THE EFFECT OF CLIMATE CHANGE ON GLOBAL TIMBER MARKETS

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ABSTRACT

Ecological models predict that climate change will have widespread impacts on the distribution and growth of forests around the globe. This paper carefully links these impacts to a dynamic global timber market model in order to determine how markets will adapt to these changes. The results suggest that climate change will expand long term global timber supply, timber prices will fall, and the welfare from timber will increase between 3.0 and 6.7%. Although global harvests increase, the area of both industrial and remaining inaccessible wilderness forests expands during climate. Consumers in all regions benefit from lower prices, but producer welfare varies from region to region. In general, producer surplus in developing countries rises while it declines in developed countries.

INTRODUCTION

Ecological models predict that climate change will have widespread impacts on global forest resources. These impacts range from large-scale dieback (Solomon, 1986; Shugart et al., 1996; and King and Neilson, 1992), as shown in Figure 1, to large shifts in ecosystem productivity (Melillo, 1993). Such large changes are predicted to occur relatively rapidly over the next 70-100 years if policy does not significantly alter carbon dioxide emissions from human sources. This paper explores how global timber markets will respond if greenhouse gas emissions are allowed to double.

Climate impacts on timber markets are complex and difficult to model. First, ecological models predict that climate will affect both the distribution of biomes and forest productivity over time. The shift in biomes suggests that the type of trees living in current climate conditions will change throughout the globe over the next century or two. The shift in forest productivity suggests that forest growth rates will also change over time as carbon dioxide increases. Second, these ecological impacts are expected to vary widely from one region to the next. For example, many ecological models predict that the inaccessible boreal forests of Canada and the Soviet Union will increase substantially in area and productivity whereas other forest types will experience less change. Third, timber markets involve large stocks and so require dynamic analysis. The impacts of climate change on timber require careful intertemporal analysis in order to capture how the climate affects future stocks and how the market will react over time (see Sohngen and Mendelsohn, 1998).

Previous analyses of climate change impacts on timber failed to capture all the effects above. Most studies examined only a small fraction of global timber resources. For example, Binkley (1988) examines only changes in the boreal forests and Bowes and Sedjo (1993), Joyce et al. (1995), and Sohngen and Mendelsohn (1998) only consider changes in the United States. Perhaps more important, most previous studies did not address optimal intertemporal economic behavior. Perez-Garcia et al. (1997) consider only future yield effects. Several authors use a static equilibrium framework to study timber which completely overlooks both the dynamics of climate change's impacts on ecosystems, as well as the dynamics of the market response.

This paper addresses these shortcomings by combining a dynamic approach with a global perspective. This paper links global ecological results to a dynamic model of global timber markets to assess the optimal intertemporal adjustment in timber markets. The economic model incorporates 46 different ecosystem and management types throughout the globe, ranging from heavily managed subtropical plantations, to unmanaged inaccessible forests in tropical and boreal zones. The model endogenously predicts optimal forest harvests and investments in all modeled regions.

The paper begins by describing the dynamic timber market model. The ecological effects of climate change are then introduced into the empirical timber model. The paper relies on empirical results from a quantitative ecological model, BIOME3 (Haxeltine and Prenctice, 1996). The steady state ecological results are converted into transient scenarios using two alternative dynamic models of ecosystem change. The two alternative transient scenarios are then introduced into the economic model to determine the optimal economic response. Future global harvests, timberland management, and welfare are compared to a baseline forecast.

A MODEL OF GLOBAL TIMBER MARKETS AND CLIMATE CHANGE

Global Timber Markets

To measure the economic effects of climate change on global timber markets, we first develop a dynamic model of global timber markets. A baseline case is constructed with a dynamic model of global timber markets and empirical data found in the literature. The dynamic model developed in this paper differs from previous efforts in several key ways (Sohngen et al. 1998). First, many earlier models considered only specific regions (Walker, 1971; Brazee and Mendelsohn, 1990; and Sohngen and Mendelsohn, 1998), for example, the US or Europe. Second, earlier dynamic global models failed to incorporate several important regions of the world. For example, Sedjo and Lyon (1990) and Lyon and Sedjo (1983) modeled a large part of the world as "non-responsive." During climate change, when species distribution and productivity is shifting, management and harvests in all regions should be determined endogenously. Finally, regeneration decisions in many earlier models were made exogenously. While Sedjo and Lyon (1990) allow regeneration intensity to be determined endogenously, the decision to expand or contract plantations was determined exogenously. Given the importance placed on plantations within the literature (see Sedjo and Lyon, 1990 and Sohngen et al., 1998), it is important to determine how plantation establishment may respond to climate impacts.

The baseline timber market model begins with the assumption that the demand for timber is derived from a well-behaved utility function over industrial wood end-products, and all other goods. Although we do not monitor bi-lateral trade flows in this model, global demand is assumed to be a function of specific regional demands. Over the long run, regional prices are expected to be determined by a global price. The inverse demand function can be written:

(1) $$P(t) = D(Q(t), Z(t)),$$

where *Z(t)* is the vector of all other goods purchased. Demand will shift over time due to exogenous factors, such as population and income growth.

The global forest resource is composed of i stocks of trees, $X_i(t)$. The ecological characteristics of these stocks vary, depending on location. In the baseline case, these locational factors are assumed fixed, although this assumption is relaxed under climate change. The market model predicts how specific stocks are used over time, taking into account locational factors, quality differences, and access and harvest costs. The model balances harvests today and in the future with timber investments.

