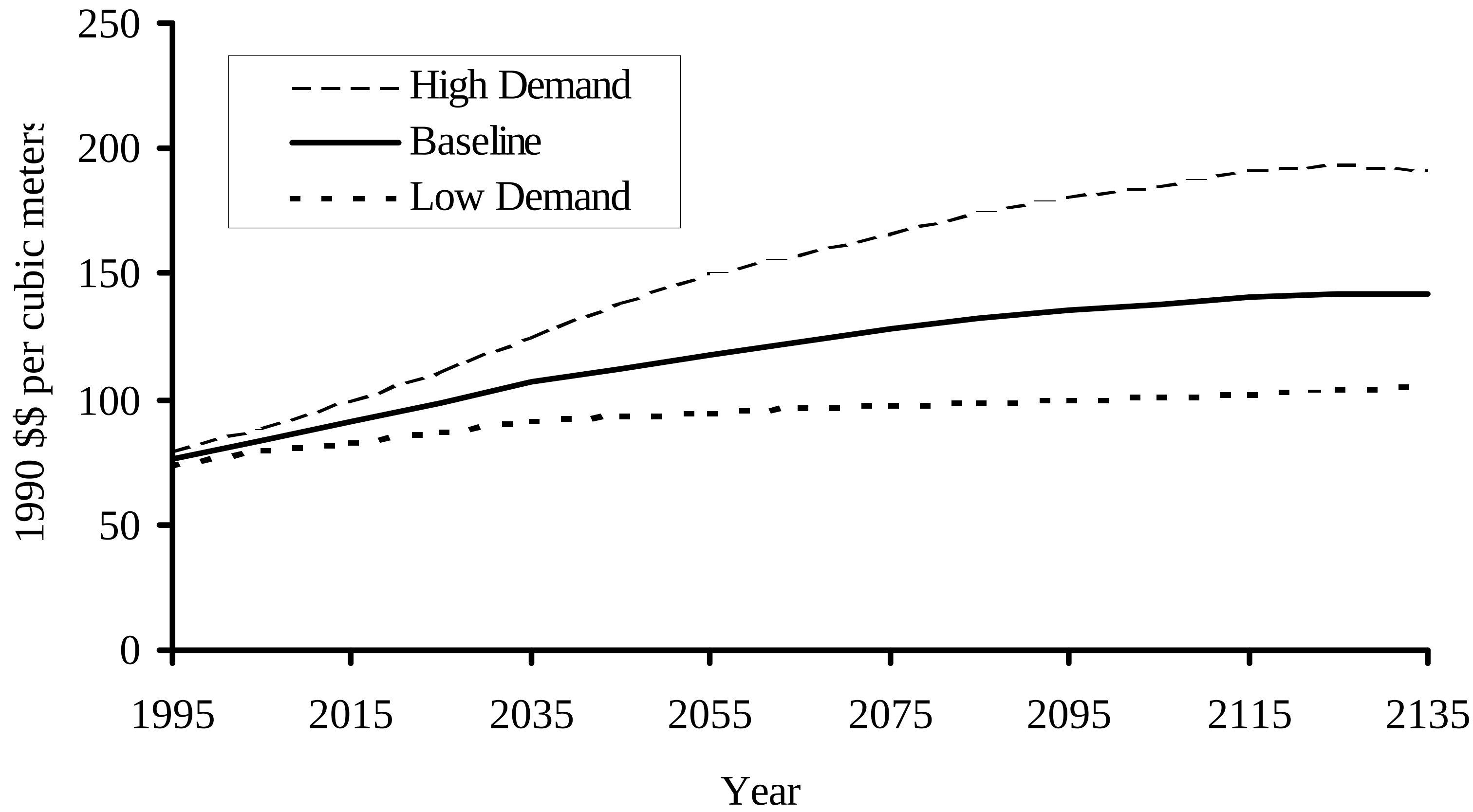

Figure 2: Baseline average annual carbon flux arising from industrial timber log harvests and management in North America, Europe, and the rest of the world.