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A Global Model of Climate Change Impacts on Timber Markets

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Several papers have now estimated the impact of climate change on national timber markets, but few studies have measured impacts globally. Further, the literature on impacts has focused heavily on changes in productivity and has not integrated movements of biomes as well. Here, a dynamic model of ecological change and economic change is developed to capture the impact of climate change on world timber markets. Climate change is predicted to increase global timber production as producers in low-mid latitude forests react quickly with more productive short-rotation plantations, driving down timber prices. Producers in mid-high latitude forests, in contrast, are likely to be hurt by the lower prices, dieback, and slower productivity increases because of long-rotation species. Consumers in all regions benefit from the lower prices, and the overall impacts of climate change in timber markets are expected to be beneficial, increasing welfare in those markets from 2% to 8%.

Key words: climate change, dynamic optimization, integrated assessment, timber markets

Introduction

Climate change is predicted to have far-reaching effects on forests throughout the world. Ecological models predict climate change will shift the geographic distribution of tree species (Emanuel, Shugart, and Stevenson; Solomon; Shugart et al.; Neilson and Marks) and alter productivity (Melillo et al.). Despite the global nature of climate change, most analyses of timber markets have restricted themselves to single countries or regions (Binkley; Bowes and Sedjo; Joyce et al.; Burton et al.; Sohngen and Mendelsohn; McCarl et al.). While regional analysis can provide insights into how landowners and markets adjust and adapt to large-scale global climate change, regional studies cannot measure how the rest of the world responds to climate change. For instance, Joyce et al.; Sohngen and Mendelsohn; and McCarl et al. simply make assumptions about how supply will change in other regions.

A global market approach is particularly important for forestry given that climate change is predicted to affect regions very differently. For example, the ecological literature suggests high latitude forests are likely to expand deeply into the tundra, mid-high latitude forests could undergo dieback and large changes in species distribution, and low

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latitude forests are likely to increase productivity (Watson, Zinyowera, and Moss; Gitay et al.).

Despite ecological predictions that species will experience stock effects and move across the landscape, most timber market studies focus solely on future changes in forest productivity (Binkley; Joyce et al.; Perez-Garcia et al.; McCarl et al.). Perez-Garcia et al. use a global economic model, but ignore the movement of species across the landscape. Alternatively, Darwin et al. (1995, 1996) present a computable general equilibrium model of both agricultural and forestry markets. While this approach captures interdependencies among important land users, it considers only steady-state changes in forest distribution. Such an approach does not capture important inter-temporal dimensions of the movement of species across the landscape, such as potential early losses of species due to dieback, and regeneration costs.

To capture the range of ecological responses, to reflect regional differences, and to capture general equilibrium price effects, it is critical that impacts be measured on a global scale. This study develops a dynamic market analysis of the impacts of climate change on global timber markets by integrating a global ecological model (Haxeltine and Prentice) with a global economic model (Sohngen, Mendelsohn, and Sedjo). The ecological model, BIOME3, is chosen because it is the only global model currently available which predicts both the shifts in species and the changes in productivity expected from climate change in a common framework. The economic model is an optimal control model, expanded from a U.S.-only study (Sohngen and Mendelsohn) to the entire globe. This is the first analysis to use this global economic model for examining the welfare impacts of climate change.

This study makes a contribution to the literature by using an optimal control model to explore how global markets may adapt to a range of ecological effects in different regions. The analysis, however, has several important limitations. First, we use only two climate scenarios and one ecological model. Consequently, we cannot present a full range of possible ecological predictions. There is considerable uncertainty about future economic, climate, and ecological conditions; readers must be careful not to interpret the scenarios as the only possible outcomes. Second, although we provide a range of dynamic outcomes, we must make some strong assumptions to derive dynamic ecological scenarios from the available equilibrium models. Third, we ignore possible shifts in the relative value of timber species with respect to one another, and instead focus on a measure of overall timber scarcity (a global timber price). Fourth, despite the importance of non-timber forest products and non-market values for forests, our analysis ignores these aspects. These important topics are ripe for future research.

Climate and Ecological Models

We use climate change predictions from two equilibrium general circulation models (GCMs). Steady-state forecasts from the Hamburg T-106 model (Claussen; Bengtsson, Botzet, and Esch) and the UIUC model (Schlesinger et al.) are used to predict changes in climate for 0.5 × 0.5 degree grid cells across the globe. The GCMs generate equilibrium global climate forecasts for current atmospheric CO_2 concentrations (340 ppmv) and for a 550 ppmv (doubling) scenario. Note that doubling refers to the effective doubling of all greenhouse gases, so that CO_2 itself is not strictly doubled in concentration. Globally, the Hamburg model predicts a 1°C increase in temperature over land and water, while the UIUC model predicts a 3.4°C change. The Hamburg scenario predicts relatively larger temperature changes in the high latitudes compared to the UIUC scenario, while the UIUC scenario predicts larger temperature changes in the low latitudes. These regional differences suggest the two climate models will have different regional impacts on timber supply.

The climate predictions are used by a global terrestrial biosphere model (BIOME3) to estimate equilibrium changes in the distribution of timber species and the productivity of those species across the globe (Haxeltine and Prentice). Biomes are ecological types which represent accumulations of different species. We focus on the forested biomes in this study, and refer to them throughout as forest types.

While some models predict net primary productivity (see Melillo et al.) and some models predict global changes in the distribution of forest types (see Neilson and Marks), most models do not capture the two effects simultaneously. Optimizing over both effects is important because changes in net primary productivity (NPP) can affect species dominance within a forest type, and the species present can affect NPP. BIOME3 also includes carbon fertilization through the physiological effects of increased carbon dioxide on water use efficiency of plants. Based on simulations with the Hamburg climate scenario, carbon fertilization enhances the gain in NPP by 35% (Haxeltine).