Separate yield functions describe the growth of trees in each forest type, $V_i(a_i(t);m_i(t_0))$, where $a_i(t)$ is the age of the stand of tree type i at time t, $m_i(t_0)$ represents management intensity for a stand planted at time t_0, and $V_{a_i}>0$ and $V_{a_i a_i}<0$. Although ecosystem types in this model are aggregations of many timber species, all species in each ecosystem type have been classified as one for our modeling purposes (see, for example, Kuchler, 1975). As such the yield function is assumed to be typical for the species in each ecosystem type. Over all species harvested in a given year, the quantity of timber harvested at time t is the sum of the area harvested, $H_i(t)$, times the yield per hectare:

$$(2) \qquad Q(t) = \sum_i H_i(t) V_i\left(a_i(t); m_i(t_0)\right).$$

While the demand curve represents the benefits of timber harvests, there are costs. One set of costs, access, harvest and transportation, can be expressed as:

$$(3) \qquad C_H(Q(t)) = \sum_i c_i^A(q_i(t)) + \sum_i c_i^H(q_i(t)).$$

$c_i^A(q_i(t))$ are the costs of accessing timber stocks and $c_i^H(q_i(t))$ are the costs of harvesting and transporting timber to markets. These costs are expressed as a function of the quantity of timber harvested in each type, $q_i(t)$, in time t. Access costs relate specifically to the costs of accessing natural forest stocks that exist at the economic margin. These costs result from the absence of roads and infrastructure, which must be built specifically to harvest these species. The marginal access cost function is an increasing function of land which is harvested in these regions (i.e. northern Canada, Siberia, tropical rainforests). Marginal harvesting and transportation costs for other species and regions are assumed to be constant in terms of the quantity of timber harvested, although they vary from region to region.

Another set of costs are those associated with regeneration. When the annual area regenerated in species i is $G_i(t)$, and $m_i(t)$ is the units of management intensity purchased at a constant price of $p_{i,m}$, these costs are:

(4) $$C_G(t) = \sum_i p_{i,m} m_i(t) G_i(t) .$$

Management intensity must be determined at the time of planting, but this will have an effect on the future stock of timber: higher (lower) management intensity, $m_i(t)$, will increase (decrease) future yields. The returns to additional units of management are assumed to be concave. In this case, the following two conditions hold, $\frac{dV_i(t_f - t_0; m_i(t_0))}{dm_i(t_0)} \geq 0$, and $\frac{d^2 V_i(t_f - t_0; m_i(t_0))}{dm_i(t_0)^2} \leq 0$, where t_f is the time of harvest for species i, and t_0 is the time the land was regenerated.

In addition to determining how intensively to regenerate land, managers can also increase or decrease the area of land in plantations. For example, if climate change increases productivity in one region, it may be economically efficient to expand the area of forests. However, establishing new timber plantations requires additional costs above other replanting because the landowner must expend resources finding new lands and preparing it for timber. Letting new lands in timber plantations be expressed as $N_i(t)$, the costs of new land are given as:

(5) $$C_N(t) = \sum_i p_{m,i} m_i(t) N_i(t) + \sum_i f_{N,i}(N_i(t)) .$$

$f_{N,i}(N_i(t))$ are labor and land conversion costs associated with establishing an additional hectare of land for plantations. These costs are assumed to be an increasing function of the total area of plantations established in type i.

The benefits of timber market activity are calculated as Marshallian consumer surplus, or the area underneath the demand function given in (1). Given costs, annual net market surplus can be expressed as:

$$(6) \qquad S(\cdot) = \int_0^{Q^*(t)} \{D(Q(t), Z(t)) - C_H(Q(t))\} dQ(t) - C_G(t) - C_N(t) - \sum_i R_i(X_i(t))$$

In equation (6), $R_i(t)$ is the annual per hectare land rental cost associated with holding $X_i(t)$ hectares of land in timber type i. Over time, timber markets will determine how many hectares to harvest, $H_i(t)$, how many to regenerate, $G_i(t)$, how many new hectares to plant, $N_i(t)$, and how intensively to regenerate, $m_i(t)$ in order to maximize the net present value of the stream of annual net benefits:

$$(7) \qquad \underset{H_i(t), G_i(t), N_i(t), m_i(t)}{Max} \quad W = \int_t^{\infty} e^{-rt} \{S(\cdot)\} dt \,,$$

where r is the interest rate.

The maximization problem without climate change is constrained by the stock of land maintained in forests,

(8) $\dot{X}_i = -H_i(t) + G_i(t) + N_i(t)$ ∀ i

Equation (8) expresses the change in the size of the total population of each type of organism in each period; it is the difference between what is harvested and what is regenerated. In addition, initial stocks must be given, and all choice variables are constrained to be greater than or equal to 0:

(9) $X_i(0) = X_{i,0}$ ∀ i

(10) $X_i(t), H_i(t), G_i(t), N_i(t), m_i(t) \geq 0$ ∀ i

Equation (9) is an initial condition for the stock variable, which defines not only the total quantity of timber harvested, but also the age distribution of the initial stock (through a yield function associated with each hectare of land).

Such a model can be solved using the maximum theorem (Pontryagin, et al., 1962). A discussion of the derivation of the first order conditions described in equations (11) - (15) is contained in Appendix A. Harvests in each timber type will occur over time according to

(11) $\dot{P}V_i\left(a_i(t); m_i(t_0)\right) + \left(P(t) - c_i^{H}{}'\right)\dot{V}_i = r\left(P(t) - c_i^{H}{}'\right)V_i\left(a_i(t); m_i(t_0)\right) + R_i(t)$, ∀ i

P(t) is the global market clearing price of industrial timber logs, and c_i^{H}' is the marginal cost of harvesting an additional unit of timber. Equation (11) shows that efficient timber harvests will occur along a path where the marginal benefits of waiting an extra moment to harvest a stand of trees are equated with the marginal costs (see Brazee and Mendelsohn, 1990, and Sohngen and Mendelsohn, 1998). The marginal benefits of waiting, the left hand side of (11), arise from additional growth in the organism, $\dot{V}_i$, and changes in price, $\dot{P}$. If prices are declining, the marginal benefits of waiting are reduced. The marginal costs of waiting, the right hand side of (11), include the opportunity costs of delaying harvests and using the land for one more period.

In some regions, such as economically inaccessible forests, land rent will be low (or 0), and forest growth will be small, but access costs will be high. In these forests, harvests will occur according to

(12) $$\dot{P} = r\left(P(t) - c_i^{H}{}' - c_i^{A}{}'\right), \qquad \forall\, i$$

where c_i^{A}' is the marginal access cost. In these inaccessible forests, the key economic decision to harvest rests on the relationship between existing prices, access costs, and harvest costs, $\left(P(t) - c_i^{H}{}' - c_i^{A}{}'\right)$. If ecological conditions change due to climate change, forest harvests in this region may increase or decrease depending on the change.