BIOME3 provides more disaggregated results than the economic model can use. We aggregate the predicted effects for each contiguous forest type in BIOME3 for each region in our economic model. These aggregated effects are used to predict changes in average productivity $\theta_i(t)$, changes in forest types $\delta_i(t)$, and the area of land that can be regenerated in each timber type i in the economic model.

BIOME3 makes predictions about equilibrium outcomes. Although new ecosystem models are developing transient ecological scenarios, these models currently cover only limited regions. We consequently generate transient scenarios directly from BIOME3 making several strong assumptions.

First, we assume climate changes linearly between now and 2060, when greenhouse gases are expected to double (Houghton et al.). In 2060, we assume climate stabilizes because of an effective control program that holds greenhouse gases at 550 ppmv. This assumption allows us to solve our optimal control problem by creating a long-term steady state. By limiting the increase in greenhouse gases to doubling, we focus on the effects of emissions over the next six decades and not on emissions after 2060. Without the stabilization program, changes would continue to occur beyond 2060. Although these future effects are not likely to have a large impact on the timber market for the next half century, they will affect events by the end of the century. Second, we assume all the equilibrium ecological changes will occur proportionately over the next 60 years. That is, we assume one-sixth of the expected shifts in forest types or productivity between 2000 and 2060 will occur each decade.

Further, we assume changes in merchantable timber growth rates are proportional to predicted changes in NPP. NPP measures the net carbon stored annually by an ecosystem. We assume this ecological measure is closely correlated with the growth rate of the merchantable portion of a tree. If NPP increases by 10%, for example, we assume the merchantable part of trees in this system will grow 10% faster. This assumption implies the merchantable part of a tree remains in the same proportion to its limbs and roots and to the carbon on the forest floor. BIOME3 assumes climate change does not alter these relative allocations, so our assumption of proportionality is consistent with that model.[1]

One problem with BIOME3 is that it predicts potential world vegetation as though humans do not exist. Land use is not taken into account. Because it is unlikely forests will displace prime agricultural land, we use data from Olson, Watts, and Allison to delineate prime farmland around the world, and to prohibit forests from using this land. This assumption protects the results from unrealistic acquisitions of cropland. However, we recognize climate change is likely to affect the boundaries between marginal crop, grazing land, and forests. Consequently, while it would be preferable to model both agriculture and forestry markets simultaneously (e.g., Darwin et al. 1995), such a framework is beyond the capacity of this study. Using Olson, Watts, and Allison precludes the use of existing cropland, but if BIOME3 predicts expansion of forests into grassland and tundra, we allow the expansion. We explore some alternative assumptions about forestland expansion in our sensitivity analyses.

Economic Impact Model

The global timber model of Sohngen, Mendelsohn, and Sedjo is used to estimate a baseline case for timber markets. The model maximizes the net present value of net global timber market surplus, subject to equations of motion on the quantity of land and stock in 46 different ecosystem and management types throughout the world. Annual net market surplus is consumer surplus from selling timber logs minus the costs of producing timber and holding timberland. Formally, the baseline (no climate change) optimization problem is expressed as:

$$\text{(1)} \quad \underset{H_i(t),G_i(t),N_i(t),m_i(t)}{\text{Max}} \int_0^{\infty} \Big\{ \int_0^{Q^*(t)} \big\{ D\big[Q\big(H_1(t) \ldots H_I(t)\big), Z(t)\big] - C_H\big(Q(\cdot)\big)\big\}\, dQ(t) - \sum_i C_i^G\big[G_i(t), m_i(t)\big] - \sum_{i \in emerg} C_i^N\big(N_i(t)\big) - \sum_i R_i\big(X_i(t)\big)\Big\} e^{-rt}\, dt,$$

where $D[Q(H_i(t) \ldots H_I(t)), Z(t)]$ is a global demand function for consuming the timber from $H_i(t)$ hectares of land harvested in each of i timber species, given income $Z(t)$. $C_H(Q(\cdot))$ are costs of accessing, harvesting, and transporting logs to markets (the notation for hectares and time is suppressed here). Each hectare of forestland has a concave yield function, $V_i(t - t_0; m_i(t_0))$, which determines the cubic meters of merchantable timber per hectare at $t - t_0$ years after regeneration. Yield is also a function of management intensity determined at the time of regeneration, $m_i(t_0)$. $C_i^G[G_i(t), m_i(t)]$ represents the cost of planting $G_i(t)$ hectares of land in each of the i forest types. The cost of regenerating land determines management intensity, $m_i(t)$. $C_i^N(N_i(t))$ are the costs of establishing $N_i(t)$ new hectares of land in high-value plantation types in subtropical regions. The term *emerg* is used to denote the set of species in this region. Initial establishment costs are higher than regenerating existing stands due to the relatively high costs of

[1] A number of ecologists suggest that while NPP rises, net ecosystem production (NEP) or net biome production (NBP) may remain stable or decline due to dieback and decay processes when plant-level effects are aggregated over larger areas (see Gitay et al.). No global terrestrial models currently predict NEP or NBP; however, we capture this process in our dieback scenario, where NEP and NBP in many forest types decline during the period 2000 to 2060, even while NPP is increasing.

establishing non-indigenous species in subtropical regions.[2] $R_i(X_i(t))$ is the land rental cost associated with holding land in each timber type. These costs range from high in regions where opportunity costs are high, such as near high-value agricultural regions, to zero in inaccessible forests.

The change in the stock of land maintained in forests at any moment is specified as:

$$\dot{X}_i = -H_i(t) + G_i(t) + N_i(t) \qquad \forall i. \tag{2}$$

The equations for different stocks of timber expressed in (2) are the difference between the area of land harvested and the area of land regenerated in any time period. Note that $N_i(t)$ will be zero in high latitude regions. In addition, initial forest stocks must be given, and all choice variables are constrained to be nonnegative. Data sources for initial inventories and yield functions, as well as functional forms for the cost functions, are provided in Sohngen, Mendelsohn, and Sedjo. The real interest rate for the baseline market scenario is 5%.

The annual global market demand function for timber logs is given as:

$$P(t) = 140 * \exp(bt) - 0.004 * Q\big[H_1(t) \ldots H_I(t)\big],$$

where $Q(\cdot)$ is the quantity of timber consumed from the i timber types in million m^3, b is the annual rate of growth in demand, and $P(t)$ is the global price per m^3. The global demand function is assumed to be the sum of the regional demand functions from nine regions. Regional demand functions are calculated assuming a uniform price elasticity of −1.0 (Sedjo and Lyon) and then allocating global shares given the 1995 observed shares of consumption in each region [Food and Agriculture Organization (FAO) 1997]. Global demand is assumed to increase at a 1% rate, declining to zero in the year 2145. However, we expect demand to increase more rapidly in developing regions than in developed regions, so we assume baseline consumption expands 0.75% per year in Organization for Economic Cooperation and Development (OECD) regions and the Former Soviet Union, and 1.50% per year in developing regions. Although world GDP is expected to grow at a 1.50% rate in the long run, we assume timber demand grows more slowly, reflecting general shrinkage in manufacturing in GDP.

The global timber model predicts decadal harvests for each timber type $H_i(t)$, the area regenerated, $G_i(t)$ or $N_i(t)$, and management intensity $m_i(t_0)$. Global timber prices $P(t)$ are calculated from the demand function. First-order conditions for the baseline model and a number of economic scenarios were presented in Sohngen, Mendelsohn, and Sedjo. Our study focuses on presenting aggregate effects across the timber types modeled in nine major timber-producing regions of the world. (More disaggregated results are available from the lead author upon request.) These regions include North America (United States and Canada), Europe (Eastern and Western Europe), Former Soviet Union, Oceania (Australia and New Zealand), China (including Mongolia), Asia-Pacific (most countries except small island states), India, South America (including Central America and Mexico), and Africa. Annual net market surplus for region L is measured as:

[2] Unlike Sedjo and Lyon, who assume exogenous technological change, this study assumes all yield increases result from price stimulus or climate change. We note that in forestry, however, technological change often includes introductions of non-indigenous species, an effect captured explicitly here. Further, climate change itself is predicted to lead to this type of technological change as southern species are predicted to be suited for replanting in more northerly locations.

$$(3) \qquad W_L(t) = \int_0^{q^*_{c,L}(t)} d\left[q_{c,L}(t), Z_L(t)\right] dq_{c,L} + P(t)\left[q_{H,L} - q^*_{c,L}\right] - C_{H,L}\left(q_{H,L}(t)\right) - \sum_{i \in L} C_i^{G,L}\left[G_i(t), m_i(t)\right] - \sum_{i \in L} C_i^{N,L}\left(N_i(t)\right) - \sum_{i \in L} R_i\left(X_i(t)\right),$$

where $(i \in L)$ 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 region 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; $P(t)$ is the global price; $C_{H,L}(\cdot)$ accounts for harvest and access costs; $C_i^G(\cdot)$ accounts for regeneration costs; $C_i^N(\cdot)$ accounts for the costs of planting new forests; and $R_i(X_i(t))$ is the land rent for $X_i(t)$ hectares of forests held at time t. Regions producing (consuming) more wood products than they consume (produce) are net exporters (importers). Net exporters (importers) benefit (lose) from international trade. These benefits (losses) are measured as $P(t)(q_{H,L}(t) - q^*_{c,L}(t))$.

Capturing Ecological Changes in the Economic Model

The model is adapted for climate change following Sohngen and Mendelsohn to predict harvests, global timber prices, and regeneration for the climate change cases.[3] This study explores the two expected impacts of climate change on forests as predicted by BIOME3: (*a*) changes in the growth of timber and (*b*) changes in the distribution of timber types. The effect of productivity changes on annual growth rates is calculated as:

$$(4) \qquad V_i\left(t - t_0; m_i(t_0), \theta_i(t)\right) = \int_{t_0}^{t} \dot{V}\left(s; m_i(t_0), \theta_i(s)\right) ds,$$

where $\theta_i(t)$ is the annual change in net primary productivity (NPP) as predicted by BIOME3 and our assumptions above. The stock of forests is a function of the cumulative effect of $\theta_i(t)$ on the annual growth of trees. During early periods, when climate is just beginning to have global effects, these changes will have little impact on timber stocks. After many years, however, $\theta_i(t)$ will have a larger impact as the cumulative effect of growing faster increases the size of the stock.[4]

The stock of forests is also a function of the movement of species across the landscape. We consider two different, and likely extreme, scenarios of dynamic processes governing the movement of species: dieback and regeneration. As forest types move because of climate change, the dieback scenario predicts the loss of a large fraction of the existing stock (see King and Neilson; Smith and Shugart). Dieback alters equation (2) as follows:

$$(5) \qquad \dot{X}_i = -H_i(t) - \delta_i(t)X_i(t) + G_i(t) + N_i(t),$$

where $\delta_i(t)$ is annual dieback as predicted by BIOME3 and our assumptions above. By directly affecting stock, dieback can cause net growth in our timber types to decline even if $\theta_i(t)$ in equation (4) is positive. Dieback also alters timber harvests because some of the stock that dies back will be salvaged. This salvage enters the equation for net market surplus through harvests. The proportion of salvage in each timber type varies

[3] For more details concerning the mathematical formulation of the model, see Sohngen and Mendelsohn, and Sohngen, Mendelsohn, and Sedjo. Technical appendices are available from the authors upon request.