There are three important components of the regeneration decision. First, for most timber types, landowners must decide whether or not to keep land in forests at all. This decision depends on comparing current marginal costs with the discounted future marginal benefits,

$$(13) \quad \left(P(t_f) - c_i^{H}{}'\right) V_i(t_f - t_0; m_i(t_0)) e^{-r(t_f - t_0)} = p_{m,i} m_i(t_0) + \int_{t_0}^{t_f} \left[R_i(s) e^{-rs}\right] ds \quad \forall\, i$$

In (13), land will be replanted in forests as long as the discounted marginal benefits of the last hectare offsets the current marginal costs. If landowners decide to keep land in timber, they must also decide how intensively to regenerate land. The model predicts that foresters can control the stocking density of forests according to,

$$(14) \quad \left(P(t_f) - c_i^{H}{}'\right) \left(\frac{dV_i(t_f - t_0; m_i(t_0))}{dm_i(t_0)} \right) e^{-r(t_f - t_0)} = p_{m,i} . \quad \forall\, i$$

At the margin, landowners continue investing in management intensity until the discounted marginal benefits just equal the current marginal costs. Depending on the response of the yield function to management intensity and future prices, substantial investments may occur in some regions, while no investments occur in others. When no investments occur, regeneration is assumed to occur naturally. Finally, determining the area of new hectares in plantations requires comparing the discounted marginal benefits of one additional hectare of land with the marginal costs of that additional hectare of land,

$$(15)\left(P(t_f)-c_i^H{}'\right)V_i(t_f-t_0;m_i(t_0))e^{-r(t_f-t_0)} = p_{m,i}m_i(t_0)+f_{N,i}{}'\left(N_i(t_0)\right)+\int_{t_0}^{t_f}\left[R_i(s)e^{-rs}\right]ds\,.$$

Equation (15) shows that the area of land in plantations depends on the relationship between current costs and discounted future benefits.

Introducing Climate Change Impacts

Ecologists suggest that climate change will affect timber in two ways. The first is redistribution of ecological boundaries. Figure 1, for example, presents the predicted area of land in forests around the globe that will shift from one ecosystem type to another during climate change. The steady state results in Figure 1 will occur only after forested ecosystems, or biomes, have migrated from one area to another. In economic terms, such a redistribution of ecosystems entails a "stock" effect on standing forests.

While ecologists generally agree that stocks will redistribute over time, they do not completely agree on how this migration will occur. For example, if climate changes and forests are no longer suited to their present location, they may dieback (Shugart et al., 1986, Solomon, 1986; King and Neilson, 1992). Dieback results in large scale fires, bug infestations, or other stresses that kill trees. Our "dieback" scenario assumes that all forests die when the ecological model predicts that they change ecosystem type.

Some ecologists maintain, however, that trees will not die back when climate changes, but instead the existing forest will continue to grow. However, when forests have been harvested or they naturally die off, the existing species will not be able to regenerate in the new climate. Under the "regeneration" scenario, there is no dieback, but rather there is a change in species type at the moment of regeneration. Migration of new species into regions where change occurs will depend on whether the land receives human regeneration inputs or it is regenerated naturally.

In addition to these biome changes, a forest productivity effect is also predicted by climate modelers through changes in the net primary productivity of forests. These changes result from carbon fertilization and climate change. Changes in timber growth are assumed to be proportional to predicted changes in net primary production. Further, these changes are assumed to be proportional to changes in temperature over time.

We begin by assuming that climate change influences the model through a climate forcing factor, $\kappa(t)$. With no climate change, $\kappa(t)$ is 0. Because greenhouse gases are assumed to increase radiative forcing, emissions cause $\kappa(t)$ to be positive. As just described, climate change has two effects on forests: it affects the future growth of trees (forest productivity), through $\theta_i(\kappa(t))$, and it affects the existing stock of trees (distribution of biomes) through $\delta_i(\kappa(t))$. These effects will vary depending on the specific predictions of the ecological models for timber in each region, i.

We first consider how climate change affects the future growth of trees. Under climate change, the growth function becomes:

(16) $$V_i\left(a_i(t);m_i(t),\theta_i(\kappa(t))\right)=\int_{t_0}^{t_f}\left[\dot{V}\left(a_i(n);m_i(t_0)\right)\theta_i(\kappa(n))\right]dn \qquad \forall i$$

where $\dot{V}_i\left(a_i(n), m(t_0)\right)$ is the annual growth of trees without climate change and $\theta_i(\kappa(t))$ is the effect of climate change on future annual tree growth. $\theta_i(\kappa(t))$ is assumed to be proportional to the change in net primary productivity of forests. If climate change increases (decreases) the rate of growth of the trees in a specific ecosystem, then $\theta_i(\kappa(t)) >$ ($<$) 1. $\theta_i(\kappa(t))$ must always be greater than or equal to 0.

Changes in timber growth can have dramatic impacts on the management of different timber types. Increases in forest productivity tend to increase the rewards of more intensive management. However, investment in more intensive management also depends upon projections of future prices. If global supply increases substantially, global prices will fall, reducing investment incentives. Management intensity decisions thus must depend not only on local conditions but also upon how the local region compares to the rest of the world.

Climate change may also affect the existing stock of trees. The first stock scenario considered above is dieback. Under dieback, the state equation in (8) above becomes

(17) $$\dot{X}_i = -H_i(t) - \delta_i(\kappa(t))X_i(t) + G_i(t) + N_i(t), \qquad \forall\ i$$

where the change in stock from one period to the next depends on the size of $\delta_i(\kappa(t))$. $\delta_i(\kappa(t))$ is the proportion of existing stocks that are subject to stock dieback, as predicted by the ecological model. When dieback occurs, it is possible that some timber can be salvaged. We assume that this is large in the most easily accessed regions (up to 0.75), and 0 in inaccessible regions. Given that the proportion of timber that can be salvaged is γ_i, the annual harvest quantity is expressed as:

(18)

$$Q(t) = \sum_i H_i(t) V_i\left(a_i(t), m_i(t_0), \theta_i(\kappa(t))\right) + \sum_i \delta_i(\kappa(t)) \gamma_i X_i(t) V_i(a_i(t), m_i(t_0), \theta_i(\kappa(t))) .$$

While dieback entails substantial impacts on existing forests, salvage can mitigate some of these impacts.