[4] The studies in the literature actually make a range of assumptions about how climate affects productivity. Thus the specific form of equation (4) depends on the underlying assumptions.

from zero to 75%, depending on access and value. For instance, in inaccessible regions throughout the world, we assume there is no salvage; but in highly valuable timber regions such as the southern United States, salvage is assumed to be 75%.

Alternatively, ecological adaptation to climate change might rest largely on the regeneration process. Existing trees will continue to grow, but they will not be able to regenerate successfully. There is no dieback in the regeneration scenario, and so forest types shift more slowly. The regeneration scenario is therefore more optimistic because there is no loss of existing trees but there is a long lag before new species get established.

Although initial stocks are not heavily influenced by climate change in the regeneration scenario, harvesting behavior can be affected. For instance, in northern regions where it becomes possible to introduce southern timber types that grow faster, landowners may have an incentive to harvest even young trees to make way for new species shown to grow more quickly. To account for this practice, we separate the timber stocks in the model into stocks which shift from one type to another during climate change (denoted as "e"), and stocks which remain in their initial timber type (denoted "i," as before). The equations of motion for the regeneration model are the same as in (2), but there are now additional equations to represent the new stocks labeled as "e." As in the dieback scenario, additional constraints are placed on $G_i(t)$ and $N_i(t)$ such that species can be shifted from one region to another only when climate has changed enough to allow them to move.

The baseline and climate change models are written and solved using GAMS software and the MINOS solver. The models include a nonlinear objective function described by equation (1). A set of constraints is imposed to reflect the movement of timber from one age class to another, stocking density of stands at regeneration time, and the conditions imposed by our assumptions about climate change impacts. The model is solved in decadal time steps starting in 1995. Terminal conditions are imposed on the system for the 150th year in order to solve the model. A long time horizon is chosen because climate change is expected to affect markets for at least the next 70 years; furthermore, markets for stock resources like forests, where there are long intervals between regenerating stands and harvesting them, will continue to adjust beyond that time frame. (Additional technical information on the model and the solution is available from the authors upon request.)

Results

In the baseline scenario, global log prices are predicted to rise approximately 0.4% per year because increases in demand outpace productivity increases. Regional stumpage prices will vary from these prices, depending on timber quality, harvest, access, and transportation costs. Most of the growth in production is predicted to occur in non-indigenous plantations established in subtropical regions of South America, Oceania, Asia-Pacific, and Africa. These areas have relatively low costs for converting poor agricultural lands and native forests to high-value plantations using southern U.S. pine, Monterrey pine, and eucalyptus. Subtropical plantations are predicted to increase in the baseline by 273,000 hectares per year on average, with 27% of the new plantations predicted to occur in South America, 20% in Oceania, 8% in Asia-Pacific, and 25% in Africa. Our baseline prediction is lower than the recent historical average annual increase in non-indigenous plantations in subtropical regions of 6 million hectares per year for the period 1980 to 1990 (FAO 1995). However, we focus only on industrial plantations and not plantations devoted to fuelwood production.

With climate change, BIOME3 predicts large conversions from one forest type to another, large conversions of nonforest land to forestland, and higher NPP. In the Hamburg scenario, BIOME3 predicts fairly large losses of existing timber stands in high latitude regions, but a global forest expansion of 27% and a 38% increase in productivity. With the UIUC scenario, predicted losses of existing stands are even more widespread; overall, forests expand less (19%), and productivity increases less (29%) in comparison to the Hamburg scenario. While the findings of this research are limited by our reliance on only one ecological model, these ecological results are broadly consistent with the literature (e.g., Watson, Zinyowera, and Moss; Gitay et al.).

Four scenarios of transient ecological change are developed to provide decadal predictions of the ecological variables described above. These include a dieback and regeneration scenario for both the Hamburg and UIUC climate scenarios. Our dynamic economic model takes these decadal predictions as exogenous, and predicts how timber markets may react. The economic model uses dynamic optimization techniques to predict how a risk-neutral supplier would change planting, management, and harvesting decisions. Aggregating these changes across the global market, the model predicts how harvest quantities, and therefore prices, will change. The model does not capture feedback effects from the market back onto climate itself because these feedbacks are expected to be small.[5] However, the market does affect ecosystem dynamics, as market forces can facilitate change by harvesting slower growing trees or trees destined for dieback and planting trees designed for the new climate.

As illustrated by figure 1, the economic model predicts that global timber supply increases and prices decline under all scenarios. The dynamic treatment in this study has important implications for welfare estimates. In order to make broad intertemporal patterns clear, we discuss near-term (1995 to 2045) and long-term (2045 to 2145) effects separately. In the near term, the dieback scenario leads to higher prices relative to the regeneration scenario because a large proportion of the world's accessible forests is destroyed by shifting biomes. Average regional dieback predicted by BIOME3 is high, as shown in table 1. Note that the averages presented in table 1 are shown to illustrate broad differences among regions; the losses for particular forest types (i) used in the economic model differ from these averages. The largest losses, however, are centered in mid-high latitude regions of North America, the Former Soviet Union, China, Oceania, and to a lesser extent in Europe—regions which currently supply 77% of the world's industrial wood (FAO 1996). In the long run, productive species replace the lost forests so that long-run productivity increases.

The mid-high latitude forests that die under the dieback scenario still change with the regeneration scenario, but no stock is lost. Prices are relatively lower in the regeneration scenario at first. However, in the long run, the period of conversion ends and the same productive forests take over, causing long-run prices to converge in both scenarios. The difference in prices between the dieback and regeneration scenarios declines before

[5] Forests could affect climate through the carbon cycle by taking carbon out of the atmosphere or by emitting it (see Sohngen and Sedjo). Forests could also affect climate by changing the reflection of light off the earth's surface. Finally, forests could have an impact on local climate by changing the local hydrological cycle.

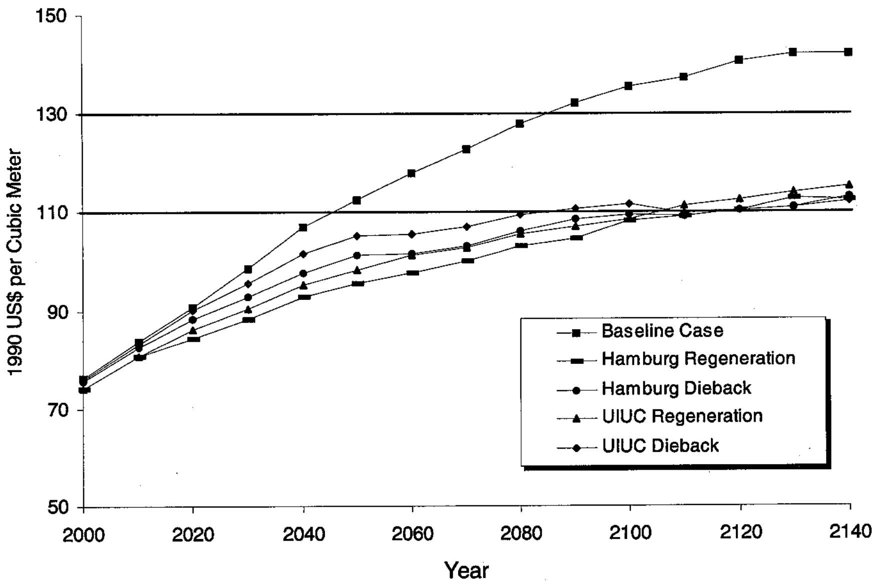

Figure 1. Global timber prices over time

the conversion process ends because it takes longer for more productive species to take hold in the regeneration scenario.

Long-run prices are consistently lower than the baseline in all scenarios. Early forest losses are offset by moving more productive southern species further north. "Net Area Change" in table 1 is the prediction by BIOME3 of the relative area of forests after climate change. While BIOME3 predicts relatively large increases in forest area, our assumption that forests do not shift into high quality agricultural land limits most of the expansion to conversions of one forest type to another, or to shifts of low-value grasslands and tundra to forests.

Accessible forests in the economic model consequently increase by only 5%. Most of the increase in forestland is predicted to occur in inaccessible boreal and tropical regions (31% to 41%) which are never used for harvests (table 1). The forestland gains in inaccessible low-mid latitude regions should be treated with caution, however, because some of these lands may be used for new agriculture (FAO 1995). Moreover, even if these lands were converted to new agricultural uses, the conversion would have minimal effects on timber prices because only a small fraction of productive forests would be at risk.

For the most part, these changes in forest areas are consistent with recent experiences in markets. In North America, there are slight losses in accessible forest area. Europe and the Former Soviet Union gain forestland. Seventy-eight percent of the gain in accessible forestland in Europe occurs at the expense of low-value shrub and poor woodlands in the Mediterranean region, including Spain and Portugal. The Former Soviet Union increases accessible forest area by converting 5–6 million hectares of currently inaccessible boreal forests due to a more than 60% increase in yield. Also, 26–28 million hectares of grass and steppe lands are converted in Belarus, Uzbekistan, southern Russia, and Kazakhstan to productive temperate softwoods and hardwoods. It is possible this

Table 1. Percentage Change in Forest Areas by 2145, Based on the Hamburg and UIUC Climate Scenarios Used for Ecological Predictions

	Hamburg Scenario				UIUC Scenario			
Timber-Producing Regions	Die-back	Net Area Change	Accessible[a] Net Change	Inaccessible Net Change	Die-back	Net Area Change	Accessible[a] Net Change	Inaccessible Net Change
	Percent (%)							
High Latitude Forests:								
North America	29	3	(7)	35	28	4	(2)	24
Europe	4	16	14	23	9	7	4	36
Former Soviet Union	12	12	14	13	21	14	15	15
China	9	41	5	188	20	20	0	109
Oceania	58	(3)	(12)	20	56	0	6	38
Low-Mid Latitude Forests:								
South America	0	42	6	44	10	27	(2)	33
India	0	10	9	—	0	(1)	(1)	—
Asia-Pacific	0	23	0	28[b]	0	33	(3)	39[b]
Africa	1	71	5	74	8	38	(4)	41
Total All Forests:	10	27	5	41	16	19	5	31

[a] Accessible forest areas are forests used for industrial purposes. For the low-mid latitude forests, accessible includes only industrial plantations or highly managed forests.

[b] For the Asia-Pacific region, inaccessible forests are the valuable dipterocarp (tropical hardwood) forests of that region. Inaccessible forests also expand in both ecological scenarios for that region, but those changes are suppressed here in order to show changes for the most important market species.

overestimates the potential forest gain in the Former Soviet Union, although we note that recent evidence suggests cropland is currently converting back to forests in those regions where forests are able to grow (FAO 1997).[6]

In the long run, the yield of forests is likely to rise because of two factors. First, BIOME3 predicts that climate change increases the annual growth of merchantable timber by raising NPP (see the "BIOME3" columns in table 2). This is the only effect captured by most other climate change studies of forests (e.g., Joyce et al.; Perez-Garcia et al.; McCarl et al.). Second, BIOME3 predicts that more productive species move poleward. In the long run, this tends to increase the average timber yield for most regions by increasing the area of more productive species, although the effects depend on the climatic predictions. For example, the prediction for North America from the NPP increase alone is that long-run timber yield should increase 17%, but with the expansion of southern species into territory previously occupied by northern species, the economic model predicts an average (continental) increase in merchantable yields of 34% to 41%.