The second transient stock redistribution scenario is "regeneration." While the area represented by $[\delta_i(\kappa(t))X_i(t)]$ becomes more suitable to a different type of forest, the existing stock of trees is not affected in this scenario. Rather, these trees can continue growing until they have been harvested. However, we assume that it is not possible to regenerate the original stock on land that is changing from one timber type to another. G_i is therefore limited by the predicted changes of ecological models.

The baseline timber market model must be altered to account for the dieback and regeneration scenarios, as well as the effects of changes in timber growth. In both scenarios, yield functions for existing and new forests will shift according to (16). Appendix A describes how the mathematical model is altered to account for the effects of these different scenarios.

EMPIRICAL ANALYSIS

Ecological Effects

The ecological predictions begin with steady state climate forecasts from two General Circulation Models (GCM's). These models generate equilibrium global climate forecasts for current atmospheric CO_2 concentrations of 340 ppmv, and for doubled greenhouse gas concentration scenarios. Two models are used: the Hamburg T-106 model ("Hamburg") from Claussen (1996) and the AGC/MLO model ("Schlesinger") from the University of Illinois at Urbana-Champaign (Schlesinger et al., 1997).

The ecological effects are predicted by the BIOME3 model, an integrated biogeochemical and biogeographical model of ecosystems (Haxeltine and Prentice, 1996). BIOME3 uses the detailed GCM climate forecasts to predict the steady state distribution of ecosystem types and net primary productivity (NPP) for 0.5 x 0.5 degree grid cells across the globe. In the BIOME3 model, the NPP calculations influence the steady state distribution of ecosystem types, and vice-versa. The baseline assumes atmospheric CO_2 concentrations of 340 ppmv, and the effective doubled CO_2 equilibrium assumes 500 ppmv. The actual CO2 concentrations do not double in this scenario because increases in other greenhouse gases also contribute to the doubling effect.

Table 1 presents the steady state ecological changes predicted by the BIOME3 model for the two GCM's. The first column presents the proportion of initial timberland area in each ecosystem type that will shift from one type to another during climate change. These proportions correspond to the areas shown in Figure 1, and it is the area used to calculate $\delta_i(\kappa(t))$. For the dieback scenario, this is the area of land that dies back, and for the regeneration scenario, this is the area of land that shifts from one type to another in the long run. The second column presents the relative size of the ecosystem type after climate change has occurred. Numbers greater than 1.0 indicate that the area of land in the ecosystem type increases during climate change, and numbers less than 1.0 indicate that the area of land in the ecosystem type decreases during climate change. The final column presents the percentage change in net primary productivity, or $\theta_i(\kappa(t))$. Increases indicate that timber growth will increase and decreases indicate the opposite.

To develop the dynamic pathways for these steady state effects, we first predict the path of change in climatic variables (i.e. temperature and precipitation). We assume that these variables change linearly over a 70 year time period and then stabilize. Linear paths such as this are consistent with the work of the Intergovernmental Panel on Climate Change (1996). We then assume that the steady state changes in ecosystems occur proportionally to the changes in climatic variables. For example, yield is predicted to change proportionally during the 70 year transition from current to future climate.

The two scenarios of ecological transition discussed above are then introduced into the economic model, dieback and regeneration,. The dieback scenario predicts that as ecosystem boundaries shift, dieback occurs. Regeneration does not impose this strict stock effect, but instead assumes that yield functions switch from one type to another in these regions after harvest or natural senescence. Adjustments in the yield function, as described by equation (16), occur in both scenarios. Combining the two GCM predictions with the two scenarios of ecological transition provides four empirical cases to examine.

An Empirical Ecological-Economic Model

The dynamic ecological scenarios are then introduced into the dynamic economic model. The model chooses harvest and regeneration patterns across regions and time that maximize the net present value of net market welfare. Economic impacts are measured by comparing welfare in the baseline case to welfare in the climate change cases.

Because land productivity is changing, the question of land shifting between forestry and other uses, such as agriculture, must be addressed. Although the BIOME3 model predicts that forests will expand dramatically during climate change, we assume that forests are not likely to encroach on areas currently used for agriculture, for example, the US Midwest. The ecological results predicted by the BIOME3 model have been adjusted so that forests cannot expand into major agricultural regions around the globe.

The ecological-economic models are programmed and solved using the GAMS programming language and the MINOS solver. Arbitrary terminal conditions are imposed on the system in order to solve the model. The terminal conditions are defined by a steady state that would evolve if demand were held at a constant level at some distant time. By choosing a moment sufficiently far in the future (150 years) in which to stabilize demand, these arbitrary terminal conditions should have little impact on the net present value of the objective.

In the baseline and climate change conditions, global demand for timber logs is assumed to be the linear sum of regional demand functions. The resulting annual global log market demand function is given as

(19) $P(t) = 140*\exp(bt) - 0.004*Q(t)$,

where Q(t) is given in million m^3, b is the rate of growth in demand, and P(t) is the price per m^3. As the demand for forest products increases (or decreases), the demand curve will shift out (or in). b is assumed initially to be 0.01, but we assume that this declines to 0.00 by the year 2140. Initial conditions are given as the current inventory of timber in each type. Under current global prices and consumption, the initial elasticity of demand in the baseline case is approximately 1.0. This is consistent with the empirical results of Sohngen (1996), and the price elasticity used by Sedjo and Lyon (1990). Additional details about functional forms and data are found Appendix B and Sohngen et al. (1998).

RESULTS

Timber Prices, Production, and Management

In all climate change scenarios, prices are predicted to be lower (and consequently, timber harvests are higher) than the baseline case (Figure 2). Long term reductions in prices result from the ecological effects predicted by BIOME3: (1) an increase in timberland productivity, and therefore yield, in most regions of the globe; and (2) an increase in the area of faster growing species (at the expense of more northerly, slower growing types). In the short term, prices are higher in the dieback scenarios than the regeneration scenarios due to the stock effects that occur in temperate forests. Although some of these stocks can be harvested as salvage, these forests contribute a large proportion of initial timber supply. It is not surprising that stock dieback influences prices in the early periods.