Alternatively, long-run merchantable timber yield in Europe is not predicted to increase as much under the Hamburg scenario as would be predicted by the change in NPP from BIOME3 alone (i.e., 23% change in NPP and 4% change in merchantable timber

[6] Current agricultural analysis predicts generally lower global prices with climate change and relatively small expansions into forests (e.g., Darwin et al. 1995, 1996; Gitay et al.). Although we do not formally predict changes in agricultural land, it is worth noting that our predicted increases in forestland allow for large expansions in agricultural land in fairly low productivity regions predicted by BIOME3 to experience substantial increases in NPP.

Table 2. Percentage Change in Timber Growth Rates by 2145, Based on the Hamburg and UIUC Climate Scenarios Used for Ecological Predictions

	Hamburg Scenario		UIUC Scenario	
Timber-Producing Regions	BIOME3 Predicted Change in NPP	Change in Merchantable Timber Yield	BIOME3 Predicted Change in NPP	Change in Merchantable Timber Yield
	Percent (%)			
High Latitude Forests:				
North America	17	34	17	41
Europe	23	4	23	24
Former Soviet Union	53	44	52	66
China	36	27	38	32
Oceania	(16)	10	13	29
Low-Mid Latitude Forests:				
South America	46	42	23	23
India	45	47	28	29
Asia-Pacific	29	28	12	11
Africa	37	37	21	21

yield; table 2), because Hamburg suggests species movement in Europe causes mostly an expansion of forests into marginal shrublands in Mediterranean areas. While more productive than shrublands, these new forests are less productive than current forests in Europe, and they lower the long-run average yield of all forests. The change is similar for Europe under the UIUC scenario (23% change in NPP and 24% change in merchantable timber yield; table 2) because UIUC predicts mostly conversions of northern species to southern species and less forest expansion (see table 1).

As expected, the regional and temporal effects on timber production for the two climate scenarios are quite different (table 3). In the Hamburg scenario, production increases most heavily in low-mid latitude regions because climate changes are predicted to be mild and the trees respond well to the higher levels of carbon dioxide. In the UIUC scenario, production increases are similar for all regions as larger tropical warming reduces productivity gains in low-mid latitude regions. While the Former Soviet Union is predicted to gain significant production relative to the baseline, these increases take many years to affect markets because species grow slowly there. Europe harvests heavily during early periods to avoid economic losses from dieback in its generally older stock of trees. In contrast, North America has relatively younger timber stocks initially, and it reduces harvests initially. Unlike high latitude forest regions, low-mid latitude forest regions take advantage of higher productivity by increasing timber production in early periods. The baseline predicts that most of the growth in timber harvests occurs in these subtropical regions. Climate change appears to strengthen this trend as fast-growing, non-indigenous plantation species are planted.

Global net market surplus is expected to increase in all scenarios, ranging from $113 billion (US$), or 3%, in the UIUC dieback scenario (table 4, panel C), to $251 billion, or 6.7%, in the Hamburg regeneration scenario (table 4, panel B). Benefits accrue mostly to consumers because prices are lower. One of the most striking regional results is the

Table 3. Percentage Change in Regional Timber Production for 50-Year Time Periods, Based on the Hamburg and UIUC Climate Scenarios Used for Ecological Predictions

	Hamburg Scenario			UIUC Scenario		
Timber-Producing Regions	1995–2045	2045–2095	2095–2145	1995–2045	2045–2095	2095–2145
	Percent (%)					
High Latitude Forests:						
North America	(1)	12	19	(2)	16	27
Europe	5	2	14	10	13	26
Former Soviet Union	6	18	71	3	7	95
China	11	29	71	10	26	31
Oceania	(3)	(5)	(10)	12	32	31
Low-Mid Latitude Forests:						
South America	19	47	50	10	22	23
India	22	55	59	14	30	29
Asia-Pacific	10	30	37	4	14	17
Africa	14	31	39	5	17	7
Total All Forests:	6	21	30	5	18	29

relatively large near-term gain in low-mid latitude production. Producers in most low-mid latitude regions are the first able to react to the climate-induced increases in productivity by expanding short-rotation plantations. These plantations allow the subtropics to react with higher production just as other regions are experiencing dieback. Low-mid latitude producers consequently gain from climate change, as they enjoy large productivity increases while world prices are close to the baseline.

Producers in mid to high latitude regions are susceptible to dieback and it takes them many years to enjoy future growth increases because of their long-rotation species. Producers in Europe and Oceania do better with dieback because they experience less of it and prices are higher than with regeneration. Producers in North America and the Former Soviet Union do worse with dieback because they lose substantial stock. In North America, for example, net surplus increases from $55 to $65 billion in the regeneration scenarios, but under dieback, net surplus is predicted to range from a $4 billion loss to an $11 billion gain.

Understanding what happens to producer surplus in the global model reveals the dangers of relying on regional impact models. In their original analysis of the United States, Sohngen and Mendelsohn predicted climate change would be mildly beneficial to producers because the productivity gains outweighed the lower prices and potential losses in stock in most cases. However, their results hinged on the rest of the world being similar to the United States. With the subtropics being able to react so much more quickly to climate change, prices fall more rapidly in the global model than the U.S. model predicted. Producers in the United States consequently lose more welfare early, and productivity gains occurring later are not enough to compensate for early losses.

Although individual country effects are not presented in the analysis, the reader can extrapolate from the results to specific countries. A country's share of consumer surplus is roughly proportional to its share of regional GDP. For example, the present value of

Table 4. Present Value of Regional Welfare Effects Under Four Transient Scenarios (1990 US$, billions; r = 5%)

	High Latitude Regions					Low-Mid Latitude Regions				
Scenario	North America	Europe	Former Soviet Union	China	Oceania	South America	India	Asia-Pacific	Africa	Total
Panel A. Hamburg Dieback:										
Consumer Surplus	55.3	30.7	25.5	12.1	1.9	12.3	2.9	18.4	6.2	165.3
Producer Surplus	(43.7)	(7.8)	(9.0)	6.2	(3.2)	29.8	5.9	13.6	10.4	2.3
Net Surplus	11.6	22.9	16.5	18.3	(1.3)	42.1	8.8	32.0	16.6	167.6
Panel B. Hamburg Regeneration:										
Consumer Surplus	95.5	52.9	44.0	20.5	3.3	20.5	5.0	31.2	10.5	283.8
Producer Surplus	(30.5)	(19.1)	(3.9)	0.6	(12.5)	17.9	3.8	3.9	6.7	(33.0)
Net Surplus	65.0	33.9	40.1	21.1	(9.1)	38.7	8.8	35.1	17.2	250.7
Panel C. UIUC Dieback:										
Consumer Surplus	35.0	19.5	16.2	7.7	1.2	7.8	1.9	11.8	4.0	105.1
Producer Surplus	(39.3)	25.8	(24.6)	8.6	12.0	14.7	3.8	3.3	3.5	7.9
Net Surplus	(4.3)	45.3	(8.4)	16.4	13.2	22.6	5.7	15.1	7.5	113.0
Panel D. UIUC Regeneration:										
Consumer Surplus	80.3	44.5	37.0	17.2	2.8	17.5	4.2	26.2	8.8	238.4
Producer Surplus	(24.7)	5.6	(0.2)	5.5	0.1	2.3	1.6	(7.5)	(0.8)	(18.1)
Net Surplus	55.5	50.1	36.8	22.7	2.9	19.8	5.7	18.7	8.0	220.3

South American consumer surplus is expected to increase by $8–21 billion depending on the climate and ecological scenario. Brazil's share of regional GDP is 44%, so its share of this consumer surplus is roughly between $4–9 billion. A country's share of regional producer surplus is roughly proportional to its share of accessible forest. This statistic is more difficult to come by because land use is generally reported in terms of total forest, not just accessible forest. Assuming one-third of Brazil's forest is accessible and half of the forest in Latin America is accessible, Brazil has 37% of the accessible forest in the region. Brazil would receive approximately $3–8 billion of producer surplus.

In addition to the sensitivity of economic impacts to climate and ecological assumptions, this study explores six other sensitivity analyses related to economic assumptions: (*a*) more rapid growth in demand for timber; (*b*) higher interest rates, (*c*) lower interest rates, (*d*) increased competition for high-quality plantation sites in the tropics and lower costs for exploring inaccessible forests in high latitudes, (*e*) more restrictive constraints on forest expansion, and (*f*) more rapidly expanding agricultural sectors in the low latitudes. Each of the sensitivity scenarios is run for the Hamburg and UIUC climate scenarios under dieback and regeneration.

The results from the sensitivity scenarios produce aggregate results similar to those in the baseline scenario—i.e., global net surplus increases, consumers benefit, high latitude producers tend to lose, and low-mid latitude producers tend to gain. Several new insights about regional effects on producer surplus arise from the sensitivity analysis, however. To show these differences, we average the effects for the dieback and regeneration scenarios, and then focus on producer surplus for five of the sensitivities under one of the climate scenarios—Hamburg (table 5). The results for the UIUC sensitivity analysis are consistent with those presented for the Hamburg scenario.

Table 5. Present Value of the Change in Producer Surplus for Sensitivity Analysis on the Hamburg Climate Change Scenario, with Results Averaged for Dieback and Regeneration Scenarios (1990 US$, billions)

Timber-Producing Regions	Baseline Hamburg Scenario[a]	[1] High Demand[b]	[2] High Interest Rate (0.07)[b]	[3] Low Interest Rate (0.03)[b]	[4] High Plantation/ Low Inaccessible Cost[b]	[5] No Forest Expansion[b]
High Latitude Forests:						
North America	(37)	(38)	(20)	(158)	(35)	(36)
Europe	(14)	(23)	(3)	(67)	(14)	(14)
Former Soviet Union	(7)	(6)	(3)	(14)	(1)	(8)
China	3	6	7	(6)	8	2
Oceania	(8)	(11)	(27)	(26)	(10)	(8)
Low-Mid Latitude Forests:						
South America	24	29	15	35	18	24
India	5	6	3	8	4	5
Asia-Pacific	9	10	10	3	5	7
Africa	9	12	5	10	6	9
Total All Forests:	(15)	(13)	14	(215)	(19)	(5)

[a] Average producer surplus effect from dieback and regeneration in the Hamburg scenarios presented in table 4.
[b] Note that the high demand, high interest rate, low interest rate, and high plantation/low inaccessible cost scenarios are compared to a different economic baseline, while the no forest expansion scenario is compared to the original baseline.