The overall area of forests is predicted to expand 22% in the Schlesinger scenario and 29% in the Hamburg scenario. Most of these increases in forest lands come at the expense of less productive regions like the tundra, savanna, or other grasslands. Further, many of these expansions occur in regions that are currently inaccessible to timber markets. For example, temperate forests (which are all accessible) are predicted to expand only 6% in both climate scenarios, whereas boreal inaccessible forests expand 30% to 40%, and tropical inaccessible forests expand 30% to 50%.

Because climate change reduces timber prices, new inaccessible forests are not likely to be harvested. Not only is climate change predicted to increase the area of these inaccessible forests, but harvests are expected to fall because global timber prices are lower (see Table 2). Harvests of inaccessible boreal forest in the Former Soviet Union increase slightly as gains in forest productivity are particularly large there. Nonetheless, inaccessible forest in all regions expand so dramatically, that there should be more inaccessible forest with climate change than there would have been without it. The model predicts that the area of remaining inaccessible forests will increase by 12 to more than 50% (in the tropics) with climate change.

While climate change increases productivity and yield in subtropical "emerging" plantations, future establishment increases by 1.5% on average in the Hamburg scenario, but it decreases 3% in the Schlesinger scenario. Despite lower prices in the Hamburg scenario, emerging regions take advantage of higher yields to increase the area of plantations. Plantations also play an important short term role. Because they have relatively short rotations (10-20 years in most cases compared to >30 years in temperate forests), plantation regions can take advantage of increased yield and dieback in the temperate forests relatively quickly. Establishment in most regions increases from 3 to 5% between 1990 and 2050 when dieback occurs to compensate for the loss of stock in the temperate forest regions.

Management intensity depends upon the rotation length of the trees, productivity, and prices. Short rotation trees can respond to temporary conditions. In the short run, productivity is increasing but there is little price effect. Management intensity in short rotation emerging plantations consequently increases from 1 to 12% between 1990 and 2050. In the long run, global timber prices respond to the rising productivity by falling, and the price effect counterbalances the productivity increase. By 2140, management intensity declines 11% relative to the baseline in temperate forests and it remains the same in emerging plantations in the Hamburg scenario. In the Schlesinger scenario, intensity declines 10% in both temperate and emerging forests.

These effects have large consequences for regional timber production (Table 3). Global harvests increase approximately 30% by late in the next century. While harvests in most regions increase, the model predicts lower harvests in Australia and New Zealand in the Hamburg case as lower forest productivity reduces timber yield. Harvests in North America decline initially in the dieback scenarios, as that region responds to dieback by harvesting less in the first few periods.

Most increases in timber harvest occur after 2040 when increased growth rates have their most significant impacts. Because the current stock of timber is given, only future growth is affected by the changes in growth rates predicted by the ecological model. The effect of this is most dramatic in temperate regions, where timber stocks grow for long periods before harvest (Europe and the Former Soviet Union in particular). While the Former Soviet Union has the most dramatic overall increase in timber harvests, it must wait many years to capture these benefits due to the generally slow growing conditions.

Global and Regional Welfare Effects

Market welfare from timber activity is calculated with the net present value of global net market surplus (equation 6). During climate change, the flow of stocks to and from forests are monitored in order to properly calculate welfare. Land rental costs are measured as the annual land rent times the area of land in each timber type. When stocks enter or leave forestry due to climate change, the resulting flows increase or reduce total land rental costs, depending on the direction of change.

Regional net market surplus can be determined by realizing that global demand is the sum of regional demand functions. By following these regional demand functions through time, and accounting for net imports, annual net market surplus for each region can be measured as

(20)
$$W_L(t) = \int_0^{q_{c,L}^*(t)} \{ d\left(q_{c,L}(t), Z_L(t)\right) dq_{c,L} + P(t)\left(q_{H,L} - q_{c,L}^*\right) - C_{H,L}(q_{H,L}(t)) - C_{G,L}(t) - C_{N,L}(t) - \sum_{i \in L} R_{i \in L}(X_{i \in L}(t))$$

In equation (20), L denotes the particular region in question, and ($i \in L$) represents the i species within region L. $d(q_{c,L}*(t),Z_L(t))$ is region L's demand function for forest products, $q_{c,L}*(t)$ is the quantity of wood products consumed by country L in time t, $Z_L(t)$ is the demand for all other goods in region L, $q_{H,L}(t)$ is the quantity harvested, and P(t) is the global price. Regions that produce (consume) more wood products than they consume (produce) are net exporters (importers). Net exporters (importers) accrue benefits (losses) from international trade. These benefits (losses) are measured as $P(t)(q_{H,L}(t) - q_{c,L}*(t))$. The cost variables are the same as in (6), but they are counted only for the specific region in question.

To estimate regional welfare effects, we first develop regional demand functions that are growing over time. The regional rate of growth in demand for timber products, b_i. Regional demand functions are written empirically as

$$(21) \quad P(t) = (A_i)*\exp(b_i t) – B_i(t)*Q(t).$$

Because economic growth in developing regions like the Asia - Pacific region, China, South America, and Africa, may be more rapid than in the developed countries, we assume that b_i is 1.50 % for developing regions, and 0.75% for the OECD countries and the Former Soviet Union. Over time, the rate of growth of demand is declining to 0 in each region over the 150 year time period of this model.

Using equation (20), annual estimates of the regional benefits or losses from climate change are developed. The net present value of these annual effects are presented in tables 4 and 5 for the four scenarios. Globally, net market surplus is expected to increase from $105.1 billion (USD) in the Schlesinger dieback scenario to $283.8 billion in the Hamburg T-106 regeneration scenario. These changes amount to increases of 3.0 % to 6.7 % of the total value of the market. These benefits are enjoyed almost entirely by consumers. Producers experience gains in the dieback scenarios because prices are relatively higher in the short term. These gains are concentrated in the developing regions, where dieback effects are minimal, productivity increases, and these regions can take advantage of the relatively short rotation lengths in plantations.