- First, higher growth in global demand tends to increase the flow of benefits to producers in low-mid latitude countries because the increase in demand is met with new subtropical plantations.
- Second, in present value terms, high interest rates cause overall producer benefits. High latitude producers tend to gain, and low-mid latitude regions tend to lose. High interest rates reduce the influence of new investments (i.e., subtropical plantations) and raise harvests in existing high latitude stocks. Oceania relies on plantations and thus is adversely affected by higher interest rates. Asia-Pacific relies heavily on existing tropical hardwood stocks and thus benefits slightly from higher interest rates. Lower interest rates produce the opposite effects.
- Third, higher plantation costs, coupled with lower access costs for inaccessible forests in high latitude regions, reduce producer surplus in low-mid latitude regions because it is more costly to establish plantations. Less accessible high latitude forests are used more heavily, providing the most benefits to producers in regions with large remaining inaccessible forests, i.e., the Former Soviet Union and North America.
- Fourth, restricting the expansion of forests has small effects on producer surplus. In high latitude forests, small changes in producer surplus occur because forest rotations are longer and it would take considerable time for forests in these new areas to affect supply. Long-term prices are higher when forest expansion is

constrained, but these effects occur far into the future, and thus do not translate into large producer effects. The effects are similarly small in tropical regions because most forest expansions predicted by BIOME3 are low-value forests, not high-productivity plantations.

- Finally, we do not present the effects of the sensitivity scenario on increasing agricultural land area in the low latitudes in table 5, but we note this scenario has only a small effect on producers because the land at risk of conversion is not occupied by high-productivity plantations, but rather low-valued forests. Nevertheless, we note that if agricultural expansion in low latitude regions were to compete with these highly productive plantation lands, the flow of benefits to low-mid latitude producers would decline, as suggested by the scenario with high plantation costs.

Conclusion

This study presents estimates of regional welfare impacts in timber markets from climate change. Global climate, ecological, and economic models are linked to measure welfare changes. Studies considering only regional ecological or economic models often fail to measure and incorporate global impacts caused by climate change across the world. Global studies consequently are important for modeling both the timing and the magnitude of price effects. Existing global studies have focused heavily on productivity effects, ignoring important dynamic features (see, e.g., Darwin et al. 1995; Perez-Garcia et al.).

The results of our global models suggest net surplus in timber markets rises during climate change. Sensitivity analysis employing alternative ecological and economic assumptions indicates global welfare in timber markets could increase 2% to 8% over a 150-year time horizon. In general, consumers benefit from lower prices, producers in high latitude countries are harmed by dieback and near-term low prices, and producers in mid-low latitude countries gain, particularly in the near term (1995–2045).

Based on these ecological-economic results, climate change offers new opportunities for forestry that can first be realized by subtropical producers but which eventually will be realized in other latitudes. Climate change is consequently expected to strengthen the current shift in timber production from high latitude to mid-low latitude regions. These findings contrast with the estimates of Solomon et al. who use static analysis to predict large, negative global effects.

Most regional studies predict increases in consumer surplus and reductions in producer surplus, as does the present global study. Many regional studies, however, predict larger producer losses because they do not allow species to shift across space. For instance, assuming an average 17% change in net primary productivity (NPP) for all U.S. species, the U.S. results of McCarl et al. suggest a 14% loss in net present value of producer surplus. We unfortunately do not disaggregate the United States from North America, but our results imply smaller impacts for a similar change in NPP: producer welfare declines 4% to 6% because producers adapt by shifting more productive species, such as southern pine, northward.

Nevertheless, our results are more cautious for the United States than previous research where species migration has been allowed. Sohngen and Mendelsohn estimate that the change in producer surplus in the United States could range from −4% to +3%, where the negative effects occur with large dieback, declining NPP, and contracting forest area. The ecological scenarios in this study are milder with only predictions of increased NPP, but producers in North America are projected to lose in any case because prices decline more as low-mid latitude countries increase production over the next half century.

Capital-intensive sectors such as forestry require dynamic models. What will happen in each region depends on the existing stock, the pace of ecological change, and the speed of adaptation in that region. Low-mid latitude regions adapt rapidly to climate change because they rely on short-rotation plantations. In contrast, regions with long rotations take longer to adapt because new stands take longer to mature for harvest. Capturing these dynamics is important because the long-run results can be quite different from the short-term results. A comparative static analysis would show that in the long run, the high latitudes would benefit from climate change because species move northward. The static analysis will miss important dynamic effects, such as larger near-term losses in this region due to lower prices, long lags associated with long-rotation species, and potential dieback effects.

Although only a well-behaved slow transition in climate is considered in this analysis, the dieback scenario provides some insight into adaptation under the types of ecological impacts which could occur if climate changes more rapidly. Dieback is often associated with the effects of rapid climate change (Gitay et al.). Under dieback, our results suggest adaptation will be more difficult, consumer benefits will be smaller, and producer impacts will be larger. These effects are predicted to be more pronounced in high latitudes because many long-lived trees will die and these regions currently supply a large proportion of global timber.

Agriculture and forestry markets are not modeled together, as in Darwin et al. (1995, 1996), so we cannot discern whether new cropland will compete with existing or new forests. However, our results and sensitivity analysis identify some possible impacts of agriculture. First, we predict that inaccessible forests expand into tundra and grasslands, and that lower prices reduce pressure on these forests. For the most part, this expansion of inaccessible forests is predicted to occur in low productivity areas of the planet, not existing cropland. Second, if agriculture does not compete with these forests, the area of untouched forests is likely to increase. Third, based on the sensitivity analyses constraining accessible and inaccessible forests to their existing areas, even if agriculture does compete for new forestland areas, near-term forestry prices are not heavily affected. Thus, unless climate change causes existing forest lands in high latitude zones to be converted to agriculture, our results do not appear to be affected by shifting agriculture.

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