The results are not constant across regions, however, as some regions experience gains and others losses. For example, in the Schlesinger regeneration scenario, North America and the Former Soviet Union experience welfare losses during climate change as producers struggle with the consequences of dieback. Although gains in forest productivity offset dieback in the long run, these benefits do not occur for many years, and discounting minimizes these distant effects.

These results suggest that it is important to measure the intertemporal effects of climate change, particularly in stock resources such as forestry. Figure 3 shows the pathway of welfare effects for North America. In both dieback cases (Hamburg T-106 and Schlesinger), there are short term losses in welfare. Although consumers in North America benefit in all time periods, producer welfare declines in the early periods. These early losses cause the net present value of welfare to decline relative to the baseline.

Similarly, consumers in Oceania gain from climate change because prices are lower. In the Hamburg scenarios, however, producers are affected by lower ecological production and timber yield. These producer effects are compounded because Oceania is expected in the baseline to be large supplier of future timber as plantations in that region expand.

Consumers and producers gain from climate change in developing countries. Consumers gain from lower prices, and producers gain from minimal dieback and higher forest productivity. Producers in these regions take advantage of dieback and longer rotations in developed countries by expanding production in plantations in early periods. The long term benefits, however, are mainly a result of increased timber yields, as these regions production increases from the effects of climate change.

Asia-Pacific and Africa do experience producer losses in the Schlesinger regeneration scenario. Although ecosystem production increases in these regions, it increases less than in other plantation regions. Harvests therefore do not increase enough to offset the losses in standing timber value caused by lower global prices. In the dieback scenario, higher short term prices lead to additional harvesting in these regions, and gains in producer welfare.

CONCLUSION

This paper presents the potential impacts of climate change on global timber markets. The results of Global Circulation Models are used by an empirical ecological model to predict the steady state impacts of climate change on global forested ecosystems. These results are then introduced into two dynamic scenarios of ecological change during climate change. The dynamic ecological results are then linked to a dynamic timber market model of the world to estimate harvest, management, and welfare effects in nine global regions.

In general, the results suggest that markets are likely to benefit from climate change. Benefits occur as prices decline relative to the baseline case and timber supply expands. For example, forests are predicted to expand approximately 20%. These expansions, however, are not uniform, as they occur predominately in boreal and tropical inaccessible forests. In temperate regions, the total area of land in forests expands only 6%. Forest productivity is also expected to increase. The models predict that on average, forest net primary productivity will increase by 18 to 44% depending on the climate scenario.

In temperate regions, more productive timber types are expected to replace less productive timber types as species migrate. Climate change allows southern species to survive in regions farther to the north, and markets will quicken the pace of migration as managers respond to changing conditions. Although overall management intensity declines in temperate forests, timber yields are increasing as productive forests are converted to more productive timber types during climate change.

Production in subtropical regions is expected to increase in response to higher productivity. The productivity increase also causes management intensity to rise in the near term in the subtropical region. In the long run, the reduction in global prices mutes this productivity incentive and subdues future management intensity increases.

Inaccessible regions will experience an increase in ecological productivity and a slight increase in harvests as well. However, the most marked change in the boreal forest will be an extensive northward expansion in area towards the North Pole. This new boreal forest is predicted to remain largely inaccessible because of the lower timber prices. This implies that climate change will actually increase the amount of wilderness forest in the world, although this new wilderness will lie close to the North Pole.

Global welfare is expected to increase from 3.0% to 6.7%. Consumers gain in all cases as timber prices are predicted to be lower than the baseline. Producer surplus results vary from region to region. In general, producers in developing countries gain from climate change because they experience larger productivity gains whereas producers in developed countries lose. These general results, however, can vary by country as some areas experience productivity declines in certain scenarios.

In general, producers and consumers gain in developing countries from climate change. Although prices are lower in these regions, these producers gain from increased timber yields, and lower long term management costs. The results in developed countries vary from region to region. Consumers gain in these regions in all periods, however producer welfare tends to decline. Timber yields increase in these regions, but foresters are less able to adapt to climate change because timber stocks are longer lived. In the dieback scenarios in particular, these regions experience direct losses in the value of the initial standing stock of trees.

These results are broadly consistent with Sohngen and Mendelsohn (1998), who suggested that US timber market benefits would range from 1% to 10% of baseline welfare. However, these results stress the importance of capturing global market effects. This is particularly true given that the ecological models predict widely divergent results from region to region. For example, BIOME3 predicts that dieback effects are particularly heavy in North America, while less prevalent in emerging plantation regions and elsewhere. These results also highlight the importance of the timing of welfare effects. Although North America and the Former Soviet Union experience long term gains in annual welfare effects, the net present value of the annual effects is negative due to producer losses early during climate change.

The regeneration scenarios predict larger gains than the dieback scenarios, a result that is also consistent with Sohngen and Mendelsohn (1998). Consumer surplus is unambiguously larger in the regeneration case due to lower prices. However, the gain or loss in producer surplus differs from region to region. Producers surplus is smaller in the regeneration scenario in the developing regions due to lower prices, for example. In regions that experience dieback, like North America, the loss in producer surplus is smaller in the regeneration case because there is no direct loss of stock due to dieback.

The results of this study contrast with earlier estimates of Solomon et al. (1996), who predicted that there would be large negative consequences from climate change, particularly in developing countries. That study employed simple steady state models which do not adequately capture either intertemporal effects or global adjustments. While Perez-Garcia et al. (1997) utilized a global timber market model, they did not examine either a change in forest area, or the change in timberland management. Given the short term importance of plantations for mitigating global effects, these adjustments are important to include.

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Table 1: Change in the distribution and production of major global ecosystem types predicted by the BIOME3 ecological model for a doubled CO_2 climate.

	Hamburg T-106			Schlesinger		
FORESTED BIOME	Prop. Changing	Relative Size	NPP % Change	Prop. Changing	Relative Size	NPP % Change
Boreal Deciduous	0.65	0.62	180%	0.30	2.45	143%
Boreal Coniferous	0.31	1.08	12%	0.42	1.36	7%
Temp.-Boreal Mixed	0.36	1.41	12%	0.74	0.53	1%
Temp. Conifer	0.46	1.53	17%	0.79	1.07	17%
Temp. Deciduous	0.20	1.71	20%	0.67	0.68	19%
Temp. Broad. Ever.	0.12	1.31	28%	0.56	1.04	19%
Tropical Seasonal	0.13	1.50	43%	0.33	0.89	25%
Tropical Rain	0.09	1.09	37%	0.20	0.93	24%
Tropical Deciduous	0.20	2.37	41%	0.62	0.98	23%
TOTAL FOREST	0.28	1.30	44%	0.52	1.00	18%

Table 2: Initial area of land in northern inaccessible boreal and forests and tropical forests, area harvested between 1995 and 2140, and area remaining in these forests in 2140 for the baseline case and the two climate change scenarios. The results are averaged for the dieback and regeneration scenarios.

	North America	Europe	FSU	Tropics
	Million Hectares			
Inaccessible area in 1995	157	20	322	826
Panel A. Baseline				
Area Harvested, 1995 - 2140	47	5	15	74
Remaining Inaccessible Area in 2140	110	15	307	752
Panel B. Hamburg				
Area Harvested, 1995 - 2140	41	5	21	62
Remaining Inaccessible Area in 2140	147	18	348	1187
Panel C. Schlesinger				
Area Harvested, 1995 - 2140	43	4	21	54
Remaining Inaccessible Area in 2140	136	20	352	1031

Table 3: Comparison of timber harvests between the climate change cases and the baseline case. The values represent proportional change in regional timberland harvests relative to the baseline case. The results are averaged for the regeneration and dieback scenarios over 50 year time periods.

Years	NA	Eur.	FSU	Oc.	SA	China	India	A-P	Af.	Total
Panel A. Hamburg T-106										
1990 - 2040	-0.01	0.05	0.06	-0.03	0.19	0.11	0.22	0.10	0.14	0.06
2040 - 2090	0.12	0.02	0.18	-0.05	0.47	0.29	0.55	0.30	0.41	0.21
2090 - 2140	0.19	0.14	0.71	-0.10	0.50	0.33	0.59	0.37	0.39	0.30
Panel B. Schlesinger										
1990 - 2040	-0.02	0.10	0.03	0.12	0.10	0.10	0.14	0.04	0.05	0.05
2040 - 2090	0.16	0.13	0.07	0.32	0.22	0.26	0.30	0.14	0.17	0.18
2090 - 2140	0.27	0.26	0.95	0.31	0.23	0.31	0.29	0.17	0.07	0.29

Abbreviations for regions are as follows: NA=North America; Eur=Europe; FSU=Former Soviet Union; Oc=Australia and New Zealand; SA=South America; A-P= Asia-Pacific.

Table 4: Regional welfare effects under the Hamburg T-106 scenario. Dollar values are net present values of the stream of welfare benefits (losses), calculated in 1990 US$. The dollar values represent the change in welfare from the baseline.

	DIEBACK			REGENERATION		
	Consumer Surplus	Producer Surplus	Net Surplus	Consumer Surplus	Producer Surplus	Net Surplus
	1990 US $$					
Panel A. Developed Countries						
North America	$ 55.3	($ 43.7)	$ 11.6	$ 95.5	($ 30.5)	$ 65.0
Europe	30.7	(7.8)	22.9	52.9	(19.1)	33.9
FSU	25.5	(9.0)	16.5	44.0	(3.9)	40.1
Oceania	1.9	(3.2)	(1.3)	3.3	(12.5)	(9.1)
Panel B. Developing Countries						
South America	12.3	29.8	42.1	20.8	17.9	38.7
China	12.1	6.2	18.3	20.5	0.6	21.1
India	2.9	5.9	8.8	5.0	3.8	8.8
Asia-Pacific	18.4	13.6	32.0	31.2	3.9	35.1
Africa	6.2	10.4	16.6	10.5	6.7	17.2
Global Total	**$ 165.3**	**$ 2.3**	**$ 167.6**	**$ 283.8**	**($ 33.0)**	**$ 250.7**

Table 5: Regional welfare effects under the Schlesinger scenario. Dollar values are net present values of the stream of welfare benefits (losses), calculated in 1990 US$. The dollar values represent the change in welfare from the baseline.

	DIEBACK			REGENERATION		
	Consumer Surplus	Producer Surplus	Net Surplus	Consumer Surplus	Producer Surplus	Net Surplus
	1990 US $$					
Panel A. Developed Countries						
North America	$ 35.0	($ 39.3)	($ 4.3)	$ 80.3	($ 24.7)	$ 55.5
Europe	19.5	25.8	45.3	44.5	5.6	50.1
FSU	16.2	(24.6)	(8.4)	37.0	(0.2)	36.8
Oceania	1.2	12.0	13.2	2.8	0.1	2.9
Panel B. Developing Countries						
South America	7.8	14.7	22.6	17.5	2.3	19.8
China	7.7	8.6	16.4	17.2	5.5	22.7
India	1.9	3.8	5.7	4.2	1.6	5.7
Asia-Pacific	11.8	3.3	15.1	26.2	(7.5)	18.7
Africa	4.0	3.5	7.5	8.8	(0.8)	8.0
Global Total	**$ 105.1**	**$ 7.9**	**$ 113.0**	**$ 238.4**	**($ 18.1)**	**$ 220.3**

Figure 1: Forestland area predicted to shift from one ecosystem type to another during climate change by the BIOME3 model using the Hamburg T-106 climate change scenario. Black areas are those undergoing conversion, tan areas are unforested land, or forests not undergoing change.

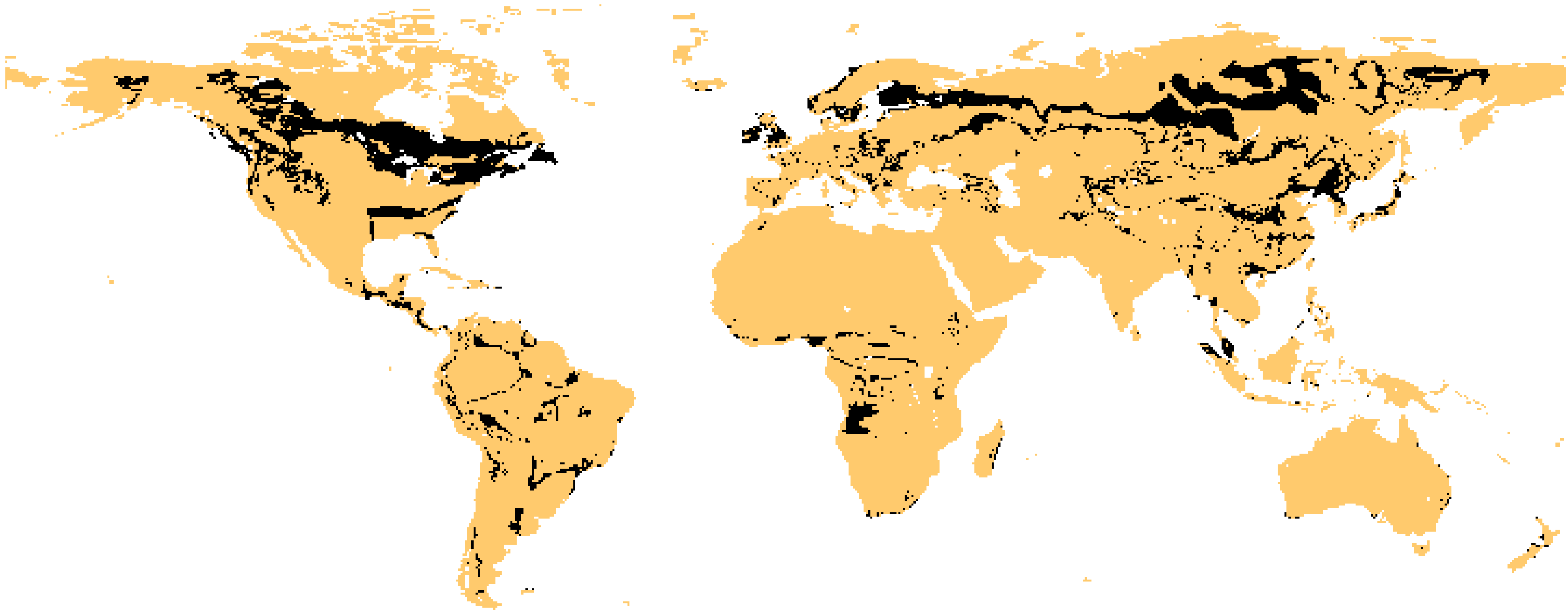

Figure 2: Global timber prices in baseline case and two climate change cases.

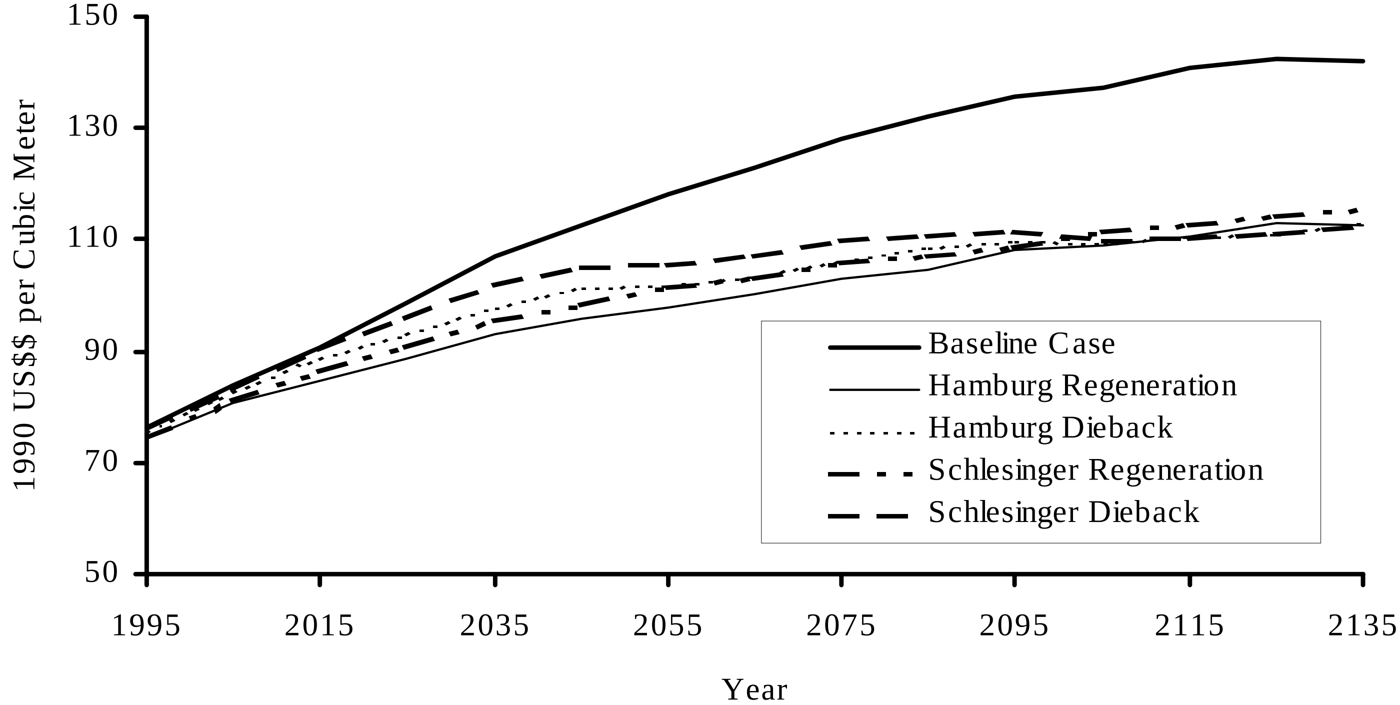

Figure 3: Annual welfare effects for North America under the four cases. The figure represents the change in welfare relative to the baseline case